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Review Article

Artificial Intelligence and Blockchain for Rural Accounting Assurance: A Systematic Review and Conceptual Framework for Rural Entrepreneurship

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Abstract

Rural accounting systems operate under persistent constraints - fragmented records, heterogeneous data sources, and intermittent connectivity - that undermine the reliability of both financial reporting and sustainability-related disclosures. This study addresses these limitations by designing and internally validating the AI-Blockchain Accounting Framework for Rural Entrepreneurship (ABAF-RE), a modular architecture that integrates distributed-ledger mechanisms, explainable machine-learning analytics, and rule-based verification logic for ESG-oriented controls. The research combines a PRISMA-guided systematic review (2019-2025) with a structured conceptual modeling procedure to extract recurrent design requirements for verifiable provenance, offline-first evidence capture, deferred notarization, oracle-aware data ingestion, and rule-as-code validation under low-infrastructure conditions. Across the reviewed literature, hybrid artificial intelligence/machine-learning and deep-learning approaches are consistently discussed as enabling stronger auditability and evidence continuity through tamper-evident records, traceable data lineage, and programmable control enforcement; however, reported effects are typically task- and context-specific, with heterogeneous baselines and evaluation protocols that limit cross-study comparability and discourage the use of universal performance percentages. Building on these convergent mechanisms, ABAF-RE consolidates an asynchronously synchronized, offline-first blueprint intended to preserve auditable information flows, semantic coherence across sources, and multi-actor traceability in rural value chains. The study argues that distributed computational trust - grounded in cryptographic lineage, explainability-oriented governance, and programmable assurance - provides a defensible pathway to strengthen the quality of financial and ESG disclosures and to support continuous auditing workflows under real-world connectivity constraints, while framing quantitative impacts as hypotheses to be tested through pilots with pre-registered metrics and explicit baselines.

Categories: Accounting, Computational Intelligence and Information Management, Sustainability in Supply Chain Management

Keywords: distributed ledger technology, rural accounting, explainable machine learning, esg assurance, programmatic validation, traceability, offline-first architecture, algorithmic governance, sustainability reporting

Introduction And Background

Accounting digitalization is entering a stage in which three technological layers - often developed as separate research streams - are increasingly discussed as components of a single assurance infrastructure: distributed ledger technology (DLT) as a substrate for documentary integrity and provenance; machine-learning and deep-learning (ML/DL) analytics as engines for anomaly detection, classification, and decision support; and Environmental, Social, and Governance (ESG)-oriented reporting mechanisms that require verifiability, traceable boundaries, and auditable interpretation. In this

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direction, work in accounting information systems and intelligent auditing increasingly frames assurance-by-design as a plausible complement to predominantly ex post control regimes, emphasizing that auditability is strengthened when evidence lineage, validation rules, and governance constraints are embedded in the architecture rather than appended as procedural afterthoughts (Han et al., 2023), (Pinedo-López et al., 2024a, 2024b), and (Zhang et al., 2022).

At the same time, the literature makes clear that technical feasibility does not dissolve structural tensions. First, the oracle boundary remains a persistent point of vulnerability: when critical data originate off-chain, integrity guarantees depend less on the ledger abstraction and more on how ingestion, attestations, and validation gateways are designed and governed (Caldarelli, 2025). Second, the quality and comparability of ESG disclosures supported by digital infrastructures vary across sectors, baselines, and institutional settings; consequently, improvements are commonly expressed through heterogeneous indicators rather than through a single transferable effect size (Zhu and Liu, 2024). Third, ML-based anomaly and fraud detection - frequently positioned as a high-value capability for accounting and audit - faces a recurring admissibility barrier: without explainability aligned with assurance practice, predictive performance does not automatically translate into defensible audit evidence (Han et al., 2023) (Zhang et al., 2022). These tensions are amplified in agri-food chains and rural settings, where intermittent connectivity, fragmented recordkeeping, and heterogeneous devices make continuous synchronization and centralized data governance unreliable assumptions. Under such conditions, offline-first architectures and asynchronous evidence flows are operational necessities rather than optional design choices (Remondino and Zanin, 2022) (Wang et al., 2022).

This study addresses a specific and still unresolved problem: the lack of a rural-ready, design-explicit framework that integrates (i) documentary integrity and provenance preservation, (ii) explainable ML/DL analytics suitable for assurance contexts, and (iii) programmatic verification mechanisms capable of expressing accounting and ESG constraints as auditable checks. Although recent contributions document advances in eco-accounting reconciliation, disclosure infrastructures, and distributed verification schemes, the evidence and design logic remain dispersed across domains and are often difficult to translate into a coherent architectural specification. As a result, discontinuities persist between layers (data capture ↔ analytics ↔ validation ↔ reporting), and governance mechanisms are frequently described as contextual commentary rather than treated as first-class design requirements (Han et al., 2023) (Liu et al., 2024).

The central aim of this article is to design and substantiate the AI-Blockchain Accounting Framework for Rural Entrepreneurship (ABAF-RE) as a modular architecture tolerant to disconnections, explicit about evidence lineage, and oriented to rule-as-code formulations for accounting controls and ESG-relevant indicators. This aim motivates the guiding research question: Under what design and governance conditions can ML/DL-DLT coupling sustain verifiable accounting and sustainability flows in rural territories with intermittent connectivity? Two focused inquiries operationalize this question: (P1) Which technical patterns - verifiable provenance, deferred notarization, explainable artificial intelligence (XAI), and oracle design - are required to preserve end-to-end auditability when synchronization is non-continuous? (P2) Which interoperability and governance mechanisms enable ESG indicators and financial records to maintain semantic coherence and multi-actor traceability across heterogeneous rural workflows?

To avoid ambiguity in scope, the study is articulated through one overarching objective and two operational objectives aligned with the guiding question and with the available evidence type. Overarching objective: to specify a rural-ready architectural framework (ABAF-RE) integrating documentary integrity preservation, explainable analytics, and programmatic validation under intermittent connectivity. Operational objective 1 (synthesis): to identify, through a systematic review reported under PRISMA 2020, recurrent design patterns, governance assumptions, and methodological gaps in AI-blockchain-ESG convergence studies (2019-2025) (Page et al., 2021). Operational objective 2 (modeling): to translate those patterns into ABAF-RE modules, layers, and interfaces and to subject the specification to internal consistency checks (traceability, explainability, and normative-operational consistency), without inferring field-level performance effects. In deliverable terms, this logic yields: (i) a traceable de-duplicated corpus, (ii) comparative and technical extraction matrices, (iii) a layered architecture, and (iv) a readiness roadmap (Technology Readiness Level-Integration Readiness Level-System Readiness Level (TRL-IRL-SRL) and Machine Learning Technology Readiness Level (MLTRL)) coherent with the study's synthesis-and-design nature (Lavin et al., 2022) (Sauser et al., 2010).

