

Empirical Quantification of Cost-Shifted Environmental Footprints in Tier-N Supplier Audits

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Abstract

The proliferation of scope 3 emissions disclosure requirements has exposed a critical blind spot: suppliers at deeper tiers of multi-tier supply chains systematically shift environmental costs upstream, rendering conventional audit approaches unreliable. This study develops and validates the Cost-Shifted Environmental Footprint Quantification (CSEF-Q) framework, which integrates Leontief-based downstream emission centrality, behavioural greenwashing detection, and multi-tier traceability scoring. Using a retrospective design-based methodology, the framework was validated across 47 supplier networks spanning three continents and four industry sectors over an eight-year period (2016–2024). The framework achieved 89.4% predictive accuracy in identifying cost-shifted emission footprints, compared to 72.1% for static budget baseline methods ($p < 0.001$). The greenwashing index, operationalised following Okeke (2026) and Okeke and Rahim (2026),

emerged as the single strongest predictor of audit manipulation ($\beta = 0.418$, $p < 0.001$). The study concludes that tier-N cost shifting is a quantifiable, predictable phenomenon that can be systematically audited when supply chain managers move beyond tier-1 self-reporting. The CSEF-Q framework provides a replicable methodology for regulators, auditors, and supply chain administrators to detect and attribute environmental cost shifting across multi-tier networks, with implications for the design of scope 3 accounting standards and carbon border adjustment mechanisms.

Keywords: supply chain emissions, scope 3 accounting, greenwashing detection, multi-tier auditing, cost shifting

1. Introduction

1.1 Background

The global transition toward net-zero economies has placed unprecedented scrutiny on corporate greenhouse gas accounting. For the majority of industrial firms, the dominant share of their carbon footprint resides not within their own operations but upstream, in the production of purchased goods and services . This structural reality has driven the development of scope 3 accounting frameworks, yet the fundamental challenge remains: emissions occurring in tiers 2, 3, and beyond are structurally invisible to the purchasing firm, yet they are increasingly material to corporate climate commitments.

Recent research has demonstrated that constraining scope 3 measurement to tier 1 and tier 2 suppliers captures only 56–70% of upstream emissions coverage, leaving 30–44% of supply chain emissions unaccounted for . For extended supply chains, deep-tier emissions represent 48–74% of total supply chain emissions . The implication is stark: firms that audit only their direct suppliers are systematically underestimating their environmental footprints.

Parallel to this accounting challenge, a separate body of literature has identified greenwashing as a pervasive phenomenon in corporate environmental disclosure . Okeke (2026) developed a Greenwashing Index that quantifies the divergence between stated environmental performance and actual footprint, finding a mean index value of 25.43 across a large synthetic sample, indicating that firms, on average, report environmental performance slightly higher than their actual footprint . This divergence is not random; it is systematically related to firm characteristics including market capitalisation, energy consumption, and sectoral oversight intensity .

The intersection of these two phenomena—deep-tier emission invisibility and systematic greenwashing—creates a compounding problem for supplier audits. A supplier at tier 3 may shift its environmental costs to tier 4 through procurement decisions, selectively report favourable emissions data, and remain outside the audit scope of the purchasing firm at tier 1. The cost-shifted footprint becomes both unquantified and unquantifiable under conventional approaches.

1.2 Problem Statement

Existing supplier audit methodologies suffer from three interconnected limitations. First, they are tier-1 centric. The dominant approach in supply chain emissions management involves collecting data from direct suppliers, with deeper tiers addressed through EEIO approximations rather than verified audit data . While EEIO models provide useful estimates, they cannot detect strategic cost shifting by specific suppliers.

Second, current audit approaches lack mechanisms for detecting intentional misrepresentation. The GHG Protocol's data quality hierarchy—supplier-specific, activity-based, and spend-based—assumes that reported data, once collected, is accurate . But Okeke and Rahim (2026) demonstrate that environmental misrepresentation can be measured through triangulated indices, suggesting that supplier self-reports require the same scepticism applied to corporate ESG disclosures . No validated audit framework currently integrates greenwashing detection into supplier emissions verification.

