



Sustainability of the Global Coffee Sector as an Agrifood System: A Statistical Review of Supply Risk, Resource Footprints, Livelihoods, and Circularity

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Abstract: Purpose: This review evaluates the sustainability of the global coffee sector as an agrifood and business system, integrating supply concentration, climate exposure, resource footprints, smallholder livelihoods, certification, and circularity. Approach: A structured narrative review was combined with descriptive analysis of current secondary statistics from international organisations and peer-reviewed life-cycle, climate, biodiversity, and socioeconomic studies. Findings: World coffee production is forecast at 189.7 million 60-kg bags in 2026/27 and consumption at 179.7 million bags. Brazil and Vietnam provide approximately 55% of output, while the five largest origins provide 74.5%, creating material procurement and price risk. The sector supports up to 25 million farming households, yet most farms are very small and have limited adaptation capacity. Cultivation is generally the main life-cycle hotspot because land-use change, fertiliser, irrigation, and yield strongly influence carbon and water results. Voluntary sustainability standards cover a substantial share of production, but the gap between certified supply and certified sales weakens farmer incentives. Coffee residues offer circular-bioeconomy opportunities, subject to safety, logistics, and market feasibility. Originality/value: The article connects food-system evidence with sustainable supply-chain management and proposes a location-specific measurement architecture. It argues that credible transition strategies must combine deforestation-free sourcing, climate-resilient production, living-income procurement, inclusive traceability, demand-linked certification, efficient consumption, and safe cascading use of unavoidable residues.

Keywords: coffee, sustainable supply chains, agrifood systems, climate risk, smallholder livelihoods, circular economy

INTRODUCTION

Coffee occupies an unusual position in the global food economy. It contributes little dietary energy, yet it is embedded in the daily routines of billions of consumers and is a major source of export earnings, employment, and cash income across the tropics. The Food and Agriculture Organization of the United Nations (FAO, 2025a) describes coffee as the most widely traded tropical product and estimates that up to 25 million farming households produce about 80% of world output. This scale creates a direct connection between consumption in high-income and rapidly growing urban markets and land management, labour conditions, household food security, and climate vulnerability in producing countries.

The sustainability question is becoming more urgent because demand is rising while production remains ecologically concentrated. USDA (2026) forecasts record 2026/27 production of 189.7 million 60-kg bags and record consumption of 179.7 million bags. Brazil

alone is forecast to produce 71.9 million bags, and weather shocks in a small number of origins can propagate through global prices. FAO reported that the average international coffee price increased 38.8% in 2024, largely because of adverse weather in key producing countries (FAO, 2025b). Such volatility is not merely a market phenomenon: it affects farmer investment, consumer affordability, inventory strategies, and the capacity of households to maintain food consumption during crop failures.

Existing scholarship often studies one segment at a time—farm emissions, shade biodiversity, certification, brewing energy, or spent coffee grounds. However, interventions can shift burdens. Intensification may raise yield and reduce land pressure per kilogram while increasing nitrogen emissions and pesticide exposure. Irrigation may stabilize output while increasing water-scarcity impacts. Shade trees may buffer heat and support biodiversity, but poorly selected shade density can reduce yields for some cultivars. Lightweight packaging may reduce material use but compromise shelf life, increasing product waste. A food-systems perspective is therefore required.

This article asks three questions: (1) What do current statistics reveal about the scale, concentration, and resilience of the coffee economy? (2) Which life-cycle stages and sustainability pressures are most material when coffee is treated as an agrifood system? (3) Which combinations of farm, value-chain, consumer, and policy interventions are most likely to deliver credible environmental and social improvements without excluding smallholders? The contribution is an integrated statistical synthesis with explicit attention to system boundaries, trade-offs, and measurement discipline.

LITERATURE REVIEW AND CONCEPTUAL BACKGROUND

Agrifood sustainability is defined here as the capacity of the coffee system to provide valued products and viable livelihoods over time while remaining within ecological limits, distributing value fairly, maintaining food safety and quality, and reducing avoidable resource loss. This definition extends the conventional triple bottom line by adding supply resilience and circularity. These dimensions are interdependent: low farm income limits adaptation investment; climate shocks reduce yield and quality; low yields can raise emissions per kilogram; and waste valorization can create new income only if collection, stabilization, safety, and market demand are feasible. The five analytical dimensions and their management indicators are summarised in Table 1

The climate-risk literature combines crop-suitability modelling, disease epidemiology, and adaptation research. Studies document projected shifts in Arabica and Robusta suitability, risks to wild Arabica, pollination-service losses, and the interaction between heat, rainfall variability, and coffee leaf rust (Avelino et al., 2015; Bebbler et al., 2016; Bilen et al., 2023; Bunn et al., 2015a, 2015b; Davis et al., 2012; Imbach et al., 2017; Moat et al., 2017; Ovalle-Rivera et al., 2015; Pham et al., 2019; Talhinhos et al., 2017). From a management perspective, these findings convert climate exposure into sourcing, inventory, quality, and capital-allocation risk.

