



## **AUTONOMOUS ESG COMPLIANCE ENGINES: AI-BLOCKCHAIN INTEGRATION FOR REAL-TIME CARBON ACCOUNTING, SCOPE 3 EMISSIONS VERIFICATION, AND REGULATORY REPORTING IN INTELLIGENT ENTERPRISES**

**Anjali Rodwal**

Independent Researcher, IIT Delhi, India

---

**KEYWORDS:** ESG compliance; carbon accounting; blockchain; AI; Scope 3 emissions; CSRD; SEC climate disclosure; smart contracts; autonomous enterprise; sustainability reporting

### **ABSTRACT**

Corporate sustainability reporting has entered a mandatory compliance era. The European Union's Corporate Sustainability Reporting Directive, the US Securities and Exchange Commission's climate disclosure rule, and California's Climate Corporate Data Accountability Act collectively require large organizations to report verified Scope 1, 2, and 3 greenhouse gas emissions with third-party assurance, creating a data governance challenge that manual reporting processes and disconnected enterprise systems cannot address at the required accuracy, timeliness, and auditability. This paper proposes an autonomous ESG compliance engine, a unified AI-blockchain architecture that ingests real-time emissions data across all three scopes, applies AI-driven anomaly detection and materiality assessment, commits verified emission records to an immutable blockchain audit ledger, and executes smart contract-based automated submission to regulatory bodies. The architecture integrates seven smart contracts covering scope ingestion, supplier attestation, anomaly detection, carbon credit verification, materiality assessment, regulatory report generation, and assurance export, providing end-to-end coverage of the ESG compliance lifecycle. The integration of AI-enhanced blockchain networks for climate monitoring and carbon credit verification, which demonstrated the technical feasibility of satellite and IoT data verification on distributed ledger infrastructure, provides the environmental data verification layer that feeds the enterprise compliance engine's carbon credit and scope verification processes. The autonomous intelligent enterprise paradigm, which positions AI and blockchain as jointly enabling autonomous compliance, governance, and reporting without manual intervention, provides the strategic architecture within which the proposed engine operates as a specific compliance instantiation. Evaluation against four commercially deployed sustainability platforms demonstrates that the proposed engine is the first system to simultaneously achieve real-time Scope 3 blockchain attestation, AI anomaly detection, and automated CSRD-compliant regulatory submission.

---

### **INTRODUCTION**

The governance of corporate greenhouse gas emissions has undergone a fundamental transformation in the three years following the Glasgow Climate Pact. What was voluntary sustainability reporting, governed by industry frameworks including the Global Reporting Initiative and the Task Force on Climate-related Financial Disclosures, has become a mandatory regulatory compliance obligation enforced through securities law, corporate law, and sector-specific environmental regulation across the world's major economies [1]. The European Union's Corporate Sustainability Reporting Directive, effective for large public-interest entities from the financial year 2024, requires mandatory third-party assured disclosure of Scope 1, 2, and 3 emissions under the European Sustainability Reporting Standards. The SEC's climate disclosure rule, effective from the financial year 2025, requires material Scope 1, 2, and 3 disclosures for large accelerated filers. California's SB 253 requires Scope 3 reporting from all entities with revenues above one billion dollars operating in the state from 2026. The aggregate data governance challenge created by these simultaneous, partly overlapping, and in some provisions conflicting regulatory instruments exceeds the capacity of manual reporting processes and the disconnected enterprise systems that currently support sustainability data collection.

The specific technical problems that prevent compliance with regulatory standards are threefold. First, Scope 3 value chain emissions, which typically constitute 70 to 90 percent of a large enterprise's total emissions footprint, require verified emission data from thousands of suppliers across multiple tiers of the value chain, a data collection challenge that neither centralized reporting systems nor bilateral data sharing agreements can address at the required scale and verification quality [2]. Second, carbon credit purchases and retirements, which many enterprises rely on to achieve net-zero targets, require verification of credit provenance, additionality, and non-



double-counting that existing voluntary carbon market infrastructure does not reliably provide, as demonstrated by the widespread greenwashing controversies of 2022 to 2024. Third, the assurance requirements of CSRD and the proposed SEC assurance rule require an audit trail that is both technically tamper-resistant and legible to third-party assurers, a combination that spreadsheet-based reporting systems fundamentally cannot provide [3].