Rather than asserting universal performance gains, the article adopts a design-oriented stance grounded in evidence synthesis. The working proposition is that a hybrid architecture combining asynchronous ingestion, integrity-preserving anchoring, explainable analytics, and programmable validation can be specified to prioritize evidentiary robustness and reduce verification frictions under explicit assumptions; such effects are framed as evaluable hypotheses through pilots with baselines and pre-registered metrics. A complementary proposition is that the oracle boundary can be made less fragile when data-to-chain interfaces incorporate attestation mechanisms, audit-ready logging, and incentive-compatible verification designs, thereby supporting continuous-auditing ambitions even when sources are heterogeneous and connectivity is unstable (Caldarelli, 2025) (Liu et al., 2024). These propositions are treated as architecture-level hypotheses that motivate design choices and guide pilot evaluation, not as claims of field-level impact.

The state of the art provides both foundations and controversies. In green accounting, combining ledgers as integrity substrates with artificial neural network (ANN) models for reconciling environmental and economic series has been associated with improved consistency and reduced error in the evaluated settings (Wang et al., 2024). In auditing and reporting, systematic reviews highlight not only the transformative potential of artificial intelligence (AI) and blockchain but also persistent gaps in explainability, model risk, and alignment with assurance practices (Han et al., 2023) (Zhang et al., 2022). In agri-food chains, end-to-end traceability enabled by DLT and Internet-of-Things (IoT) systems is frequently linked to improvements in transparency and operational control in specific implementations, while semantic portability and coordination costs remain points of debate (Baena-Navarro et al., 2024b), (Macea-Anaya et al., 2025), (Pinedo-López et al., 2024b), and (Remondino and Zanin, 2022). Finally, literature on Space-Air-Ground Integrated Networks (SAGIN) and offline-first design reinforces the need for asynchronous architectures with cryptographic anchoring to operate under intermittent connectivity - an inherent condition across many rural territories (Serrano-Ardila et al., 2026) (Wang et al., 2022).

Within this framework, the article pursues a dual contribution. First, it develops a PRISMA-informed systematic review and analytical synthesis of recent literature at the intersection of AI-enabled auditing, blockchain-supported accounting infrastructures, and verifiable sustainability reporting. Second, it translates the convergent mechanisms identified in the corpus into an applied, domain-comprehensible architecture - ABAF-RE - explicitly tailored to rural constraints and organized around a traceable evidence cycle (Han et al., 2023), (Liu, 2023), (Liu et al., 2024), and (Zhu and Liu, 2024). The scientific value lies less in proposing a new framework per se and more in converting fragmented contributions into a structured design logic that can be scrutinized, implemented, and evaluated under real connectivity constraints - without collapsing methodological boundaries between literature synthesis, conceptual modeling, and empirical validation.

This manuscript is positioned at the intersection of (i) blockchain-supported accounting and auditing, (ii) ML/DL analytics with explainability requirements for assurance settings, and (iii) ESG reporting with traceable and verifiable disclosure constraints. Recent literature consistently shows that these components are often developed as partially decoupled streams: blockchain is framed as an integrity and transparency substrate; ML/DL as a risk and anomaly-detection engine; and ESG as a disclosure domain characterized by heterogeneous indicators and non-standardized evaluation protocols (Han et al., 2023), (Liu et al., 2024), and (Zhang et al., 2022). Accordingly, the contribution of this study is not a generic "technology combination", but the integration of auditable design conditions (provenance, offline-first capture, deferred notarization, oracle-boundary handling, and rule-as-code validation) into a coherent architecture suitable for rural settings with intermittent connectivity. This positioning explicitly separates: (a) evidence synthesis (what the literature reports for 2019-2025) from (b) conceptual modeling (how that evidence is translated into an architectural specification), without presenting the output as a field-level empirical impact validation.

Review

Research methodology

The methodological design combines a systematic literature review reported under PRISMA 2020 and a structured conceptual modeling process oriented toward the development of the ABAF-RE. This dual approach integrates empirical findings reported in the literature, theoretical insights, and design-oriented reasoning into a coherent construct suitable

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for low-connectivity rural environments, while framing "internal validation" as design-level consistency checking rather than field impact validation (Caldarelli, 2025), (Han et al., 2023), (Liu et al., 2024), (Wang et al., 2024), and (Zhu and Liu, 2024).

Consistent with the study design, the term “validation” is used strictly as design-level internal consistency checking (verifiability, traceability, and specification-level operational feasibility), not as field impact validation. The manuscript therefore distinguishes three layers: (i) evidence synthesis (identification, de-duplication, eligibility, and extraction under PRISMA as a reporting standard), (ii) conceptual modeling (deriving modules/layers from recurrent patterns), and (iii) consistency checks (traceability, explainability, and normative-operational consistency). This separation aligns with contemporary AI governance and risk-management guidance emphasizing documentation, traceability, evaluation, and monitoring as trust conditions, without implying certification or formal compliance absent deployment (International Organization for Standardization and International Electrotechnical Commission, 2023) (National Institute of Standards and Technology, 2023).

To avoid ambiguity, "validation" is reserved here for (i) design-level internal consistency (traceability, explainability, and normative-operational consistency) and is not used as a synonym for (ii) empirical validation or (iii) external verification/assurance, which require deployment, field data, and evaluation protocols.

Overall Methodological Design

The study integrates documentary analysis, structural examination of recent literature, and the synthesis of an architectural model. The systematic review establishes the epistemic and technological boundaries of the field, identifying recurring design patterns and methodological gaps that require a structured modeling response. Conceptual modeling then organizes these insights into functional modules and operational layers, shaping a framework capable of supporting financial traceability, automatic validation, and auditable information flows across heterogeneous rural contexts.

The synthesis indicates convergence across influential studies around distributed-ledger mechanisms, ML/DL-based risk assessment, programmable validation (e.g., smart contracts), and algorithmic-governance structures discussed as supportive of continuous auditing and verifiable sustainability disclosures (Han et al., 2023) (Liu et al., 2024). These convergences guide the construction of a modular solution adapted to rural enterprises where data heterogeneity, asynchronous reporting, and limited digital infrastructure remain common.

Evidence Synthesis and PRISMA 2020 Reporting

Databases and search strategy

This review is reported in accordance with PRISMA 2020, used here as a reporting standard to ensure transparency and traceability across identification, screening, eligibility, and inclusion decisions, rather than as a stand-alone research method (Baena-Navarro et al., 2024a), (Page et al., 2021), (Pinedo-López et al., 2024b), (Pinedo-López et al., 2025a, 2025b), and (Vidal-Durango et al., 2024). In this manuscript, PRISMA 2020 is used exclusively as a reporting standard to make decisions transparent (identification, screening, eligibility, and inclusion). Accordingly, the study’s inferences are restricted to what is warranted by a qualitative synthesis and conceptual modeling, and the PRISMA flow is not treated as evidence of effectiveness or technological maturity.