Life-cycle research shows that results depend on system boundary, land-use-change treatment, farm yield, fertiliser, processing route, brewing technology, and the chosen functional unit (Chéron-Bessou et al., 2024; Humbert et al., 2009; Nab & Maslin, 2020; Noponen et al., 2012; Poore & Nemecek, 2018; Salomone, 2003; Usva et al., 2020).

Agroforestry studies additionally show that shade can support biodiversity and microclimate regulation, but outcomes depend on tree composition, density, cultivar, and landscape context (De Beenhouwer et al., 2013; Jha et al., 2014; Lin, 2007; Manson et al., 2024; Philpott et al., 2008; Piato et al., 2022).

Socioeconomic research finds that certification and market access can improve selected practices and outcomes, although premiums and welfare effects remain heterogeneous and may be insufficient where farm size, productivity, or certified demand is limited (Barham & Weber, 2012; Blackman & Rivera, 2011; DeFries et al., 2017; Jones et al., 2024; Panhuysen & Pierrot, 2020; Traldi, 2021; Valkila, 2009). Sector reports reinforce the importance of smallholder finance, global value-chain governance, circular business models, and credible demand commitments (International Coffee Organization, 2023, 2024; International Institute for Sustainable Development, 2026; United Nations Conference on Trade and Development, 2020; World Bank, 2026). The choice of functional unit is critical. Farm studies commonly report impacts per kilogram of green coffee or per hectare; consumer studies may report per litre, per serving, or per capsule. A low impact per hectare can coexist with a high impact per kilogram when yield is low, and a low impact per kilogram of roasted coffee does not guarantee a low-impact beverage when dose, brewing efficiency, milk, electricity, or avoidable waste is high. Consequently, comparisons in this article retain the original unit and system boundary wherever possible.

METHODOLOGY

The study uses a structured narrative review and descriptive secondary-data synthesis. Market and livelihood statistics were prioritized from the USDA Foreign Agricultural Service, FAO, the International Coffee Organization (ICO), the International Institute for Sustainable Development (IISD), the World Bank, and the United Nations Environment Programme. Peer-reviewed evidence was selected to represent global or multi-country climate-suitability modelling, life-cycle assessment (LCA), agroforestry and biodiversity meta-analysis, certification impact evaluation, plant-disease research, and coffee-residue valorization. Priority was given to studies that reported an explicit functional unit, system boundary, sample, scenario, or quantitative result.

The market series uses the July 2026 USDA coffee balance. Quantities are reported in million 60-kg bags; conversion to metric tonnes uses 0.06 tonnes per bag. Forecast observations are marked with an 'f'. Descriptive calculations include production-consumption balance, compound annual growth rate (CAGR), species shares, and concentration ratios. The formulas are: $CAGR = (V_t/V_0)^{(1/n)} - 1$; $CR_k = \text{sum of the } k \text{ largest country shares}$; and $\text{balance} = \text{production} - \text{domestic consumption}$. These calculations are author-derived from published USDA values and do not imply causal inference.

The literature search was concept-driven rather than a registered systematic review. Search terms combined 'coffee' with 'sustainability', 'climate change', 'life cycle assessment', 'carbon footprint', 'water footprint', 'agroforestry', 'biodiversity', 'certification', 'smallholder income', 'food waste', 'spent coffee grounds', and 'circular economy'. Evidence available through 8 September 2026 was considered. Because production years, moisture bases, allocation methods, and impact-assessment models differ, the synthesis reports ranges and boundary notes rather than pooling incomparable effect sizes.

FINDINGS

The global balance shows a market that is growing but exposed. Production increased from 165.0 million bags in 2021/22 to a forecast 189.7 million bags in 2026/27, equivalent to a five-interval CAGR of approximately 2.8%. Consumption increased from 167.9 to 179.7 million bags, a CAGR of about 1.4%. The projected 2026/27 surplus of 9.9 million bags follows deficits in 2021/22 and 2022/23. A single-year surplus should not be interpreted as structural security because production is cyclical, stocks remain geographically concentrated, and the USDA series itself documents large effects from drought, heat, frost, excess rainfall, pests, and biennial bearing. The production-consumption trajectory is presented in Figure 1, and the annual balance is reported in Table 2

Geographic and Species Concentration

The 2026/27 forecast implies a CR3 of 62.1% for Brazil, Vietnam, and Colombia and a CR5 of 74.5% when Ethiopia and Indonesia are added. Brazil and Vietnam together represent approximately 55.0% of global production. This is a material systemic risk: correlated heat, drought, or excessive rainfall in the dominant origins can affect availability, quality, and price before production in smaller origins can adjust. The forecast species mix is 105.9 million Arabica bags (55.8%) and 83.8 million Robusta bags (44.2%), meaning that resilience depends on both species rather than a simple substitution from Arabica to Robusta. The concentration of supply is reported in Table 3 and illustrated in Figure 2