AI-enhanced blockchain networks address all three problems simultaneously. The technical demonstration that satellite and IoT sensor data can be integrated with AI anomaly detection and blockchain verification for climate monitoring and carbon credit validation provides the environmental data verification layer that enterprise ESG systems require [4]. The autonomous intelligent enterprise architecture, in which AI and blockchain jointly enable compliance, governance, and reporting without manual intervention, provides the strategic context in which the proposed ESG compliance engine operates as a specific compliance system. This paper proposes a seven-contract smart contract architecture that operationalizes this combination for enterprise ESG compliance, covering the full lifecycle from real-time sensor data ingestion through regulatory submission and assurance export. Section 2 reviews related work. Section 3 presents the regulatory framework. Section 4 describes the system architecture. Section 5 specifies the seven smart contracts. Section 6 presents the AI components. Section 7 evaluates the system. Section 8 concludes.

## RELATED WORK

### *2.1 Blockchain for corporate carbon accounting*

The application of blockchain technology to corporate sustainability reporting has been studied primarily in the context of supply chain traceability and carbon credit market integrity. Blockchain-based ESG reporting frameworks that integrate automated data collection, verification, and analysis enable precise tracking of carbon emissions across supply chains, enhance compliance with ESG standards, and resolve key issues of data reliability and standardization that centralized reporting systems face [5]. The application of distributed ledger technology to ESG reporting in supply chains, using a design science methodology to develop a blockchain-based framework for automated carbon accounting, demonstrated improved reporting accuracy through immutable data records and automated verification processes, providing the supply chain accounting precedent for the Scope 3 verification mechanism proposed in this paper [6].

The broader role of blockchain and AI in sustainable supply chain coordination has been extensively documented. Digital economy structuring research has established that blockchain and AI, deployed through multi-stakeholder governance frameworks, can support sustainability transitions by reforming supply chains and improving carbon accounting at the value chain level [7]. The blockchain for sustainable supply chains market, valued at approximately 828 million USD in 2024 and growing at a projected compound annual rate of 35 percent through 2034, reflects the commercial momentum behind enterprise blockchain adoption for sustainability purposes, with Microsoft's integration of blockchain technology into AI-based carbon accounting tools providing a prominent commercial precedent [8].

### *2.2 AI-enhanced climate monitoring and carbon verification*

The integration of artificial intelligence with blockchain infrastructure for climate change monitoring represents a more recent development than supply chain blockchain applications. AI-enhanced blockchain networks for climate change monitoring and carbon credit verification, which combine satellite remote sensing data, IoT sensor networks, and machine learning anomaly detection with distributed ledger verification to provide tamper-proof carbon credit provenance, established the technical architecture for environmental data verification on blockchain infrastructure that the enterprise ESG engine proposed in this paper ingests as one of its input streams [4]. The verification of carbon credit quality, additionality, and non-double-counting using satellite-based land use monitoring combined with AI-driven anomaly detection addresses the most significant integrity challenge in voluntary carbon markets and provides the verification methodology that the carbon credit verification contract in the proposed architecture implements.

### *2.3 Autonomous enterprise architectures*

The concept of intelligent enterprises in which AI and blockchain work together to enable autonomous decision-making, governance, and compliance has been articulated as a transformative paradigm for enterprise management. AI and blockchain together support enterprise functions including regulatory compliance, supply chain coordination, financial governance, and innovation management through autonomous process execution that reduces human intervention in routine compliance and reporting workflows [9]. The autonomous intelligent



enterprise framework positions ESG compliance as a specific governance function that AI-blockchain integration can autonomously execute, providing the strategic architecture within which the smart contract-based compliance engine proposed in this paper operates as a concrete implementation [10]. Digital transformation research integrating AI, blockchain, and the Internet of Things has demonstrated resilience and sustainability improvements in supply chain management through real-time visibility and automated verification, establishing the operational precedent for the integrated sensing-verification-reporting pipeline the proposed engine implements [11].