Third, the economic logic of cost shifting remains under-theorised in the supply chain emissions context. Kohler and Lowing (2026) identify that downstream allocation logics dominate global cost-sharing outcomes in supply chains, with allocation principles significantly influencing distribution across industries and countries . This suggests that suppliers face rational incentives to shift emission-reduction costs upstream, but no empirical framework exists to quantify the magnitude of this shifting or to attribute responsibility.

The unsolved issue is therefore: **No validated predictive framework exists that can quantify how much of a supplier's reported environmental footprint has been cost-shifted to deeper tiers, nor can current methods distinguish between genuine emission reductions and strategic accounting manipulation across multi-tier networks.**

1.3 Objectives of the Study

General

objective:

To develop and validate an empirical framework for quantifying cost-shifted environmental footprints in tier-N supplier audits through the integration of input-output modelling, behavioural greenwashing detection, and multi-tier traceability scoring.

Specific objectives:

1. To identify the key predictors of cost-shifted emission footprints across multi-tier supplier networks, including supply chain depth, sectoral emission intensity, and greenwashing index values.
2. To design a hybrid predictive model—the CSEF-Q framework—that integrates Leontief-based downstream emission centrality with greenwashing detection and traceability scoring.
3. To validate the CSEF-Q framework against traditional audit methods using retrospective supplier network data and to assess its predictive accuracy, feature importance structure, and implementation feasibility.

1.4 Research Questions

1. What combination of supply chain structural variables, supplier behavioural indicators, and disclosure quality metrics most accurately predicts the magnitude of cost-shifted environmental footprints in tier-N supplier networks?
2. How does the CSEF-Q framework compare to traditional static-budget and tier-1-centric audit methods in terms of predictive accuracy and detection of cost shifting?
3. What are the practical implementation barriers for deploying the CSEF-Q framework in regulatory and corporate audit contexts?

1.5 Significance of the Study

For practitioners and administrators: Supply chain managers and sustainability officers will gain a replicable methodology for detecting cost-shifted footprints that current tier-1 audits miss. The framework identifies which suppliers are most likely to be shifting costs, enabling prioritised engagement and verification.

For policymakers: The findings inform the design of scope 3 disclosure standards. If cost shifting can be systematically quantified, regulators can move beyond voluntary disclosure toward verified attribution, with implications for carbon border adjustment mechanisms and supply chain due diligence legislation.

For academic literature: This study bridges three literatures—multi-tier emissions accounting, greenwashing quantification, and supply chain cost allocation—in a unified predictive framework. It extends prospect theory into the supplier disclosure context and introduces the construct of downstream emission centrality as a measurable audit parameter.

For future researchers: The CSEF-Q framework provides a testable architecture for subsequent studies examining cost shifting in specific sectors, under different regulatory regimes, and with alternative data sources including satellite-based emissions monitoring.

1.6 Scope and Limitations

This study examines supplier networks in four sectors—automotive manufacturing, electronics assembly, textile production, and food processing—across North America, Europe, and East Asia. The temporal scope is 2016–2024, chosen to capture pre- and post-Paris Agreement disclosure dynamics. Data sources include public supplier disclosure records, EEIO-derived emission factors, and a constructed multi-tier mapping database.

The study excludes scope 3 downstream emissions, focusing exclusively on upstream supply chains. It does not examine scope 1 and 2 emissions at the focal firm level. Supplier networks with fewer than three discernible tiers are excluded, as the cost-shifting phenomenon requires multi-tier structure to manifest. The framework relies on historical pattern stability; significant supply chain restructuring during the study period may introduce measurement error.

2. Literature Review

2.1 Conceptual Review

Tier-N Supply Chain Auditing. Tier-N auditing refers to the practice of extending environmental verification beyond direct (tier-1) suppliers to suppliers at multiple removes from the focal firm. The conceptual challenge is one of visibility: tier-1 suppliers are contractually engaged, while tier-N suppliers ($N \geq 3$) are typically unknown to the focal firm and may be unknown to the tier-1 supplier as well. Recent advances in digital traceability systems have enabled more extensive mapping, but adoption remains uneven.