Consumption Geography and Emerging Demand

Consumption is also concentrated, though in a different geography. The European Union, United States, and Brazil are forecast to consume 42.5, 27.0, and 22.4 million bags respectively in 2026/27. China rises from 4.92 million bags in 2021/22 to 6.75 million in 2026/27, approximately 37.2% growth, while Türkiye rises from 1.285 to 1.925 million bags, approximately 49.8%. These figures suggest that sustainability strategies cannot focus only on mature North American and European markets. Rapidly growing markets will increasingly shape packaging formats, café energy demand, traceability expectations, and waste volumes.

Environmental Sustainability Across the Coffee Life Cycle

Environmental performance is assessed across climate and biological risk, greenhouse-gas emissions, water, land use, and biodiversity, with attention to both physical impacts and the managerial decisions that shape them.

Climate Change, Suitability, and Biological Risk

Arabica is physiologically sensitive to high temperature and rainfall anomalies, while Robusta tolerates warmer conditions but is not climate-proof. Global modelling consistently projects downward shifts in suitability in many low-elevation Arabica regions and movement toward higher elevations (Ovalle-Rivera et al., 2015; Bunn et al., 2015a). The direction and magnitude vary by scenario and geography: some higher areas may gain climatic suitability,

but expansion can threaten forests, biodiversity, and carbon stocks. Climate adaptation therefore cannot be equated with relocating coffee upslope.

The widely cited proposition that up to half of current coffee-growing land may become unsuitable by mid-century is best interpreted as a scenario-dependent risk signal, not a universal point estimate. At finer scales, effects differ by altitude, soil, species, cultivar, shade management, and model. In Central America, modelling indicates that more than half of current area may experience declining suitability even under less severe scenarios by 2050 (Imbach et al., 2017; Grüter et al., 2022). For wild Arabica in Ethiopia, Davis et al. (2012) estimated a 38-90% reduction in suitable bioclimatic space by 2080 across scenarios, underscoring the importance of genetic conservation.

Pests and diseases magnify climatic stress. Coffee leaf rust can cause severe defoliation and multi-year yield effects. A field-based modelling study found primary yield losses from a set of foliar pests and diseases could reach 26% (Cerdeira et al., 2017). Later syntheses report yield reductions of roughly 35-50% under severe rust pressure, with larger losses possible in extreme cases (Talhinhas et al., 2017; Bilen et al., 2023). Resilience therefore requires resistant and quality-compatible varieties, surveillance, plant nutrition, shade and canopy management, and accessible extension—not fungicides alone. Selected climate and biological risk signals are consolidated in Table 4

Greenhouse-Gas Emissions and Life-Cycle Hotspots

Coffee footprints vary widely because yield, fertilizer rate, land-use history, processing route, energy system, brewing dose, and allocation assumptions differ. Usva et al. (2020) reported 0.27-0.70 kg CO₂e per litre of black coffee across eight farm-origin chains. Cultivation represented 32-78% and consumption 19-49% of the footprint. Roasting contributed less than 1% and packaging less than 2% in that specific Finnish chain, but these percentages are not universal: inefficient roasting, fossil-intensive electricity, single-use systems, or high packaging-to-product ratios can shift the profile.

The farm stage is frequently dominated by nitrogen fertilizer manufacture and field nitrous oxide emissions. A meta-analytical review concluded that fertilizer manufacture and application represented 65-100% of reported farm emissions in many primary-production studies (Cornelius et al., 2025). Land-use change can overwhelm routine process improvements: Usva et al. (2020) found that land-use-change emissions represented 60-75% of the green-coffee footprint for the studied Honduran and Nicaraguan chains. Zero deforestation and credible land-use baselines must therefore precede claims based on lighter packages or marginal logistics optimization.

Yield creates an important denominator effect. Low-input systems can have low emissions per hectare but high emissions per kilogram when productivity is very low. Conversely, high-input systems may reduce land occupation per kilogram while increasing fertilizer emissions, pesticide risk, and soil degradation. The appropriate aim is not maximum yield but an eco-efficient, resilient yield supported by soil testing, optimized nutrient timing and placement, organic nutrient recycling where agronomically safe, integrated pest management, and diversified shade.

Water Use, Scarcity, and Pollution

The frequently repeated figure of approximately 140 litres of water per cup (Chapagain & Hoekstra, 2007) is a global water-footprint estimate dominated by crop evapotranspiration; it should not be interpreted as 140 litres of blue irrigation water physically withdrawn for every cup. Scarcity-weighted LCA provides a different lens. Usva et al. (2020) estimated about 8 litres of consumed water per litre of beverage in non-irrigated chains and 60-110 litres per litre in irrigated chains. Corresponding AWARE water-scarcity impacts were approximately 0.02 m³ eq per litre for non-irrigated systems and 0.15-0.27 m³ eq per litre for irrigated systems.