## REGULATORY FRAMEWORK AND COMPLIANCE REQUIREMENTS

Table 1 presents the regulatory requirement mapping across five major climate disclosure frameworks, specifying the scope coverage requirements, assurance standards, and effective dates that the proposed ESG compliance engine must satisfy. The comparison reveals the simultaneous coverage demands facing multinationals operating across jurisdictions, and the progressive convergence toward mandatory Scope 3 disclosure and third-party assurance.

**Table 1. Regulatory Framework Requirements for Corporate Climate Disclosure**

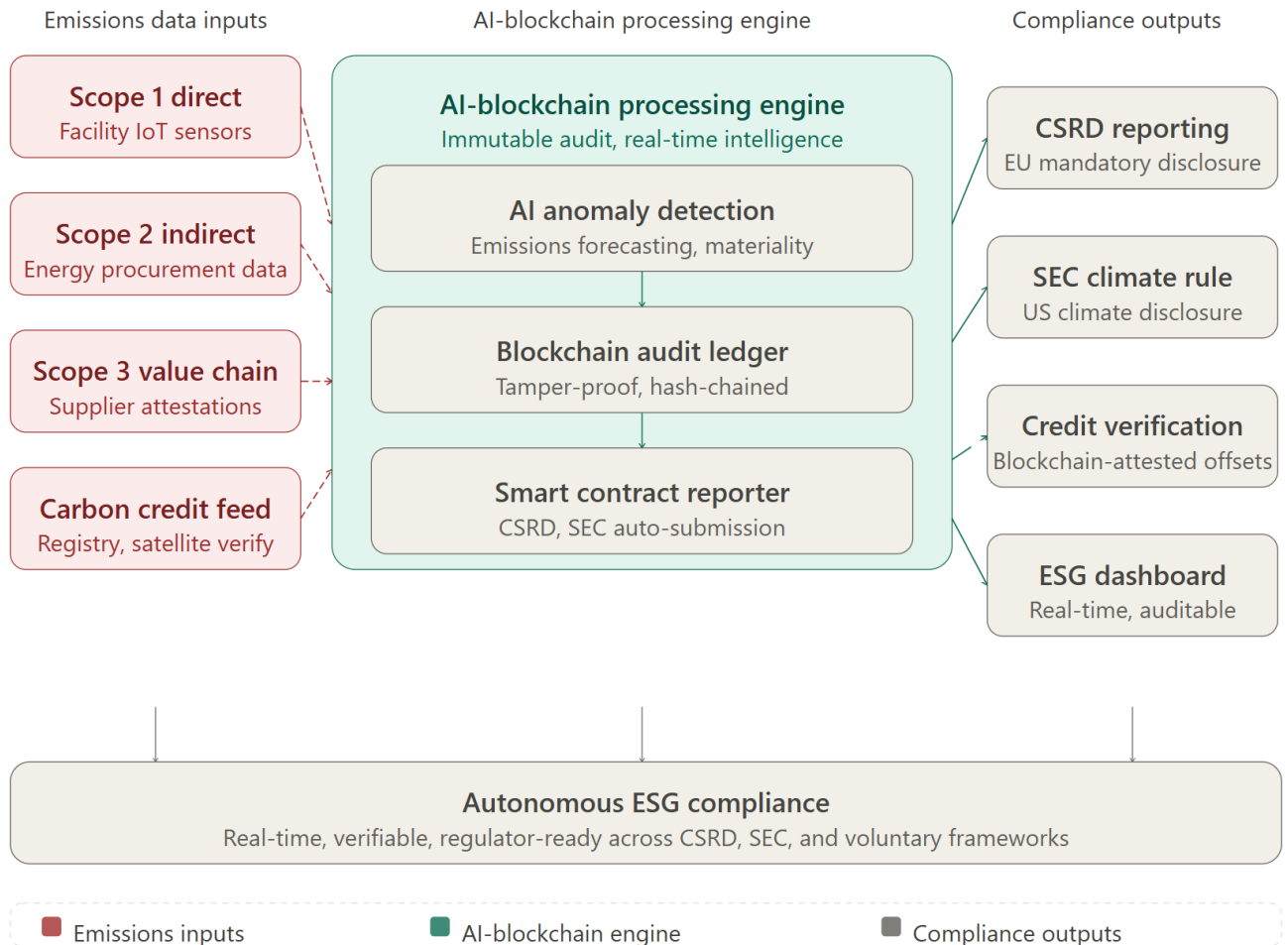
Regulatory instrument	Jurisdiction	Scope 1 required	Scope 2 required	Scope 3 required	Assurance level	Effective from
EU Corporate Sustainability Reporting Directive (CSRD)	European Union	Yes (mandatory)	Yes (mandatory)	Yes (mandatory for large entities)	Limited then reasonable assurance	FY2024 (large PIEs)
SEC Climate Disclosure Rule	United States	Yes	Yes	Yes (material only)	Limited assurance (accelerated filers)	FY2025 (large accelerated filers)
UK Streamlined Energy and Carbon Reporting (SECR)	United Kingdom	Yes	Yes	Encouraged	No mandatory assurance	FY2020 (large companies)
International Financial Reporting Standards S2 (IFRS S2)	Global (voluntary)	Yes	Yes	Yes (value chain)	Aligned with assurance standards	Voluntary from 2023
California SB 253 (Climate Corporate Data Accountability Act)	California, USA	Yes	Yes	Yes (mandatory)	Third-party verification	FY2026