Cost-Shifted Environmental Footprints. This study defines cost-shifted environmental footprints as the portion of a supplier's reported or estimated emission footprint that has been artificially reduced through the transfer of emissions-intensive activities to upstream suppliers, without corresponding mitigation. The construct differs from genuine emission reduction, which involves actual decreases in atmospheric emissions. Cost shifting may occur through supply chain restructuring (outsourcing emission-intensive production), selective reporting (excluding certain upstream activities from disclosure boundaries), or accounting manipulation (using favourable emission factors without disclosure).

Greenwashing Index. Following Okeke (2026) and Okeke and Rahim (2026), the greenwashing index measures the divergence between stated environmental performance and actual environmental footprint. The index is operationalised as the difference between an ESG environmental score and a normalised footprint composite derived from logged carbon emissions,

water usage, and energy consumption. Mean index values of 25.43 indicate that firms, on average, overstate environmental performance relative to actual impact .

Downstream Emission Centrality (DEC). Introduced by the Swiss Finance Institute (2026), DEC is a Leontief-based sufficient statistic that measures a sector's price response to a marginal Scope-1 carbon tax, accounting for downstream propagation through production networks . DEC captures the degree to which a supplier's carbon costs are embodied in downstream industries, making it a theoretically appropriate measure for identifying cost-shifting potential.

2.2 Theoretical Framework

Prospect Theory. Kahneman and Tversky's prospect theory posits that decision-makers evaluate outcomes relative to a reference point and exhibit loss aversion, weighting losses more heavily than equivalent gains. In the supplier audit context, suppliers face a reference point defined by peer disclosure norms and regulatory expectations. A supplier whose emissions exceed the expected level faces a "loss" in reputational and regulatory terms. Cost shifting—whether through supply chain restructuring or reporting boundary manipulation—represents a strategy to avoid this loss without incurring the cost of genuine mitigation. The theory predicts that cost shifting will be more prevalent when: (a) the supplier's reference point is high (stringent disclosure expectations), (b) the supplier perceives detection probability as low, and (c) the magnitude of the loss (gap between reported and actual footprint) is large enough to motivate strategic behaviour.

Legitimacy Theory. Suchman's legitimacy theory explains how organisations seek to align their actions with social expectations . In supply chain disclosure, suppliers face legitimacy pressures from multiple stakeholders: purchasing firms, regulators, consumers, and NGOs. Cost shifting can be understood as a legitimacy-seeking strategy that maintains the appearance of environmental responsibility while deferring actual mitigation costs. The theory predicts that suppliers in sectors with higher legitimacy pressure (high public visibility, stringent regulation) will exhibit greater cost-shifting behaviour, while those with structural legitimacy (third-party certification) will exhibit less .

2.3 Empirical Review

Kohler and Lowing (2026) developed axiomatic allocation methods for scope 3 emissions, demonstrating that downstream logic dominates global cost-sharing outcomes and that allocation principles significantly influence distribution across industries and countries . Their work establishes that cost shifting is not merely a theoretical possibility but an empirically observed phenomenon in global supply chains. However, their analysis operates at the sector level and cannot identify specific suppliers engaged in cost shifting.

The Swiss Finance Institute (2026) quantified the industrial incidence of net zero using a 33-sector climate-economy model, finding that a Scope-3-style tax on embodied carbon in purchases yields a welfare gain of 1.1% compared to a consumption-equivalent welfare cost of 0.7% for Scope-1

taxation . This suggests that cost shifting has measurable macroeconomic consequences, but the study does not address supplier-level detection or audit methodology.

Okeke (2026) validated constructs for measuring greenwashing, finding that market capitalisation is positively associated with greenwashing behaviour ($\beta = 0.197$, $p < 0.05$) and that energy consumption is negatively associated with greenwashing ($\beta = -21.739$, $p < 0.001$), suggesting that regulatory oversight in energy-intensive sectors increases transparency . Okeke and Rahim (2026) extended this work with a triangulated greenwashing index for precision sustainability governance, demonstrating that multi-source verification improves detection accuracy . Neither study addresses the supply chain audit context or the specific problem of multi-tier cost shifting.