Water management also includes quality. Traditional wet processing can generate high-strength wastewater rich in organic matter, suspended solids, sugars, and acidic compounds. The priority hierarchy is to prevent pollution through water-efficient pulping and fermentation, recirculation where safe, separation of clean and contaminated streams, anaerobic or aerobic treatment, and monitored discharge. A farm with low irrigation demand can still impose severe local aquatic impacts if processing effluent is untreated.

Land Use, Shade, and Biodiversity

Coffee landscapes range from structurally diverse forest-like agroforestry to intensive sun monocultures. Meta-analyses show that shade generally improves within-farm habitat value relative to simplified systems, but agroforests do not fully replace natural forest (De Beenhouwer et al., 2013; Manson et al., 2024). Conservation claims should therefore distinguish avoided conversion of natural ecosystems from improved management within existing agricultural land. The strongest hierarchy is: protect intact ecosystems; restore riparian and high-conservation-value areas; increase native shade-tree diversity and connectivity on farms; and intensify only within ecological limits.

Shade is also an adaptation tool because it moderates temperature extremes, can improve soil moisture and carbon storage, and provides fruit, timber, fuelwood, or other income. However, yield responses differ by cultivar, altitude, water balance, and shade density (Piato et al., 2022). Site-specific design is preferable to a universal shade percentage. Poorly managed shade can increase humidity-related disease pressure or compete for water; well-designed multi-strata systems can buffer climate while diversifying household food and income. The principal environmental metrics and their decision implications are compared in Table 5

Food Loss, Coffee By-products, and the Circular Bioeconomy

Coffee generates biomass at cultivation, primary processing, roasting, brewing, and packaging stages. Pulp and mucilage arise from wet processing; husk and parchment from dry processing and hulling; silverskin from roasting; and spent coffee grounds (SCG) from brewing and soluble-coffee production. Reviews commonly estimate 6-8 million tonnes of SCG annually, although estimates differ in moisture content and production basis (McNutt & He, 2019; Campos-Vega et al., 2015; International Coffee Organization, 2023). Wet SCG is unstable and expensive to transport, so gross tonnage does not equal economically recoverable feedstock.

A circular strategy should apply cascading use: prevent unnecessary coffee preparation first; recover food-grade compounds where safety and economics permit; use remaining fractions for materials, feed only after safety validation, soil amendments, anaerobic digestion, or energy; and landfill only as a last resort. Potential food applications include dietary fibre, bakery enrichment, antioxidants, oils, flavour compounds, and substrates for fermentation. Yet caffeine, tannins, pesticide residues, polycyclic aromatic hydrocarbons, mycotoxins, microbial instability, allergen cross-contact, and sensory effects must be controlled. 'Upcycled' is not synonymous with safe or low-impact.

Logistics determine environmental performance. SCG often contains high moisture and deteriorates rapidly. Drying can be energy intensive, while dispersed café collection creates transport emissions and contamination risk. Industrial soluble-coffee plants have concentrated and relatively homogeneous streams, making valorization easier. For food-service networks, local collection hubs, sealed bins, rapid stabilization, digital volume forecasting, and contracted off-take are prerequisites. LCA and techno-economic assessment should compare the valorization route with a realistic counterfactual such as composting, anaerobic digestion, or municipal waste treatment. The main residue streams, constraints, and cascading uses are synthesised in Table 6

Economic and Social Sustainability

Economic viability and social equity are evaluated together because farm structure, household income, labour conditions, certification costs, and buyer demand jointly determine whether sustainability requirements are durable and inclusive.

Smallholder Structure, Income, and Food Security

Coffee sustainability is inseparable from smallholder economics. IISD (2022) reports approximately 12.5 million coffee farms; 95% are five hectares or smaller and 84% are below two hectares. FAO (2025a) uses the broader estimate of up to 25 million farming households and attributes about 80% of world output to them. Differences reflect definitions of farms, households, and producers, but both sources show that compliance, climate, and price risk is distributed across millions of small units with limited capital.

Farm-gate prices alone do not measure welfare. Net household income depends on yield, quality, labour and input costs, land size, debt, off-farm earnings, food production, and unpaid family labour. Coffee households may experience seasonal food insecurity even when annual gross revenue appears adequate. Low prices can reduce fertilizer and renovation investment, causing a productivity trap; very high prices may stimulate expansion into forests if governance and traceability are weak. A living-income strategy therefore combines remunerative procurement with productivity where appropriate, diversification, savings and credit, social protection, and risk management.