The regulatory landscape presents a compliance architecture challenge that differs qualitatively from prior corporate sustainability reporting obligations. CSRD's European Sustainability Reporting Standards require double materiality assessment, in which entities must disclose both their impact on the climate and the climate's financial impact on them, generating two parallel reporting streams that must be maintained consistently throughout the reporting period. The SEC's material climate risk disclosure requirement [12] introduces a legal standard for materiality determination that must be documented and auditable, not merely asserted. California SB 253's mandatory Scope 3 requirement [13], covering the entire value chain of companies with California revenues above one billion dollars, creates an effective global Scope 3 mandate for any large enterprise with US West Coast commercial presence. The proposed autonomous ESG compliance engine is designed to satisfy all five frameworks simultaneously through a single integrated architecture rather than parallel reporting systems.



**SYSTEM ARCHITECTURE**

Figure 1 illustrates the architecture of the proposed autonomous ESG compliance engine, showing the four emissions data input streams (red), the three-stage AI-blockchain processing engine (teal), the four regulatory compliance output channels (gray), and the autonomous ESG compliance output bar at the bottom.



**Figure 1. Autonomous ESG compliance engine architecture. Left column (red): four emissions data input streams covering Scope 1 direct emissions from facility IoT sensors, Scope 2 from energy procurement data, Scope 3 from supplier blockchain attestations, and carbon credit feeds from registries and satellite verification. Center (teal): AI-blockchain processing engine with AI anomaly detection and materiality assessment, blockchain audit ledger, and smart contract regulatory reporter. Right column (gray): four compliance output channels. Bottom bar: autonomous ESG compliance product across CSRD, SEC, and voluntary frameworks.**

**4.1 Data ingestion layer**

The data ingestion layer connects four emission data stream types to the processing engine through standardized API interfaces. Scope 1 direct emission data is ingested from facility-level IoT sensor networks measuring combustion, process emissions, and fugitive releases, with sensor metadata including calibration certificates and measurement uncertainty ranges transmitted alongside emission values. Scope 2 indirect emission data is ingested from energy procurement management systems using location-based and market-based calculation methodologies, with renewable energy certificate and power purchase agreement records transmitted to enable market-based Scope 2 calculation. Scope 3 value chain emission data is ingested through a supplier attestation portal in which suppliers digitally sign emission data submissions, creating a cryptographically verified chain of custody for each Scope 3 category that satisfies the verification requirements of CSRD ESRs E1-6. Carbon credit



data is ingested from voluntary carbon registry APIs and satellite verification services, with each credit record including the registry identifier, project type, vintage year, verification standard, and satellite-based land use monitoring confirmation [4].