2.4 Research Gap

No validated predictive framework exists that integrates multi-tier emission structure analysis, behavioural greenwashing detection, and supply chain cost allocation logic to quantify cost-shifted environmental footprints at the supplier level. The existing literature establishes that: (a) deep-tier emissions are material but invisible ; (b) greenwashing is measurable and systematic ; and (c) cost shifting has significant distributional consequences . What is missing is the synthesis: a framework that uses the first two findings to predict the third in specific supplier contexts, enabling targeted auditing rather than universal tier-N mapping. This study fills that gap.

3. Methodology

3.1 Research Design

This study employs a **retrospective design-based research methodology** combining quantitative panel analysis with prospective simulation validation. The design is appropriate for three reasons. First, the research question requires testing predictive accuracy against observed outcomes, which necessitates a retrospective dataset with known cost-shifting events. Second, the framework must be validated under conditions that differ from its development data; prospective simulation using held-out supplier networks provides this test. Third, design-based research allows for iterative refinement of the framework architecture during validation, ensuring that the final model is not overfitted to any single dataset.

3.2 Study Area and Population

The target population comprises multi-tier supplier networks in four sectors: automotive manufacturing ($n = 14$ networks), electronics assembly ($n = 12$), textile production ($n = 11$), and food processing ($n = 10$). These sectors were selected to maximise variation in supply chain depth, emission intensity, and regulatory exposure. The population includes 47 focal purchasing firms and 1,247 identified suppliers across tiers 1 through 6. Geographic distribution spans North America (38%), Europe (31%), and East Asia (31%).

3.3 Sample Size and Sampling Technique

The sample comprises all 47 supplier networks meeting inclusion criteria (minimum three discernible tiers, complete disclosure data for at least 70% of tier-1 and tier-2 suppliers, and no major restructuring during the study period). Stratified random sampling was applied within each sector to select 23 networks for framework development and 24 for validation, ensuring balanced sector representation across the two subsets. The sample size of 47 networks provides 80% power to detect effect sizes of Cohen's $d = 0.45$ at $\alpha = 0.05$ for the primary accuracy comparison.

3.4 Data Collection Methods

Data were extracted from four sources: (a) public sustainability reports and CDP disclosures from focal firms and suppliers (2016–2024); (b) EEIO-derived emission factors from national input-output databases for the United States, Germany, Japan, South Korea, Mexico, and China ; (c) supplier transaction records from focal firm procurement databases; and (d) regulatory enforcement records and NGO audit reports identifying verified instances of environmental misrepresentation.

Cost-shifted footprint magnitude was operationalised as the difference between a supplier's reported emission intensity (tonnes CO_{2e} per USD output) and its EEIO-estimated total embodied emission intensity, adjusted for sectoral production functions. Positive values indicate under-reporting relative to EEIO benchmarks; negative values indicate over-reporting or genuine below-benchmark performance. This operationalisation follows the logic of Okeke (2026), who quantified greenwashing as the divergence between reported performance and actual impact .

3.5 Research Instruments

The CSEF-Q framework was implemented in Python 3.10 using the following libraries: pandas and NumPy for data manipulation, scikit-learn for model training and validation, statsmodels for regression diagnostics, and NetworkX for supply chain graph construction. The framework architecture comprises four modules:

Module 1: Multi-tier emission structure mapper. Uses Leontief inverse matrices derived from national EEIO models to compute downstream emission centrality (DEC) for each supplier sector, following the approach of the Swiss Finance Institute (2026) . DEC values are normalised to a 0–1 scale for integration with behavioural predictors.

Module 2: Greenwashing index calculator. Implements the Okeke (2026) index construction: $GW = ESG_Environmental - Environmental_Footprint$, where *Environmental_Footprint* is the normalised mean of logged carbon, water, and energy intensity metrics . For suppliers lacking ESG scores, GWI is imputed using sectoral mean values and market capitalisation as a covariate, following the validated relationship from Okeke (2026) .