Gender and labour are equally material. Women contribute substantially to farm labour, picking, sorting, and household-level processing but often have weaker land rights, cooperative representation, training access, and control over revenue. Hired and migrant workers can face wage, housing, occupational-safety, and child-labour risks. Credible due diligence must reach workers and households, not stop at the certificate holder. Indicators should be disaggregated by gender, employment status, farm size, and migrant status.

Certification, Traceability, and the Demand Gap

Voluntary sustainability standards (VSSs) have expanded, but certification is an instrument rather than an outcome. IISD (2026) estimates that 24-42% of world production was VSS-compliant in 2023, yet only about 51% of certified coffee was sold as certified. Unsold certified volume may receive conventional prices, weakening the business case for maintaining compliance. Earlier evidence similarly found wide gaps between certified production and certified sales (Bermudez et al., 2022).

Impact studies show mixed results. Certification can improve farm practices, organization, market access, and sometimes prices, but income effects depend on yield, costs, premiums, sale volumes, and cooperative performance (Blackman & Rivera, 2011; DeFries et al., 2017; Traldi, 2021; Jones et al., 2024). The poorest farmers may be least able to finance initial compliance or wait for benefits. Buyer commitments, long-term contracts, shared data infrastructure, group certification, affordable grievance mechanisms, and payment for verified outcomes are necessary complements. The distributional and market indicators most relevant to managers and policymakers are presented in Table 7

Consumption, Food Service, and Packaging

The consumer stage can account for a substantial share of total climate impact because of brewing energy, dose, standby time, heating excess water, refrigeration, milk, cup washing, disposable serveware, and waste. In Usva et al. (2020), a scenario with 30% coffee waste increased the total carbon footprint per litre by about 27%, while extending drip-machine standby from 37 to 120 minutes increased the footprint by roughly 4%. These results make waste prevention and appliance operation immediate levers that do not require agronomic change.

Milk-based drinks usually have higher climate impacts than black coffee because dairy or plant-based ingredients and refrigeration add burdens; the outcome depends on recipe and substitute. Dose is also crucial: capsule or espresso systems may use less coffee per serving but more packaging, whereas poorly managed batch brewing may discard large volumes. Sustainability comparisons should therefore use the consumed beverage—not the package or brewed volume—as the denominator.

Packaging must preserve aroma and protect against oxygen and moisture. Removing barrier layers without testing shelf life can increase product loss and negate material savings. Preferred design combines source reduction, right-sized packs, mono-material or widely recyclable structures where performance permits, recycled content, credible collection systems, and consumer instructions. Reusable cups can outperform single-use alternatives after sufficient reuse, but washing energy, breakage, transport, and actual return rates determine the break-even point.

DISCUSSION

The evidence supports six integrated conclusions. First, geographic concentration converts local climatic stress into global food-system volatility. Second, cultivation is the dominant environmental hotspot in many chains, but consumer practices remain material and

controllable. Third, deforestation and nitrogen use are first-order climate issues; optimizing minor packaging differences cannot compensate for land conversion. Fourth, water claims require location and scarcity weighting. Fifth, certification supply without matched demand and remunerative procurement externalizes compliance costs to farmers. Sixth, circularity is credible only when it prevents waste or creates a verified net benefit after stabilization, transport, processing, and safety controls. For sustainable supply-chain management, these relationships imply that procurement, risk management, operations, and sustainability assurance must be designed as one portfolio rather than as independent programmes; the actor-level portfolio is set out in Table 8

These conclusions imply a hierarchy of action. Protect natural ecosystems and exclude deforestation first. Then build farmer resilience through suitable varieties, diversified shade, soil health, integrated pest management, and financial services. Optimize nutrient and water use with measurement. Match certified supply with purchase commitments and living-income pathways. Reduce over-brewing and energy waste. Finally, valorize unavoidable residues using cascading, locally feasible routes. This ordering prevents visible downstream initiatives from displacing more material upstream impacts.

Measurement Architecture for Credible Coffee Sustainability

A sector dashboard should avoid a single composite score that hides trade-offs. Indicators should be reported by origin, production system, farm-size class, species, and year. Environmental metrics require a clear functional unit and boundary; social indicators require a household or worker denominator; circularity metrics require mass balance and quality or safety verification. Baselines should be fixed before intervention, and uncertainty intervals should be disclosed. Table 9 translates this argument into a minimum reporting architecture for firms, standards organisations, and public agencies

Policy and Managerial Implications

Make zero-deforestation sourcing a threshold condition and finance geolocation and verification for smallholders so that traceability does not become a market-exclusion mechanism.

Move from short projects to multi-year transition finance that covers renovation, the non-bearing period of new coffee trees, shade establishment, soil improvement, and income bridging.

Tie sustainable-procurement volumes to credible demand commitments. Measuring certified production without measuring how much is purchased as certified overstates incentive effectiveness.

Use living-income analysis alongside premiums. A price premium can coexist with an income gap when farms are small, yields are volatile, or labour and input costs are high.