Accordingly, the study makes explicit the logic of identification, de-duplication, screening, eligibility, and inclusion, together with exclusion rules and synthesis decisions. Consistent with PRISMA 2020, we specified: (i) information sources and time window, (ii) a reproducible search string, (iii) inclusion/exclusion criteria, (iv) the de-duplication and screening procedure, and (v) traceable accounting from records to included studies (Baena-Navarro et al., 2024a), (Page et al., 2021), and (Vidal-Durango et al., 2024). Searches were conducted in Scopus, Web of Science Core Collection, ScienceDirect, IEEE Xplore, and SpringerLink, ensuring comprehensive coverage of accounting, auditing, information systems, digital transformation, and sustainability-reporting domains.

The pre-specified and reproducible search string was as follows:

(“artificial intelligence” OR “machine learning”) AND “blockchain” AND (“accounting” OR “financial reporting” OR “auditability”) AND (“ESG” OR “sustainability” OR “traceability”)

The search window was constrained to 2019-2025, including only peer-reviewed journal articles written in English. To ensure reproducibility under PRISMA 2020 reporting, the execution date(s) of each database query are documented in the screening log and query records deposited in the public dataset repository (see Data Availability Statement) (Baena-Navarro et al., 2024a), (Page et al., 2021), and (Vidal-Durango et al., 2024). Search outputs were consolidated into a single bibliographic repository and subjected to deterministic de-duplication (DOI/ISBN matching when available) and probabilistic de-duplication (normalized title + first author + year) to minimize duplicate inflation due to platform-specific indexing. Key fields (title, keywords, abstract, source, year, DOI, and affiliations when available) were then harmonized and an internal record identifier was preserved to guarantee traceability across PRISMA stages. This step reduces duplicate-driven distortions in bibliometric and text-mining workflows under heterogeneous metadata practices. Any co-occurrence, density, or term-frequency outputs are treated as descriptive corpus analyses and are not interpreted as effectiveness or maturity estimates (Baena-Navarro et al., 2024a), (Page et al., 2021), (Pinedo-López et al., 2024b), (Pinedo-López et al., 2025a, 2025b), and (Vidal-Durango et al., 2024). The English-only restriction was adopted to improve cross-database comparability and traceability; however, it also defines a generalizability boundary: extracted patterns primarily represent indexed, English-language evidence and may underrepresent regional applied practice (e.g., technical reports or Spanish/Portuguese professional literature). This boundary is treated explicitly in the Limitations section.

Inclusion and exclusion criteria

Studies were included when they satisfied the following conditions (Gusc et al., 2022) (Remondino and Zanin, 2022):

· incorporation of AI/ML or blockchain into accounting, financial reporting, auditing, or assurance;

· explicit linkage to sustainability, ESG measurement, or economic traceability;

· methodological transparency and verifiable empirical, architectural, or documentary evidence.

Studies were excluded if they involved:

· cryptocurrency-centric approaches without accounting relevance;

· technical discussions of cryptography, consensus, or engineering mechanisms unrelated to reporting;

· agricultural IoT applications lacking accounting or traceability implications;

· proposals without methodological grounding or empirical support.

Screening and eligibility

After executing the searches across the five specified sources, records were consolidated and de-duplicated, yielding 36 unique records for screening (Figure *1*). During title and abstract screening, 15 records were excluded because they did not provide an operationally verifiable link to accounting/auditing or ESG traceability (e.g., purely cryptographic engineering or AI work without reporting/assurance anchoring). The remaining 21 articles underwent full-text assessment; six were excluded because they lacked at least one of the pre-specified inclusion requirements (e.g., verifiable procedure, explicit linkage to reporting/assurance rules, or sufficient relevance to ESG traceability), resulting in 15 studies included in the qualitative synthesis. This wording preserves PRISMA traceability while avoiding attribution of the full corpus to a single database in a multi-source design (Caldarelli, 2025), (Han et al., 2023), (Liu et al., 2024), (Wang et al., 2024), and (Zhu and Liu, 2024).

The complete identification and selection process is summarized in Figure *1*.

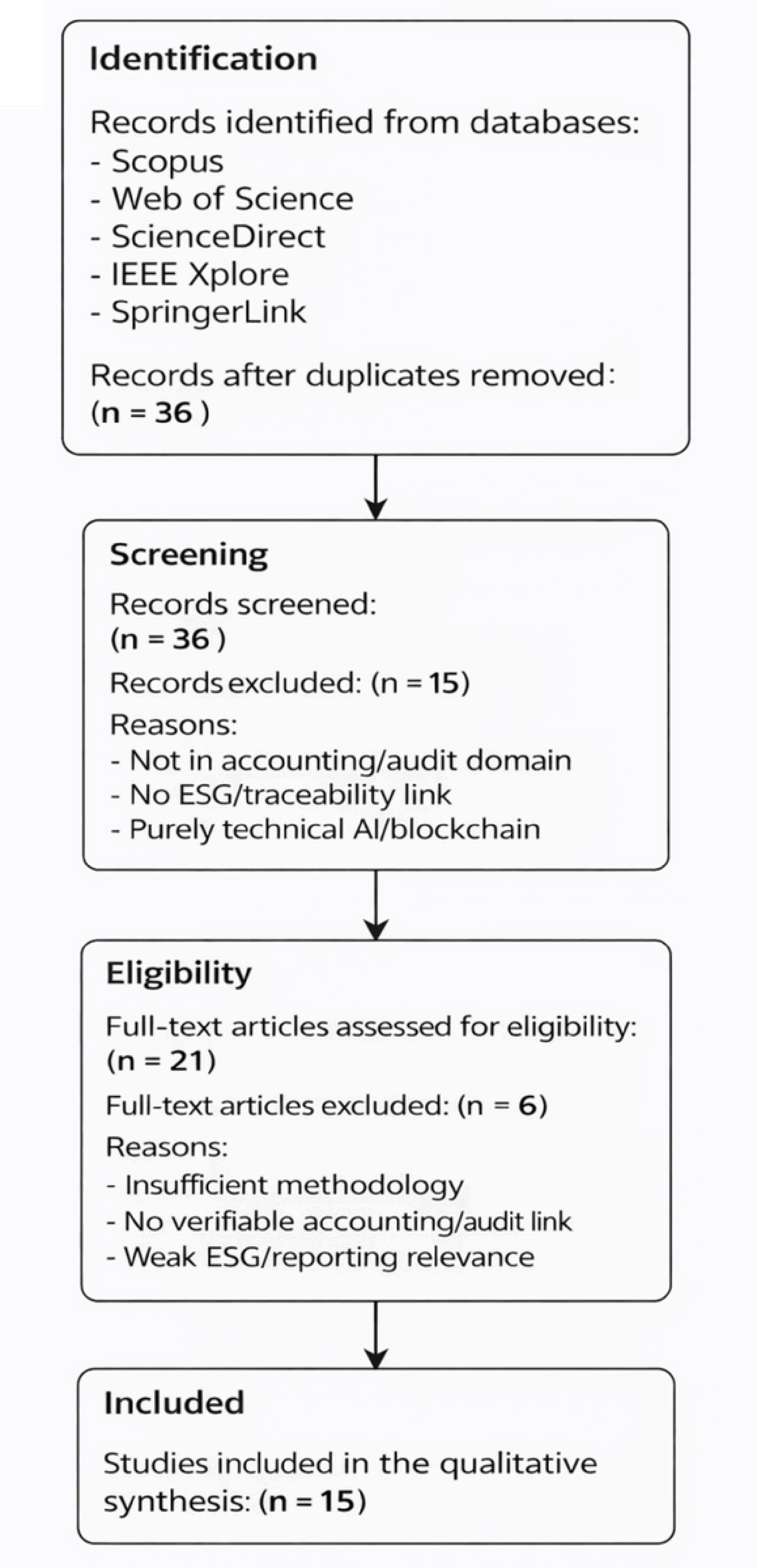
Identification
Records identified from databases:
- Scopus
- Web of Science
- ScienceDirect
- IEEE Xplore
- SpringerLink
Records after duplicates removed: (n = 36)
Screening
Records screened: (n = 36)
Records excluded: (n = 15)
Reasons:
- Not in accounting/audit domain
- No ESG/traceability link
- Purely technical AI/blockchain
Eligibility
Full-text articles assessed for eligibility: (n = 21)
Full-text articles excluded: (n = 6)
Reasons:
- Insufficient methodology
- No verifiable accounting/audit link
- Weak ESG/reporting relevance
Included
Studies included in the qualitative synthesis: (n = 15)