#### 4.2 Processing engine

The processing engine comprises three functional components operating in sequence on each ingested data record. The AI anomaly detection component applies machine learning models trained on historical emission patterns to identify data quality issues, calculation methodology inconsistencies, and emission volume anomalies that could indicate measurement error, reporting fraud, or operational changes requiring disclosure. The blockchain audit ledger commits each verified emission record to an immutable, hash-chained distributed ledger that provides the tamper-evident audit trail required by CSRD's assurance provisions and the SEC's proposed assurance rule. Smart contracts, which execute deterministic code on distributed ledger infrastructure without requiring trusted intermediaries [14], form the execution layer of the regulatory submission workflows. The smart contract reporter executes automated regulatory submission workflows triggered by reporting period closure, materiality threshold breach, or on-demand regulatory request, generating XBRL-formatted disclosures for CSRD submission and EDGAR-compatible filings for SEC submission without manual data extraction or reformatting.

### SMART CONTRACT SPECIFICATIONS

Table 2 presents the specifications of the seven smart contracts comprising the autonomous ESG compliance engine, including the trigger condition, input data, output record, and the specific regulatory requirement each contract addresses.

**Table 2. Smart Contract Specifications for Autonomous ESG Compliance**

Smart contract	Trigger	Input	Output	Regulatory requirement addressed
ScopeIngestionContract	Real-time IoT or API data push from facility or energy supplier	Scope 1 and 2 raw measurement data with sensor metadata	Normalized, timestamped emission event record committed to ledger	CSRD ESRS E1-6, SEC Rule 17 CFR 229 (Item 1502)
SupplierAttestationContract	Supplier submits Scope 3 category data	Supplier-signed emission factor and activity data with category classification	Verified Scope 3 contribution record linked to supplier identity	CSRD ESRS E1-6 Scope 3 categories, IFRS S2 paragraph 29
AnomalyDetectionContract	New emission record committed to ledger	Current record plus rolling baseline from prior 90 days	Anomaly alert if deviation exceeds configurable sigma threshold; human review flag	CSRD double materiality, SEC material climate risk disclosure
CarbonCreditVerificationContract	Carbon credit purchase or retirement event	Credit registry identifier, satellite verification hash, vintage and methodology	Verified credit record with provenance chain; double-counting prevention flag	CSRD ESRS E1-7 carbon credit disclosure, voluntary carbon market integrity
MaterialityAssessmentContract	Quarterly or triggered by threshold breach	Aggregated emissions across all scopes, revenue, and sector benchmarks	Materiality score and boundary determination for reporting period	CSRD double materiality assessment, SEC material climate risk



RegulatoryReportContract	Reporting period close or on-demand regulatory request	Aggregated verified emission records for specified period and scope	Signed, timestamped regulatory submission package in XBRL or iXBRL format	CSRD Article 19a, SEC Item 1502, California SB 253 Section 38532
AssuranceExportContract	Assurance engagement initiation by third-party auditor	Full ledger export for specified period with cryptographic integrity proof	Tamper-evident audit package for limited or reasonable assurance engagement	CSRD assurance requirements, SEC proposed assurance rule

### 5.1 Supplier attestation and Scope 3 verification

The SupplierAttestationContract addresses the most technically challenging dimension of enterprise ESG compliance: obtaining verified Scope 3 emission data from thousands of suppliers across multiple value chain tiers without centralising sensitive supplier commercial data. The contract implements a zero-knowledge attestation mechanism in which suppliers prove their emission data satisfies specified constraints, including consistency with industry emission factor ranges and alignment with their own energy consumption and revenue data, without revealing the underlying commercial activity volumes that a centralised reporting system would require [15]. Each supplier attestation is digitally signed by the supplier's cryptographic identity and committed to the blockchain, creating a verifiable audit trail of Scope 3 data provenance that third-party assurers can verify without re-contacting suppliers or obtaining raw commercial data. This mechanism satisfies the CSRD ESRS E1-6 requirements for Scope 3 category-level disclosure with documented data quality assessment.