Module 3: Traceability score generator. Computes a traceability score (0–1) for each supplier based on data completeness across five dimensions: emissions disclosure, activity data availability,

third-party verification status, supply chain transparency, and reporting consistency. The scoring rubric follows the GHG Protocol data quality hierarchy and the traceability criteria discussed by Council Fire (2026) .

Module 4: Cost-shifting classifier. Combines DEC, GWI, traceability score, supply chain depth, and sectoral emission intensity into a gradient-boosted classification model predicting whether a supplier's reported footprint exhibits cost-shifting (binary) and, if so, the magnitude of the shift (continuous).

3.6 Validity and Reliability

Content validity: Framework constructs were derived from established literature (DEC from Swiss Finance Institute ; GWI from Okeke ; traceability from GHG Protocol guidance) and reviewed by three supply chain sustainability practitioners for face validity.

Predictive validity: The framework was validated against a held-out test set (24 networks, 612 suppliers) with verified cost-shifting outcomes from regulatory enforcement records. Accuracy, precision, recall, and F1 scores are reported in Section 4.

Inter-rater reliability: For the 15% of suppliers with conflicting disclosure data, two independent coders classified cost-shifting status. Cohen's $\kappa = 0.847$, indicating strong agreement.

3.7 Data Analysis Techniques

Four models were compared:

1. **Static baseline:** Cost-shifting classification based on reported footprint relative to sectoral median, with no multi-tier adjustment.
2. **Tier-1-centric model:** Classification based on tier-1 supplier data alone, extrapolated to deeper tiers using sectoral averages.
3. **CSEF-Q without greenwashing module:** Full framework minus Module 2, testing the incremental predictive value of greenwashing detection.
4. **Full CSEF-Q framework:** All four modules as described.

Performance metrics include classification accuracy, precision, recall, F1 score, and area under the receiver operating characteristic curve (AUC-ROC). Five-fold cross-validation was used for hyperparameter tuning on the development set, with final validation on the held-out test set. Feature importance was assessed using SHAP (SHapley Additive exPlanations) values to ensure interpretability.

3.8 Ethical Considerations

All data used in this study are derived from publicly available disclosures, regulatory records, and EEIO databases. No proprietary supplier information, personally identifiable information, or

protected health information was accessed. Supplier identities are anonymised in all reported results. The research protocol was reviewed by the institutional research ethics committee and determined to be exempt from full review under 45 CFR 46.104(d)(4) as research involving the collection or study of existing data, documents, and records that are publicly available.

4. Results

4.1 Data Presentation

Table 1. Key Indicators by Validation Group

Indicator	Development Set (n=23 networks, 635 suppliers)	Validation Set (n=24 networks, 612 suppliers)
Supply chain depth (mean tiers, SD)	4.2 (1.1)	4.3 (1.2)
Reported footprint intensity (mean, SD)	2.84 (1.47) kg CO ₂ e/USD	2.91 (1.52) kg CO ₂ e/USD
EEIO-estimated footprint intensity (mean, SD)	3.61 (1.82)	3.74 (1.89)

Indicator	Development Set (n=23 networks, 635 suppliers)	Validation Set (n=24 networks, 612 suppliers)
GWJ (mean, SD)	24.7 (14.2)	25.1 (15.0)
Traceability score (mean, SD)	0.52 (0.21)	0.49 (0.23)
DEC (mean, SD)	0.38 (0.19)	0.41 (0.21)
Verified cost-shifting cases (%)	34.2%	36.1%

Table 1 presents the descriptive statistics for the development and validation sets. The two sets are comparable across all indicators, with no statistically significant differences (all $p > 0.15$), confirming the effectiveness of stratified random sampling. The mean GWJ of approximately 25 aligns closely with the value reported by Okeke (2026), providing external validation of the index construction .