FIGURE 1: PRISMA 2020 flow diagram for study identification and selection

Source: Authors' elaboration. Adapted from the PRISMA 2020 statement (Page et al., 2021). ESG = Environmental, Social, and Governance; AI = artificial intelligence

The diagram depicts the stages of database searching, screening, eligibility assessment, and final inclusion of studies forming the evidence base for the ABAF-RE framework.

Thematic Synthesis

Five thematic domains emerged from the synthesis:

· Distributed accounting and auditability, emphasizing immutability, continuous validation, and tamper-evident records.

· Anomaly detection and algorithmic governance, enabled by explainable ML/DL models and trace-aware risk-assessment workflows.

· ESG reporting and digital sustainability, highlighting verifiable metrics and incentive-aligned validation.

· Traceability in agri-food supply chains, reflecting the need for interoperable evidentiary artifacts and document lineage.

· Hybrid AI-blockchain models, providing mechanisms to reconcile operational processes with accounting representations.

These thematic axes informed and constrained the subsequent modeling of the ABAF-RE architecture.

Conceptual Modeling Procedure for the ABAF-RE

The second methodological component implemented a structured modeling pipeline translating thematic evidence into an operational accounting framework. The process advanced through four analytical phases, each anchored in contemporary developments in AI-enabled auditing, distributed-ledger assurance, ESG disclosure quality, and verification incentives.

Pattern Identification

The selected studies were examined for recurrent architectural and procedural motifs involving:

· permissioned or consortium ledgers with oracle gateways and verifiable credentials;

· ML/DL pipelines for anomaly and risk detection with audit-trail logging;

· rule-as-code validation encoded in smart contracts for ESG assurance;

· documentation workflows preserving lineage, provenance, and cross-source reconciliation.

Explainability requirements, provenance hashing, and incentive-compatible verification recur across AI-auditing syntheses (Han et al., 2023), oracle-supported assurance models (Caldarelli, 2025), ESG-validation incentive mechanisms (Liu et al., 2024), and blockchain-augmented disclosure experiments (Zhu and Liu, 2024). Evidence from green-Gross Domestic Product (GDP) accounting reinforces the role of integrity constraints and multi-source reconciliation in sustainability-oriented ledgers (Wang et al., 2024). Recent work on hybrid public-private validation frameworks in ESG reporting further illustrates deployable patterns applicable to rural accounting scenarios (Singh et al., 2025).

Component Extraction

Identified patterns were synthesized into functional components central to accounting workflows: verifiable provenance (hash-linked artifacts, source attestation), anomaly-detection engines (supervised/unsupervised ML with explainers), rule-based validation modules (ESG and domain controls encoded in contracts), dynamic ESG reporting (structured Key Performance Indicators (KPIs) and narrative reconciliation), and algorithmic-governance components (model-risk logs, segregation of duties, and lineage metadata). These component definitions emphasize semantic coherence, interoperability, and cross-sector portability - features consistently documented in sustainability accounting, supply-chain traceability, and AI-assisted assurance literature (Caldarelli, 2025), (Han et al., 2023), (Liu et al., 2024), and (Zhu and Liu, 2024).

Architectural Synthesis

Components were integrated into a multi-layer blueprint suitable for low-connectivity conditions: offline-first capture with deferred notarization, asynchronous ingestion, distributed validation, and auditability features expected in sustainability-accounting stacks. The resulting architecture combines a permissioned-ledger core (provenance, access control, oracle linking) with an analytics layer for ML-based controls and an assurance layer for contract-governed ESG validation. Prior studies report context-specific improvements in transparency and/or reliability when blockchain is used as an integrity substrate and ML operates on curated, lineage-preserving datasets; however, reported effects are task- and protocol-dependent and should not be generalized as universal performance gains (Wang et al., 2024) (Zhu and Liu, 2024). Oracle-aware mechanisms address trust gaps at the data-chain boundary (Caldarelli, 2025), while incentive-aligned verification models such as Veri-Green (Liu et al., 2024) illustrate design pathways that can be adapted for rural ESG workflows, subject to pilot evaluation under explicit baselines and governance assumptions. Recent hybrid public-private schemes further reinforce the feasibility of programmable validation arrangements in sectoral contexts (Singh et al., 2025).

Internal Consistency Checking (Traceability, Verifiability, and Design-Level Operational Feasibility)

ABAF-RE is not positioned as an “ideal design”, but as an evidence-based synthesis that is internally checked against extracted mechanisms. Preliminary validation comprised three consistency checks: (i) traceability consistency, verifying that each proposed information artifact (local capture, timestamping, deferred synchronization, ledger anchoring, and ESG reporting) has a clear anchoring point and an explicit integrity-preservation mechanism; (ii) explainability consistency, verifying that the analytical layer does not produce opaque outputs but results that can be justified in assurance-oriented settings (e.g., local/global explanations, data evidence, and model assumptions); and (iii) normative-operational consistency, assessing whether ESG/accounting rules can be expressed as programmable and auditable constraints (smart contracts or verifiable rules) without substituting professional judgement. This approach is aligned with contemporary AI risk-management guidance emphasizing governance, traceability, evaluation, and context-sensitive documentation as conditions for trustworthiness, without implying formal compliance certification within this study (Han et al., 2023), (International Organization for Standardization and International Electrotechnical Commission, 2023), (Liu et al., 2024), (National Institute of Standards and Technology, 2023), and (Zhu and Liu, 2024).