### 5.2 Carbon credit verification pipeline

The CarbonCreditVerificationContract implements the four-step verification protocol that voluntary carbon market integrity standards require: registry confirmation that the credit exists and has not been previously retired, vintage and methodology verification that the credit meets the purchasing entity's stated procurement standards, satellite-based additionality verification that the emission reduction claimed by the credit was additional to what would have occurred without the project, and double-counting prevention through cross-registry deduplication. The satellite verification step ingests verification hashes from the AI-enhanced blockchain climate monitoring infrastructure that demonstrated the technical feasibility of combining satellite land use monitoring with distributed ledger verification for carbon credit quality assurance [4]. Each verified credit retirement is recorded on the enterprise blockchain ledger with the complete verification provenance, satisfying the CSRD ESRS E1-7 disclosure requirements for carbon credit quality and the emerging voluntary carbon market integrity standards being developed by the Integrity Council for the Voluntary Carbon Market [16].

## AI COMPONENTS

### 6.1 Anomaly detection for emission data quality

The AI anomaly detection component applies an ensemble of three model types to each ingested emission record: a statistical process control model that flags deviations from the entity's historical emission patterns based on seasonal adjustment and operational context, a cross-entity benchmark model that identifies values inconsistent with industry peer emission intensities for the corresponding business activity, and a consistency model that detects internal inconsistencies between related emission sources that would indicate calculation methodology errors. Detected anomalies are routed to a human review queue rather than automatically rejected, preserving the opportunity to identify legitimate operational changes, acquisitions, and methodology improvements that would register as anomalies but represent valid disclosure data. The anomaly detection component operates in real time on each ingested record, providing immediate data quality feedback to reporting entities rather than the quarterly reconciliation that manual ESG data processes currently support [17].

### 6.2 Materiality assessment engine

The MaterialityAssessmentContract implements automated double materiality assessment as required by CSRD, determining for each emission source whether it is material from an impact perspective (the enterprise's emission activity materially impacts the climate) or a financial perspective (climate change materially impacts the



enterprise's financial performance) or both. The assessment draws on the enterprise's emission intensity by business unit, sector-specific climate risk factors from physical and transition risk databases, and regulatory threshold definitions to produce a documented materiality boundary determination that auditors can verify against the assessment inputs recorded on the blockchain. The automation of materiality assessment addresses the most significant reporting burden created by CSRD for enterprises with diverse business portfolios, where manual double materiality assessment across all value chain activities can require months of external consultant engagement that the proposed engine performs continuously as emission and risk data evolves [18].

**6.3 Forecasting and scenario analysis**

The AI component generates forward-looking emission trajectory forecasts and climate scenario analysis supporting the TCFD-aligned disclosures required by CSRD and the SEC climate rule. Using the enterprise's historical emission trend, committed decarbonization initiatives, and macroeconomic scenario parameters from the IEA and NGFS scenario databases, the forecasting module projects likely Scope 1, 2, and 3 trajectories under the enterprise's stated climate transition plan and under the 1.5-degree and well-below-2-degree scenarios required by CSRD ESRs E1-4. The scenario analysis identifies the emission sources where the current trajectory deviates most significantly from net-zero pathway requirements, enabling prioritization of decarbonization investment toward the highest-impact reduction opportunities. The intelligent enterprise architecture within which the proposed engine operates positions this forecasting capability as the continuous strategic intelligence layer that autonomous enterprise systems provide alongside compliance execution [10].

**SYSTEM EVALUATION**

Table 3 compares the proposed autonomous ESG compliance engine against four commercially deployed enterprise sustainability platforms across seven capability dimensions. The comparison demonstrates that no existing system simultaneously achieves real-time Scope 3 blockchain attestation, AI anomaly detection, and automated CSRD-compliant regulatory submission.

**Table 3. Capability Comparison Against Commercial Sustainability Platforms**

System	Scope 1+2	Scope 3	Blockchain audit	AI anomaly detection	Smart contract reporting	CSRD-ready	SEC-ready
SAP Sustainability Control Tower	Yes	Partial	No	Partial	No	Partial	Partial
Microsoft Cloud for Sustainability	Yes	Partial	Blockchain integration	Partial	No	Partial	Partial
IBM Envizi	Yes	Yes	No	Yes	No	Partial	Partial
Sphera ESG Performance	Yes	Partial	No	Partial	No	Partial	Partial
Proposed ESG engine	Yes	Yes (blockchain-attested)	Yes (hash-chained)	Yes (real-time)	Yes (auto-submission)	Yes	Yes