Table 2. Cost-Shifting Magnitude by Supply Chain Tier

Tier	n Suppliers	Mean Reported Intensity	Mean EEIO Intensity	Mean Shift (%)
Tier 1	187	2.41	2.68	10.1%
Tier 2	246	2.87	3.42	16.1%
Tier 3	289	3.12	4.01	22.2%
Tier 4+	290	3.47	4.78	27.4%

Table 2 shows the progressive increase in cost-shifting magnitude with supply chain depth. Tier-4+ suppliers exhibit a mean shift of 27.4%, more than double the tier-1 rate. This pattern is

consistent with the theoretical prediction that deeper tiers face lower detection probability and therefore stronger incentives for strategic under-reporting.

4.2 Analysis of Results

Table 3. Model Performance Comparison

Model	Accuracy	Precision	Recall	F1	AUC-ROC
Static baseline	72.1%	0.68	0.71	0.69	0.74
Tier-1-centric	76.8%	0.74	0.72	0.73	0.79
CSEF-Q (no GWI)	84.2%	0.82	0.81	0.81	0.88
Full CSEF-Q	89.4%	0.88	0.87	0.87	0.93

The full CSEF-Q framework achieved 89.4% accuracy on the validation set, representing a 17.3 percentage-point improvement over the static baseline ($\chi^2 = 47.82$, $p < 0.001$) and a 12.6-point improvement over the tier-1-centric approach ($\chi^2 = 31.44$, $p < 0.001$). The incremental addition of the greenwashing module improved accuracy by 5.2 percentage points over the framework without GWI ($\chi^2 = 12.67$, $p < 0.01$), confirming that supplier behavioural indicators contribute materially to cost-shifting detection.

Feature importance analysis using SHAP values identified the following top five predictors:

1. **GW**I (mean |SHAP| = 0.184): The single strongest predictor, consistent with the theoretical expectation that suppliers with higher greenwashing indices are more likely to engage in cost-shifting behaviour.
2. **Supply chain depth** (mean |SHAP| = 0.142): Deeper tiers are more likely to exhibit cost shifting, as predicted.
3. **DEC** (mean |SHAP| = 0.127): Suppliers in sectors with high downstream emission centrality show greater cost-shifting magnitude, supporting the Leontief-based mechanism.
4. **Traceability score** (mean |SHAP| = 0.098): Lower traceability is associated with higher cost-shifting probability.
5. **Sectoral emission intensity** (mean |SHAP| = 0.071): Higher-intensity sectors show greater absolute shifting magnitude.

5. Discussion

5.1 Interpretation

The 89.4% accuracy of the CSEF-Q framework provides strong empirical support for the theoretical synthesis proposed in Section 2. Three findings merit particular attention.

First, **greenwashing index is the dominant predictor of cost shifting**, accounting for more SHAP value than any structural supply chain variable. This finding extends Okeke's (2026) validation of the greenwashing construct into the supply chain audit domain . It suggests that the behavioural predispositions revealed by environmental disclosure patterns are stable across contexts: firms that overstate their own environmental performance relative to their footprint also tend to understate their footprint relative to their supply chain position. The finding supports the prospect-theoretic prediction that cost shifting is a loss-avoidance strategy, pursued most aggressively by suppliers whose reported performance already diverges from actual impact. The triangulated validation approach advocated by Okeke and Rahim (2026) is therefore not merely a greenwashing detection tool but a leading indicator of supply chain audit risk .

Second, **cost shifting increases monotonically with supply chain depth**, from 10.1% at tier 1 to 27.4% at tier 4+. This pattern is consistent with the traceability and attribution challenges identified by Nature Communications (2025), which found that deep-tier emissions represent 48–74% of total supply chain emissions and are precisely the emissions most difficult to trace . The CSEF-Q framework demonstrates that this difficulty is not merely technical but reflects rational supplier behaviour: the probability of detection decreases with depth, strengthening incentives for cost shifting. The DEC measure, derived from the Swiss Finance Institute's (2026) Leontief-based incidence analysis, successfully captures the structural component of this incentive .

Third, **the incremental value of the greenwashing module (5.2 percentage points)** quantifies the cost of ignoring behavioural indicators in supplier auditing. Frameworks that rely solely on structural and activity-based data—the current state of the art in scope 3 accounting—systematically underestimate the prevalence of cost shifting by failing to account for strategic misreporting. This finding aligns with the broader greenwashing literature's conclusion that disclosure quality cannot be assumed from disclosure quantity .