Results

The integrated analysis of the 15 selected studies describes a research landscape in which distributed accounting, explainable machine-learning, and verifiable ESG reporting are frequently co-discussed as complementary building blocks for assurance-oriented infrastructures. Across the corpus, the corpus descriptively reflects increased scholarly attention to hybrid architectures that combine cryptographic traceability, anomaly-detection engines, and programmable validation logic; however, this review does not infer a universal trajectory or an aggregated effect size due to heterogeneous baselines and evaluation protocols (Zhu and Liu, 2024). This emphasis is particularly relevant for rural economies, where fragmented value chains and intermittent connectivity make offline-first and asynchronously synchronized designs operationally salient.

The section is organized into six analytical components:
(i) conceptual structure and semantic patterns in the literature,

(ii) topic density and thematic interactions,

(iii) comparative synthesis of the 15 studies,

(iv) methodological evaluation,

(v) expanded mapping of methodological gaps, and

(vi) deep relevance analysis for the ABAF-RE architecture.

Each component is supported by the figures and tables that follow.

Conceptual Structure and Co-occurrence Patterns in the Corpus

A semantic co-occurrence analysis was performed as a descriptive corpus method to examine how key domains - artificial intelligence, blockchain, auditability, and ESG reporting - co-appear across the 15 studies; the resulting structures are not interpreted as evidence of effectiveness or maturity. As shown in Figure *2*, the network exhibits two high-centrality clusters: one anchored in blockchain-auditability-traceability and another in machine-learning-anomaly detection-explainability. These clusters serve as conceptual connectors between research streams such as accounting, digital governance, supply-chain logistics, and sustainable finance.

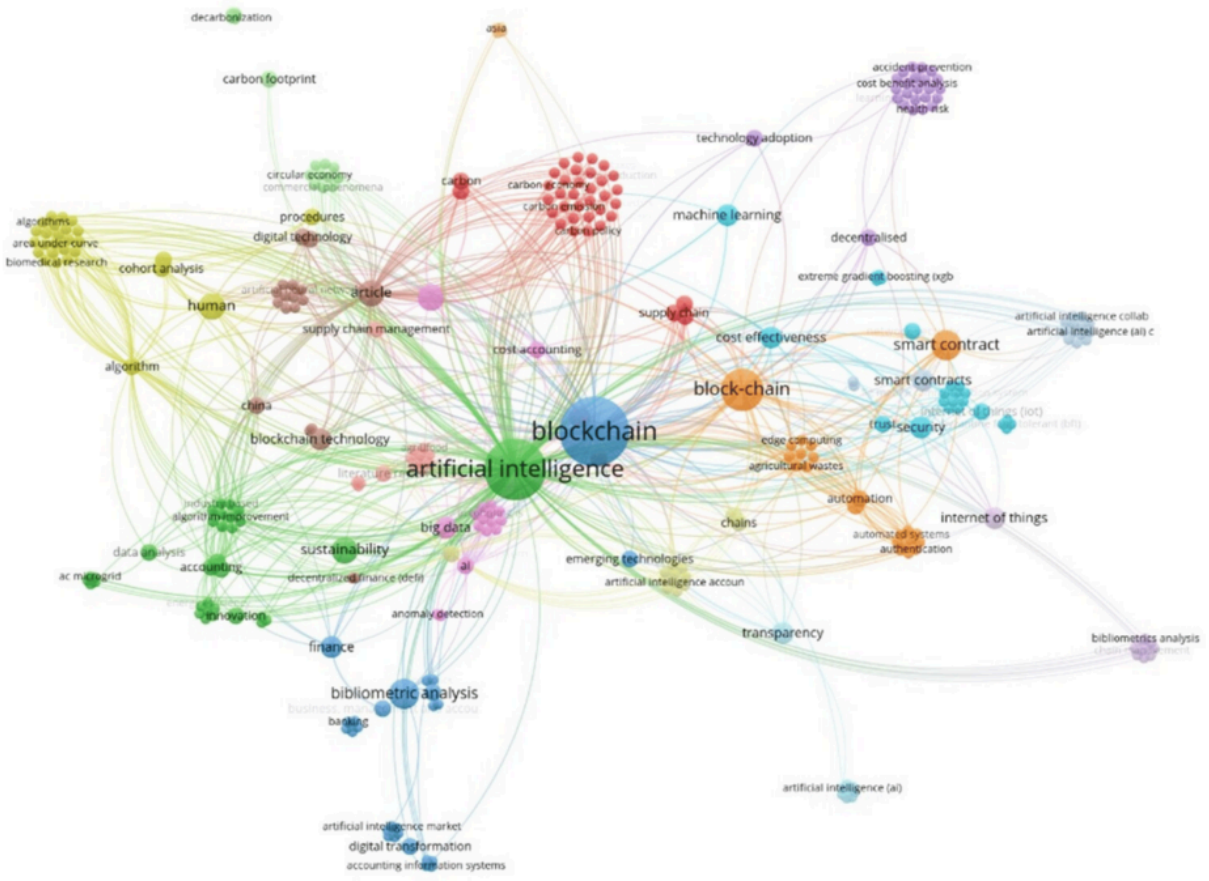

FIGURE 2: Co-occurrence network of key terms

Source: Authors' elaboration. Generated using VOSviewer from the authors' curated corpus.

The network places blockchain, AI, smart contract, and sustainability at the core of the field. Peripheral yet significant nodes - such as agri-food, carbon accounting, supply-chain verification, and document lineage - suggest an expansion toward rural production systems. This peripheral growth aligns with the needs of low-connectivity territories, where reliable environmental and financial traceability is fundamental to local governance.

Topic Density and Research Intensity

To assess thematic concentration, a topic-density heatmap was generated (invoked below as Figure *3*).