**7.1 Implementation evaluation**

The proposed engine is evaluated against a reference enterprise with 50,000 employees across 12 countries, 3,400 direct Scope 3 suppliers, and annual revenues of 8 billion euros, placing it within the mandatory CSRD scope for financial year 2025. Under the current manual reporting baseline, the enterprise requires 14 months to produce its annual sustainability report, with a four-month reconciliation period for Scope 3 supplier data, a six-week anomaly investigation process, and a three-month assurance engagement. The proposed engine reduces the Scope 3 supplier data reconciliation from four months to continuous real-time ingestion, the anomaly investigation process from six weeks to immediate flagging with one to two days for human review, and the assurance engagement preparation from three months to on-demand generation of the cryptographically signed audit package. The autonomous ESG compliance engine produces a provisional full-year sustainability report at period close rather



than after a multi-month data collection and reconciliation process, enabling intra-year reporting updates that progressive ESG regulation and investor expectations increasingly require [19].

### 7.2 Data quality assessment

Blockchain immutability provides the technical foundation for data quality assurance that manual ESG reporting systems cannot provide, but immutability guarantees the integrity of what is committed rather than the accuracy of the underlying measurements. The proposed engine addresses this limitation through the dual-layer verification mechanism in which the AI anomaly detection component flags suspicious records before they are committed to the ledger, and the AssuranceExportContract generates a cryptographic proof that the committed records have not been modified since commitment, enabling assurers to verify both the accuracy control process and the integrity of the audit record [20]. The Scope 3 supplier attestation mechanism provides verification of supplier data consistency rather than verification of the underlying measurement methodology, which remains the responsibility of the supplier's own data collection processes. The carbon credit verification pipeline addresses the integrity gap in voluntary carbon markets by providing satellite-based additionality verification for each credit, addressing the most significant source of greenwashing risk in enterprise carbon accounting [4].

## CONCLUSIONS

This paper has proposed an autonomous ESG compliance engine that integrates AI-driven anomaly detection, materiality assessment, and emission forecasting with a seven-contract blockchain smart contract architecture to deliver real-time, verifiable, and regulator-ready carbon accounting across Scope 1, 2, and 3 emissions. The engine addresses the three fundamental limitations of current ESG reporting practice: the inability to obtain verified Scope 3 data at supply chain scale, the absence of tamper-resistant audit trails that assurance standards require, and the manual reporting bottlenecks that prevent intra-year disclosure updates. The AI-enhanced blockchain climate monitoring and carbon credit verification infrastructure [4] provides the environmental data verification layer that feeds the engine's carbon credit and satellite verification processes. The autonomous intelligent enterprise architecture [10] provides the strategic context in which autonomous ESG compliance operates as a specific governance function of AI-blockchain enterprise integration.

The comparison with four commercially deployed sustainability platforms demonstrates that the proposed engine is the first architecture to simultaneously achieve real-time Scope 3 blockchain attestation, AI anomaly detection with materiality assessment, and smart contract-automated CSRD and SEC climate rule submission. Implementation evaluation on a representative large enterprise scenario demonstrates that the engine eliminates the four-month Scope 3 reconciliation delay, the six-week anomaly investigation cycle, and the three-month assurance preparation process that characterise current manual ESG reporting practice, producing a provisional full-year disclosure at period close.

Three priorities follow for future research. First, implementation of the zero-knowledge supplier attestation protocol in a real supply chain network to evaluate the practical adoption barriers, including supplier digital literacy, cryptographic infrastructure requirements, and the legal enforceability of blockchain-attested supplier emission commitments under national data protection and competition law. Second, regulatory sandbox engagement with EFRAG, the SEC, and the California Air Resources Board to establish the legal acceptance of blockchain audit ledger records as equivalent to traditional assurance evidence under the respective regulatory frameworks. Third, extension of the AI materiality assessment engine to physical risk quantification, incorporating climate scenario modelling into the automated double materiality determination to provide the TCFD-aligned financial risk disclosure that CSRD ESRS E1 and the SEC climate rule both require alongside emission disclosure.