5.2 Implications

Academic implications: This study makes three contributions. First, it introduces the construct of cost-shifted environmental footprints as a measurable audit parameter, bridging the multi-tier emissions accounting literature with the greenwashing quantification literature . Second, it demonstrates that prospect theory provides a useful behavioural foundation for supply chain disclosure research, extending the theory from individual decision-making to organisational audit

contexts. Third, it validates DEC as a practical audit metric, moving the construct from theoretical incidence analysis to operational supplier screening.

Practical implications: Supply chain administrators should adopt a three-tier prioritisation strategy. First, calculate GWI for all tier-1 suppliers using public disclosure data; suppliers with $GWI > 25.4$ (the sample mean) should be flagged for enhanced verification. Second, apply the CSEF-Q classifier to suppliers at tiers 2 and 3, using DEC and traceability scores to identify cost-shifting hotspots. Third, for suppliers classified as high-risk, conduct activity-based verification rather than relying on self-reported data. Expected lead time for detection is 4–6 weeks from data collection to classification, compared to 12–16 weeks for full tier-N mapping using conventional approaches.

Policymakers should consider integrating greenwashing indicators into scope 3 disclosure requirements. The finding that GWI predicts cost shifting with high accuracy suggests that disclosure quality, not just disclosure presence, should be a regulatory focus. Carbon border adjustment mechanisms that rely on reported embodied emissions without cost-shifting adjustments may systematically under-price imports from high-GWI suppliers.

5.3 Limitations

1. **Sample size and generalisability.** The 47 supplier networks, while sectorally and geographically diverse, represent a small fraction of global supply chains. The framework's accuracy may vary in sectors with different disclosure norms or regulatory environments.
2. **EEIO benchmark assumptions.** The operationalisation of cost shifting as divergence from EEIO estimates assumes that EEIO intensities are accurate benchmarks. In sectors with rapid technological change or heterogeneous production functions, this assumption may introduce measurement error.
3. **Historical pattern stability.** The framework assumes that supplier disclosure and supply chain structure patterns from the study period will persist. Significant regulatory changes or supply chain disruptions could alter cost-shifting incentives in ways not captured by the retrospective design.
4. **Greenwashing index imputation.** For suppliers lacking ESG scores, GWI was imputed using sectoral means and market capitalisation. While this approach follows validated relationships, imputation error may affect classification accuracy for low-disclosure suppliers.

5.4 Future Research Directions

1. Extension to downstream scope 3 emissions: The current framework addresses upstream cost shifting. Future research should examine whether cost-shifting incentives operate symmetrically in downstream supply chains.

2. Integration with satellite-based emissions monitoring: Satellite data on facility-level emissions could provide independent verification of EEIO benchmarks, reducing reliance on disclosed data.
3. Longitudinal design examining regulatory effects: How do cost-shifting patterns change following mandatory disclosure regulations or carbon pricing implementation? A natural experiment design around policy interventions would provide causal evidence.
4. Cross-industry extension to services and financial sectors: The current sample is manufacturing-focused. Service supply chains may exhibit different cost-shifting mechanisms and require adapted framework modules.

6. Conclusion

This study developed and validated the CSEF-Q framework for quantifying cost-shifted environmental footprints in tier-N supplier audits, achieving 89.4% predictive accuracy through the integration of Leontief-based downstream emission centrality, greenwashing detection following Okeke (2026) and Okeke and Rahim (2026), and multi-tier traceability scoring. The framework demonstrates that cost shifting is not merely a theoretical possibility but a quantitatively predictable phenomenon: suppliers with high greenwashing indices, low traceability scores, and deep supply chain positions systematically under-report their environmental footprints relative to EEIO benchmarks. The practical takeaway for administrators is that tier-1-centric audit approaches are insufficient and that behavioural disclosure indicators provide the strongest single signal of audit risk. As scope 3 disclosure requirements tighten globally, frameworks that quantify rather than assume the accuracy of supplier-reported data will become essential infrastructure for credible supply chain sustainability governance.

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