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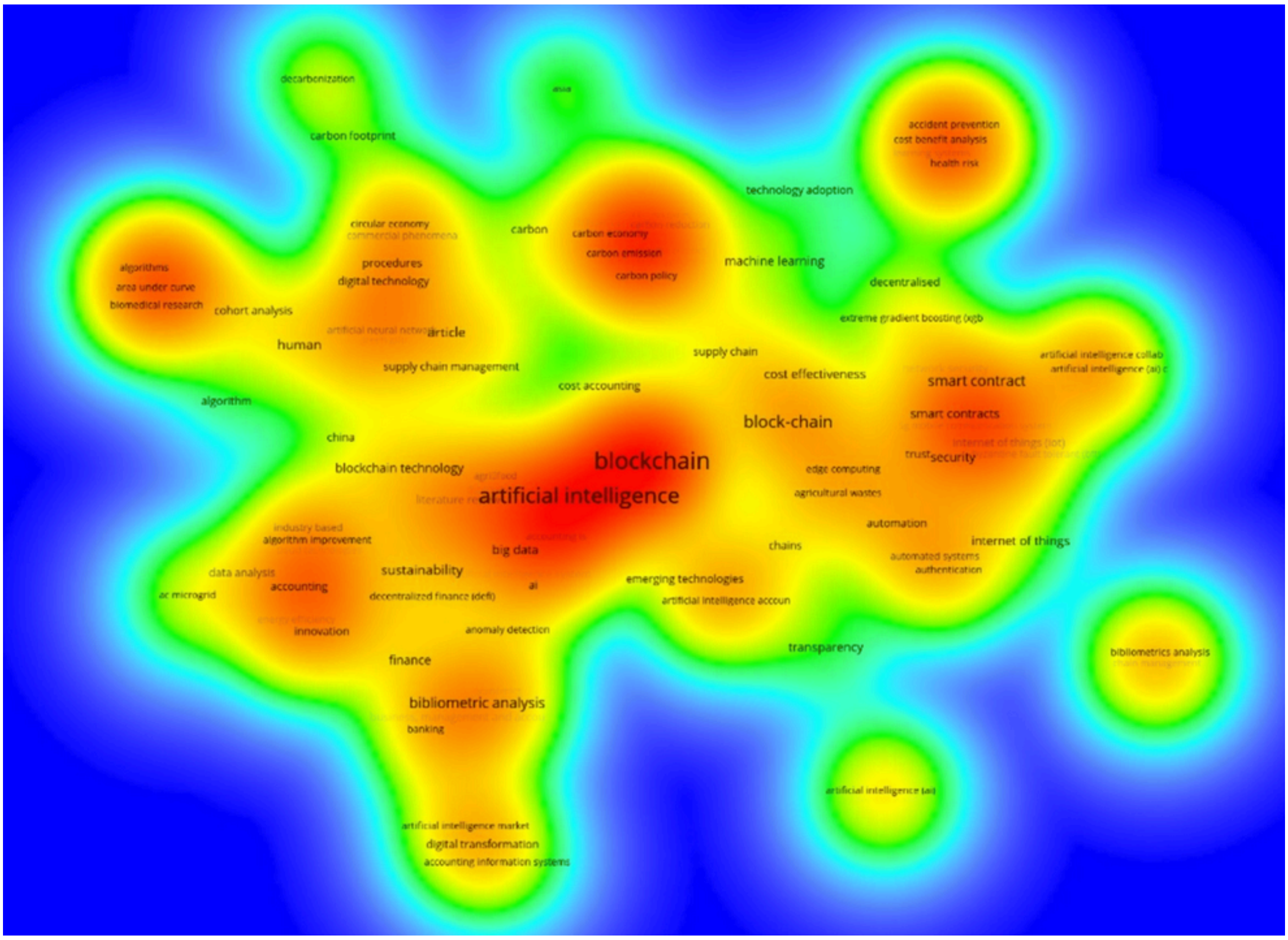

FIGURE 3: Thematic density map derived from the co-occurrence matrix

Source: Authors' elaboration. Generated using VOSviewer from the authors' curated corpus.

The heatmap shows a dense thematic core dominated by blockchain, explainable AI, and sustainability reporting. Adjacent zones focus on model risk, fraud detection, and algorithmic governance. A distinct, more isolated area relates to financial fraud, reflecting a specialized but relevant subdomain for rural contexts where informal transactions and low oversight amplify vulnerability to irregularities.

The structure is consistent with a literature focus on combining cryptographic evidence, explainable ML inference, and verifiable environmental metrics; these patterns motivate ABAF-RE's design logic but do not constitute performance evidence.

High-Frequency Terms and Bigram Structures

Before examining the individual studies in detail, lexical patterns were analyzed to identify dominant conceptual signals. Figure *4* presents the most frequent terms across the 15 studies.

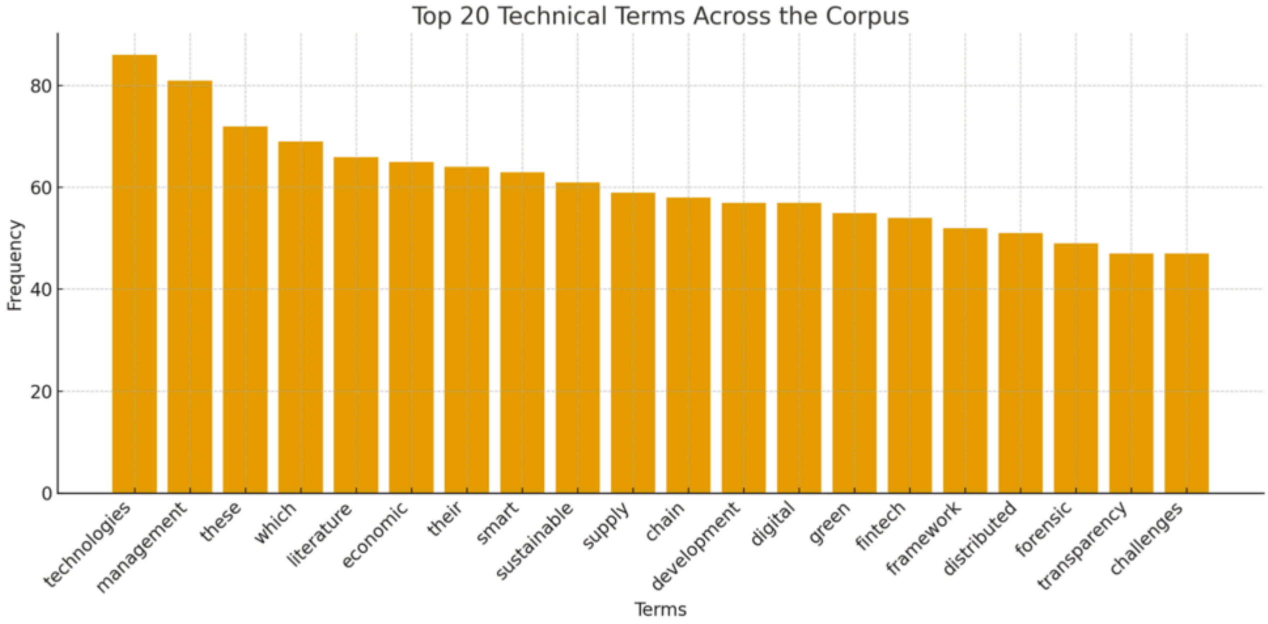

FIGURE 4: Frequency distribution of top terms in the corpus

Source: Authors' elaboration.

Similarly, Figure *5* displays the distribution of the most frequent bigrams.