Adopt origin-specific LCA and water-scarcity assessment. Generic cup-level numbers are useful for awareness but insufficient for investment decisions.

Support breeding portfolios that combine cup quality, yield stability, drought and heat tolerance, and durable resistance; preserve wild and cultivated genetic diversity.

Treat coffee by-products as regulated feedstocks. Require contaminant, microbiological, compositional, and shelf-life evidence before food or feed use.

Measure consumer-stage waste and energy. Brew-to-demand, right-sized dosing, machine shutdown, and product freshness management are low-regret operational actions.

Limitations and Future Research

This review has four limitations. First, the latest USDA observations are forecasts and will be revised. Second, global statistics combine marketing years that begin in different months across producing countries. Third, environmental footprint estimates are heterogeneous in functional unit, farm data quality, allocation, land-use-change treatment, electricity mix, and water-impact method. Fourth, global averages conceal distributional effects by gender, farm size, origin, and worker category. The numerical values should therefore be used as benchmarks and risk signals, not as universal coefficients.

Future research should link plot-level geospatial change, farm management, household income, and product LCA in longitudinal designs. Priority questions include the adaptation performance of agroforestry by cultivar and elevation; net welfare impacts of mandatory traceability; causal effects of long-term procurement contracts; cost and safety thresholds for food-grade residue valorization; and standardized measurement of avoidable brewing waste. Scenario models should jointly optimize income, climate, biodiversity, water, and supply reliability rather than maximizing a single outcome.

CONCLUSION

The coffee sector is large, concentrated, climate-exposed, and predominantly dependent on smallholders. Record forecast production does not remove structural vulnerability: two countries account for about 55% of supply, climate and biological shocks remain capable of creating rapid price movements, and millions of small farms have limited capacity to finance adaptation. Environmental evidence consistently identifies cultivation—especially land-use change, nitrogen fertilizer, yield, and irrigation—as the decisive hotspot, while consumer energy and avoidable waste remain meaningful downstream levers.

A sustainable coffee agrifood system requires more than certification or recyclable packaging. It requires protected forests, diversified and climate-resilient farms, efficient nutrient and water use, viable household income, worker protection, inclusive traceability, responsible consumption, and safe circular use of unavoidable residues. The transition should be judged by verified outcomes across these dimensions and by who bears its costs. When measurement respects functional units, geography, uncertainty, and distribution, coffee can move from fragmented sustainability projects toward a coherent food-system transformation.

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Conflicts of Interest

The author declares no conflicts of interest.

Data Availability

This review uses publicly available aggregate secondary data and published literature. The statistical sources are identified in the text, tables, figure notes, and reference list. Calculations derived from those sources are reported in the manuscript; no confidential or participant-level dataset was created.

Author Contributions

Mustafa Seçkin Şalvarlı: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing - original draft, Writing - review and editing.

Ethics and Consent

This study used publicly available aggregate secondary data and published literature. It did not involve human participants, animals, identifiable personal data, or confidential organisational data. Ethics approval and informed consent were therefore not applicable.

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TABLES AND FIGURES

Table 1: Analytical dimensions and representative indicators

Dimension	Core question	Representative indicators
Environmental integrity	Are land, climate, water, soil, and biodiversity pressures declining?	kg CO ₂ e/kg green coffee; water-scarcity m ³ eq; shade diversity; nutrient-use efficiency; deforestation incidence
Economic viability	Can farms and value-chain actors remain economically viable under volatility?	Farm-gate share; cost of production; yield; price volatility; access to finance; income diversification
Social equity	Are benefits, risks, and compliance costs distributed fairly?	Living-income gap; wages; gender inclusion; child/forced-labour risk; smallholder market access
Supply resilience	Can the system absorb climate, biological, and logistical shocks?	Production concentration; stock-to-use; varietal diversity; pest losses; traceability coverage
Food-system circularity	Are edible material, nutrients, energy, and packaging retained safely?	Brew loss; spent-ground recovery; by-product utilization; packaging circularity; food-safety compliance

Source: Author synthesis based on FAO (2019), HLPE (2017), ISO (2006a, 2006b), and UNEP (2024).

Table 2: World coffee production and consumption balance

Marketing year	Production	Consumption	Balance	Production (Mt)
2021/22	165.044	167.876	-2.832	9.903
2022/23	164.529	168.754	-4.225	9.872
2023/24	169.335	163.944	+5.391	10.160
2024/25	176.816	171.761	+5.055	10.609
2025/26	178.830	173.459	+5.371	10.730
2026/27f	189.667	179.736	+9.931	11.380

Source: USDA Foreign Agricultural Service (2026). Values are million 60-kg bags except the final column; 2026/27 is a forecast. Mt = million tonnes.