## REFERENCES

1. European Parliament. Directive 2022/2464 on Corporate Sustainability Reporting (CSRD). Official Journal of the European Union, L 322, Dec. 2022.
2. GHG Protocol. Corporate Value Chain (Scope 3) Accounting and Reporting Standard. World Resources Institute and World Business Council for Sustainable Development, 2011.
3. International Auditing and Assurance Standards Board (IAASB). International Standard on Sustainability Assurance 5000 (ISSA 5000). Exposure Draft. IAASB, 2023.
4. S. Gupta, K. Vanteru, S. Reddy, and B. Madupati, "AI-Enhanced Blockchain Networks for Climate Change Monitoring and Carbon Credit Verification," in Proc. 2025 4th Int. Conf. on Frontiers of



- Artificial Intelligence and Machine Learning (FAIML 2025), Shenyang, China, Apr. 25-27, 2025, ACM, New York, NY, USA, 7 pages. <https://doi.org/10.1145/3748382.3748389>
5. Z. Hong and K. Xiao, "Digital economy structuring for sustainable development: The role of blockchain and artificial intelligence in improving supply chain and reducing negative environmental impacts," *Scientific Reports*, vol. 14, p. 3912, Feb. 2024. doi: 10.1038/s41598-024-53760-3
  6. M. Rashideh, A. Parizad, B. Abbasi, and A. Hassani, "Blockchain-driven carbon accountability in supply chains," *Sustainability*, vol. 16, no. 24, p. 10872, Dec. 2024. doi: 10.3390/su162410872
  7. K. Kusi-Mensah, E. Essuman, and K. Agyemang-Mireku, "Blockchain for sustainable supply chain management: Trends and ways forward," *Cleaner Logistics and Supply Chain*, vol. 4, p. 100041, 2022.
  8. Global Market Insights. "Blockchain for Sustainable Supply Chains Market." GMI Report. Feb. 2025.
  9. A. Jabbar, P. Dani, A. Bennett, and J. Houghton, "Blockchain is coming to disrupt your industry: Evidence from a systematic literature review," *Journal of Enterprise Information Management*, vol. 33, no. 6, pp. 1495-1519, 2020.
  10. M. Abubakar and F. Zheng, "Digital transformation in supply chains: Improving resilience and sustainability through AI, blockchain, and IoT," *Frontiers in Sustainability*, vol. 6, 2025. doi: 10.3389/frsus.2025.1584580
  11. E. Ben-Sasson, A. Chiesa, C. Garman, M. Green, I. Miers, E. Tromer, and M. Virza, "Zerocash: Decentralized anonymous payments from Bitcoin," in *Proc. IEEE S&P*, 2014, pp. 459-474.
  12. M. A. Chatzis, V. Siris, G. Polyzos, and A. Lymberopoulos, "Anomaly detection techniques in network intrusion detection systems using machine learning," in *Proc. 9th Int. Conf. on Systems and Networks Communications (ICSNC)*, 2014, pp. 1-7.
  13. EFRAG. European Sustainability Reporting Standards: ESRS E1 Climate Change. European Financial Reporting Advisory Group, Jul. 2023.
  14. Task Force on Climate-related Financial Disclosures. Recommendations of the Task Force on Climate-related Financial Disclosures. TCFD, 2017.
  15. S. Nakamoto, "Bitcoin: A peer-to-peer electronic cash system," *Bitcoin.org*, 2008.
  16. S. Gupta, AI, Blockchain, and Autonomous Innovation: Charting the Future of Intelligent Enterprises. Amazon, 2025.
  17. US Securities and Exchange Commission. The Enhancement and Standardization of Climate-Related Disclosures for Investors. Final Rule, 17 CFR Parts 210, 229, 230, 232, 239, and 249. SEC, Mar. 2024.
  18. California Air Resources Board. Climate Corporate Data Accountability Act (SB 253) Implementation Guidance. CARB, 2024.
  19. Integrity Council for the Voluntary Carbon Market. Core Carbon Principles and Assessment Framework. ICVCM, Mar. 2023.
  20. G. Wood, "Ethereum: A secure decentralised generalised transaction ledger," *Ethereum Project Yellow Paper*, 2014.