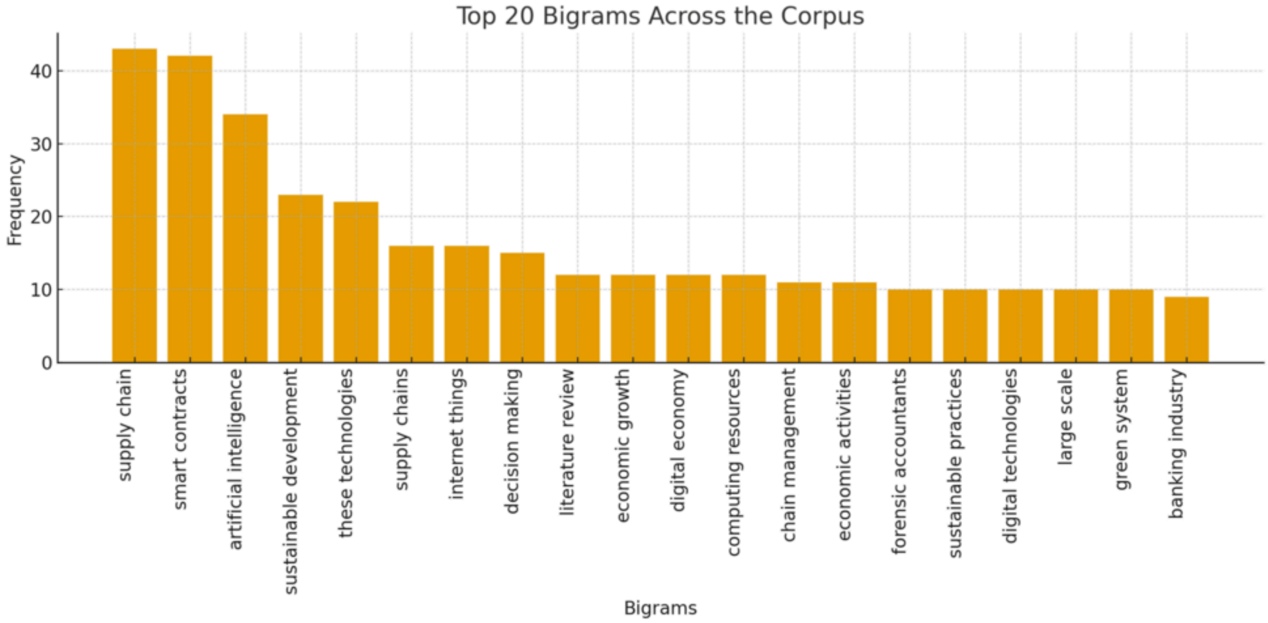

FIGURE 5: Top bigrams extracted from the full-text corpus

Source: Authors' elaboration.

These descriptive patterns are consistent with the centrality of auditability, traceability, sustainability, machine-learning, and smart contracts in the corpus. They summarize co-mentions and frequency signals, but they do not estimate effectiveness, readiness, or field impact.

Distribution of Article Keywords

To provide an additional perspective on conceptual convergence, Figure *6* is introduced, synthesizing keyword frequencies across the 15 studies.

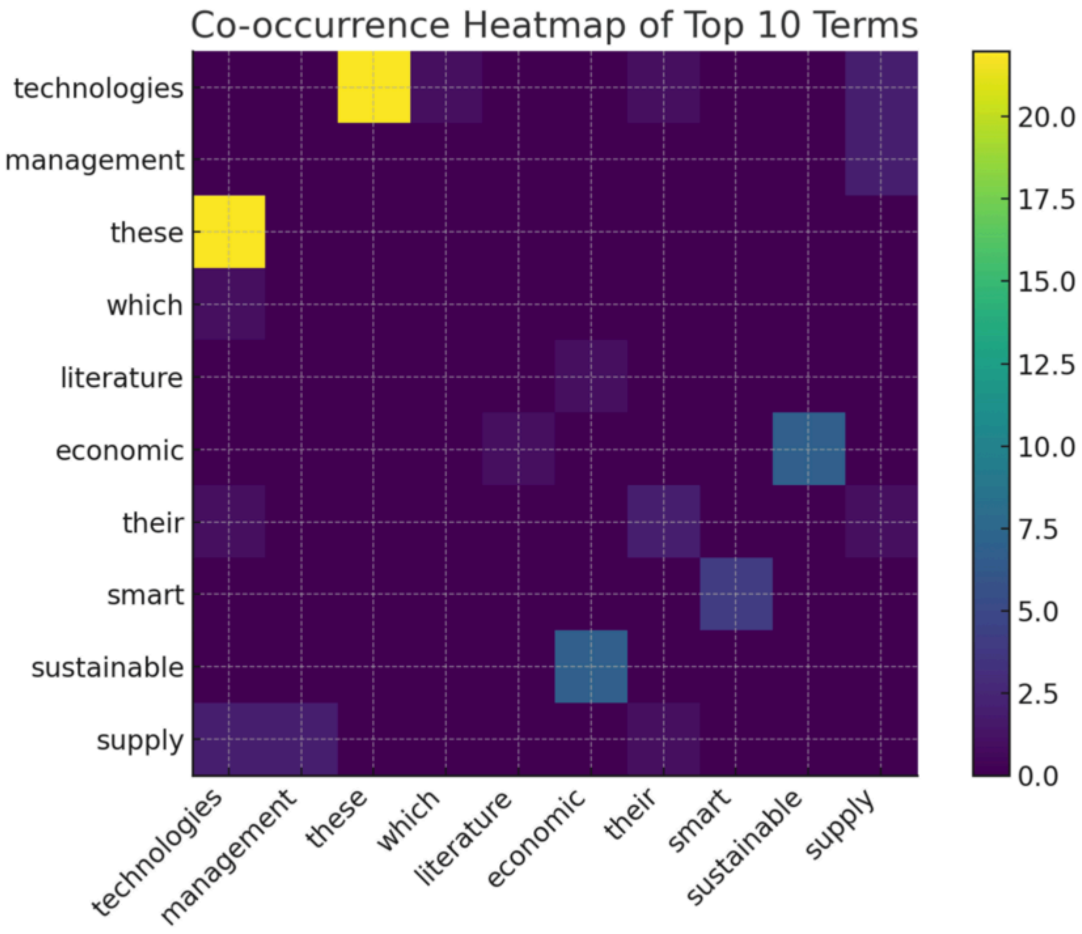

FIGURE 6: Keyword frequency distribution across the 15 studies

Source: Authors' elaboration.

The recurrence of blockchain, AI, audit, ESG, traceability, and supply-chain shows alignment with the architecture proposed for ABAF-RE, indicating that these domains are among the most recurrent lines of inquiry during 2019-2025.

Comparative Synthesis of the Studies

A structured extraction of evidence from the entire corpus is presented in Table *1*. This table consolidates key dimensions - objectives, methods, technologies, variables, verifiable findings, and relevance for ABAF-RE - into a single master comparative matrix.