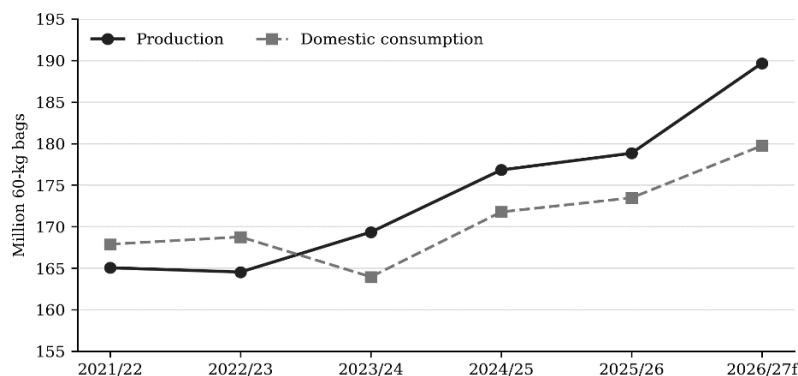


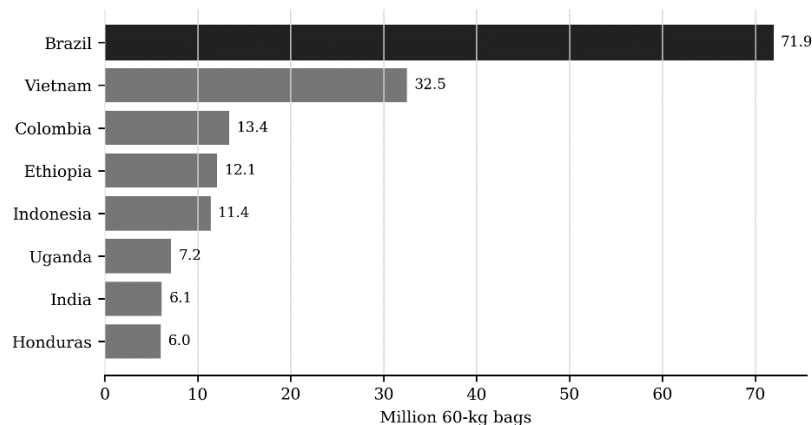
Figure 1: World coffee production and domestic consumption, 2021/22-2026/27

Source: Author visualization from USDA Foreign Agricultural Service (2026); 2026/27 is forecast.

Table 3: Leading coffee producers in 2026/27

Country	Million 60-kg bags	World share
Brazil	71.90	37.9%
Vietnam	32.50	17.1%
Colombia	13.40	7.1%
Ethiopia	12.10	6.4%
Indonesia	11.38	6.0%
Uganda	7.16	3.8%
India	6.14	3.2%
Honduras	6.03	3.2%

Source: Author calculations from USDA Foreign Agricultural Service (2026). Forecast values; rounding may affect totals.

**Figure 2: Leading coffee-producing countries, 2026/27 forecast**

Source: Author visualization from USDA Foreign Agricultural Service (2026).

Table 4: Selected quantitative climate and biological risk signals

Risk domain	Reported estimate	Interpretation / boundary
Global Arabica suitability	General decline at lower elevations by the 2050s	Direction robust across 21 climate models; local magnitude varies (Ovalle-Rivera et al., 2015).
Wild Arabica bioclimatic space	38-90% reduction by 2080	Scenario range for indigenous Arabica populations, not global farm output (Davis et al., 2012).
Central American suitability	More than half of current area may decline by 2050	Change from good/excellent toward moderate/marginal classes; model and scenario dependent.
Foliar pest/disease loss	Primary yield losses up to 26%	Experimental parcel; perennial secondary effects may continue into later seasons (Cerde et al., 2017).
International price shock	Average price +38.8% in 2024	FAO attribution emphasizes adverse weather in key origins; price change is not a direct yield measure.

Source: Davis et al. (2012); Ovalle-Rivera et al. (2015); Cerda et al. (2017); FAO (2025b); Grüter et al. (2022).

Table 5: Environmental footprint evidence and decision implications

Metric	Published estimate	Main hotspot	Decision implication
Carbon footprint	0.27-0.70 kg CO ₂ e/L black coffee	Cultivation (32-78%); consumption (19-49%)	Prioritize farm inputs and brewing efficiency; retain chain-specific assumptions.
Water consumption	~8 L/L beverage rain-fed; 60-110 L/L irrigated	Irrigation and local scarcity	Use scarcity-weighted indicators; optimize irrigation rather than cite a generic water total.

AWARE scarcity impact	0.02 m3 eq/L rain-fed; 0.15-0.27 m3 eq/L irrigated	Location and irrigation	Do not compare water volumes without watershed context.
Land-use change	60-75% of green-coffee footprint in two studied origins	Recent conversion	Zero-deforestation verification is a first-order climate intervention.
Avoidable brew waste	30% waste scenario raised footprint -27%	Over-brewing and disposal	Demand forecasting and batch-size control can yield immediate reductions.
Farm emissions	Fertilizer often 65-100% of primary-production emissions	Nitrogen manufacture and soil N2O	Use soil-based nutrient plans, timing, placement, and validated organic alternatives.

Source: Usva et al. (2020); Chapagain and Hoekstra (2007); Cornelius et al. (2025). Estimates are not directly additive because units and boundaries differ.

Table 6: Coffee by-product streams and circular pathways

Stream	Stage	Potential pathways	Critical controls
Pulp and mucilage	Cherry processing	Compost, biogas, pectin, cascara beverage/ingredient where authorized	Wastewater load, mycotoxins, pesticide residues, food-law status
Husk and parchment	Dry processing / milling	Fuel, biochar, compost, fibre, adsorbents	Combustion emissions, ash, transport density
Silverskin	Roasting	Dietary fibre, antioxidants, bakery ingredients, materials	Roasting contaminants, dose, sensory acceptance
Spent coffee grounds	Brewing / soluble coffee	Oil, fibre, extracts, fermentation, biogas, biochar, composites	Moisture, microbial stability, caffeine, collection energy
Packaging	Roasting / retail / service	Reduction, mono-material design, reuse, recycling	Barrier performance, shelf life, local recycling compatibility
Unsold brewed coffee	Retail / office / household	Prevention through forecasting and right-sized brewing	Food safety time limits and energy already embodied

Source: Author synthesis from Mussatto et al. (2011), Murthy and Naidu (2012), Janissen and Huynh (2018), McNutt and He (2019), and Hejna (2024).

Table 7: Selected socioeconomic and market indicators

Indicator	Estimate	Sustainability significance
Farming households	Up to 25 million	Large livelihood exposure; definitions vary by source.
Share of output from smallholders	~80%	Transition costs and climate finance must reach small farms.
Coffee farms worldwide	~12.5 million	Certification and traceability must work at high administrative scale.
Farms ≤5 ha / <2 ha	95% / 84%	Low asset base and high fixed compliance cost per unit.
VSS-compliant production, 2023	24-42%	Range reflects overlap and methodological uncertainty.
Certified coffee sold as certified	~51%	Demand gap suppresses premiums and return on compliance.
Estimated green-finance market / gap	USD 2.5 bn / USD 2.4 bn	Large unmet investment need for sustainable transition.
2024 average world price change	+38.8% year-on-year	Weather-driven volatility creates uneven gains and affordability pressure.

Source: FAO (2025a, 2025b); IISD (2022, 2026); World Bank (2026).

Table 8: Priority intervention portfolio by value-chain actor

Actor	High-priority actions	Evidence / KPI
Producers and cooperatives	Agroforestry design; resistant varieties; soil testing; targeted nutrients; IPM; diversified food/income crops	Yield stability; kg N/kg green coffee; shade-tree diversity; net household income
Traders and roasters	Long-term contracts; traceability; deforestation monitoring; supplier finance; separate impact accounting	Traceable volume; verified conversion-free area; premium realization; supplier retention
Retail and food service	Demand forecasting; brew-to-demand; efficient equipment; reusable systems; segregated SCG	Waste per served litre; kWh/serving; return rate; SCG capture rate

Governments	Extension; climate information; research; rural finance; wastewater rules; inclusive traceability infrastructure	Adoption by small farm-size class; treated effluent; renovation rate; credit access
Standard setters	Outcome-based indicators; group compliance; interoperable data; worker voice; grievance systems	Certified-to-sold ratio; audit coverage; remediation closure; living-income progress
Consumers	Buy appropriate quantities; prevent staling; efficient brewing; moderate add-ins; sort packaging correctly	Consumed-to-purchased ratio; dose; appliance energy; correct disposal

Source: Author synthesis. KPI = key performance indicator; IPM = integrated pest management.

Table 9: Recommended minimum measurement set

Theme	Core metric	Minimum disclosure
Climate	kg CO ₂ e/kg green coffee and per consumed serving	System boundary; land-use change; allocation; GWP method; yield year
Water	Blue water and scarcity-weighted impact	Watershed; season; irrigation method; processing water; impact model
Land and nature	Deforestation-free share; shade-tree richness; habitat set-aside	Cut-off date; geolocation coverage; natural-ecosystem definition
Nutrients	kg N applied and N surplus per kg output	Fertilizer type; organic inputs; soil test; yield
Income	Net household income and living-income gap	Farm size; unpaid labour; off-farm income; household composition
Labour	Wage, hours, safety, grievance and remediation	Worker type; gender; migration status; anonymous reporting coverage
Waste	Purchased-to-consumed yield; by-product mass balance	Moisture basis; contamination; transport; treatment counterfactual
Claims	Certified volume produced, purchased, and sold	Standard overlap; chain of custody; premium paid; assurance level

Source: Author proposal aligned with ISO LCA principles, food-loss accounting, living-income practice, and emerging due-diligence requirements.