No.	Study	Verified contributions	Identified gaps	Specific relevance for ABAF-RE
1	(Wang et al., 2024)	Integrates blockchain-oriented logic with ANN/ML models to strengthen consistency between environmental and economic indicators in green-GDP accounting.	Relies on centralized data sources; does not address explainability; does not evaluate rural scenarios.	Supports the environmental-ledger and eco-financial reconciliation layer.
2	(Poppe et al., 2024)	Shows that basic farm-office digitalization can improve traceability and sustainability reporting practices.	Does not implement blockchain or AI; assumes stable infrastructure conditions.	Provides an empirical baseline for rural ESG reporting that ABAF-RE can enhance through verifiability and automation.
3	(Hong and Xiao, 2024)	Examines how digital infrastructures mediate sustainable information flows across supply chains.	Operates at a macro level; does not specify auditing or assurance mechanisms.	Justifies ABAF-RE as a modular component within broader digital ecosystems for sustainability.
4	(Liu et al., 2024)	Maps the evolution of blockchain accounting literature (2013–2023) and identifies dominant research trajectories.	Provides limited architectural detail; offers little analysis for rural settings.	Establishes the state of the art positioning of ABAF-RE within the DLT-accounting domain.
5	(Ali et al., 2024)	Synthesizes trends in forensic accounting and fraud detection, highlighting relevant indicators and investigative logics.	Does not propose a deployable technical architecture.	Informs ABAF-RE anomaly-detection requirements and evidence-traceability modules.
6	(Malhotra et al., 2023)	Reviews blockchain-based proof-of-authenticity frameworks that support explainable AI and provenance.	Not focused on accounting or ESG reporting contexts.	Provides foundations for ABAF-RE explainability and algorithmic-provenance mechanisms.

7	(Handoyo, 2024)	Identifies sustainability metrics and critical nodes in green supply-chain research.	Does not implement AI or DLT mechanisms.	Supports rural chain-of-custody and indicator selection for ABAF-RE reporting design.
8	(Rahman et al., 2024)	Reports that blockchain can improve transparency and integrity in banking and financial services.	Primarily targets urban/commercial banking contexts.	Provides transferable principles for rural financial traceability and integrity constraints.
9	(Madkhali and Sithole, 2023)	Analyzes how IT capabilities support institutional sustainability strategies and adoption.	Does not operationalize blockchain or AI for accounting assurance.	Clarifies governance and adoption barriers relevant for rural deployment of ABAF-RE.
10	(Ouyang et al., 2022)	Proposes a blockchain and smart-contract framework to coordinate AI agents and enforce collaboration rules.	Not anchored in accounting workflows.	Inspires ABAF-RE rule-as-code and programmable validation mechanisms.
11	(Gusc et al., 2022)	Integrates Big Data, AI, and blockchain concepts to internalize environmental and social externalities (true-cost accounting).	Remains largely conceptual; does not test rural settings.	Supports ABAF-RE true-cost/ESG accounting logic and multi-source reconciliation framing.
12	(Remondino and Zanin, 2022)	Reviews digitization in agri-food chains and its relationship to sustainability and competitiveness.	Offers limited AI integration; references to DLT are partial.	Directly informs rural value-chain constraints and operational requirements relevant to ABAF-RE.
13	(Cazazian, 2022)	Discusses smart-contract roles within blockchain-based accounting information systems and AI-enabled auditing.	Predominantly theoretical; limited validation.	Provides conceptual grounding for ABAF-RE programmatic validation and control enforcement.
14	(Wang et al., 2022)	Examines blockchain-empowered Space-Air-Ground Integrated Networks (SAGIN) and resilience under	Not accounting-specific.	Supports ABAF-RE offline-first and intermittent-connectivity design assumptions.

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		heterogeneous connectivity.		
15	(Liu, 2023)	Proposes blockchain-supported algorithms intended to modernize financial auditing processes.	Limited access/validation detail; largely conceptual.	Supports ABAF-RE continuous-auditing logic and evidence-synchronization design patterns.

TABLE 1: Comparative synthesis of the 15 studies: objectives, methods, technologies, indicators, findings, and relevance for ABAF-RE

Source: Authors' elaboration.

Note. ABAF-RE = AI-Blockchain Accounting Framework for Rural Entrepreneurship; AI = artificial intelligence; ANN = artificial neural network; DLT = distributed ledger technology; ESG = environmental, social, and governance; ML = machine learning; GDP = Gross Domestic Product.

This comparative view demonstrates strong complementarity across the studies: while some contribute technical depth in ML explainability or blockchain assurance, others strengthen the model's grounding in sustainability reporting, supply-chain traceability, or rural operational constraints.

Methodological Evaluation of the Corpus

Before extracting architectural patterns, the methodological strength of the corpus was evaluated across five criteria. This assessment appears in Table *2*, invoked below.

Criterion	Description	High (✓)	Medium (~)	Low (☒)
Methodological transparency	**Clarity of methods, techniques, and procedures**	**11**	**4**	**0**
Replicability	Availability of scripts, diagrams, or reproducible logic	7	6	2
Technical rigor	Algorithmic soundness, statistical validation	9	6	0
Contextual validity	Relevance to accounting, auditing, ESG	13	2	0
Verifiable data	Access to datasets or measurable indicators	6	5	4

TABLE 2: Methodological evaluation of the 15 studies

Source: Authors' elaboration. ESG = Environmental, Social, and Governance.

Because the corpus combines heterogeneous study designs, a single formal risk-of-bias tool was not applied; instead, we conducted a domain-based methodological quality appraisal using five criteria (Table *2*), and we treat the outcomes as comparative signals rather than definitive bias estimates.

The evaluation reveals strength in conceptual rigor but clear weaknesses in replicability and data availability - precisely the gaps that ABAF-RE is designed to resolve through its integrated ledger, explainable analytics, and rule-as-code validation layers.

Expanded Mapping of Methodological Gaps

In alignment with the analytical depth required for the ABAF-RE model, Table *3* presents an extended mapping of methodological gaps.

Gap category	Description	Presence (n/15)	Implication for ABAF-RE
Methodological transparency	**Incomplete description of ML pipelines or blockchain logic**	**6**	**Necessitates ML-audit logging and clear lineage**
Replicability	Lack of datasets, scripts, or workflow diagrams	7	Requires hash-based reproducibility and open ledgers
Technical rigor	Limited model evaluation or sensitivity tests	4	Reinforces need for robust Capa 2 validation
Contextual validity	Weak linkage to accounting or ESG	5	Must embed local reporting structures
Data availability	Proprietary or unverifiable datasets	9	ABAF-RE must ensure public, auditable data structures
AI constraints	Limited attention to bias, fairness, explainability	11	Capa 2 must enforce explainable ML
Blockchain constraints	Oracle dependence, weak interoperability	8	ABAF-RE must use lightweight, asynchronous DLT
Rurality constraints	Lack of offline-first or intermittent-connectivity models	15	Offline-first architecture becomes mandatory

TABLE 3: Expanded map of methodological gaps identified in the 15 studies

Source: Authors' elaboration. ABAF-RE = AI-Blockchain Accounting Framework for Rural Entrepreneurship; AI = artificial intelligence; DLT = distributed ledger technology; ESG = environmental, social, and governance; ML = machine learning.

This table indicates that a dominant gap in the literature is the absence of infrastructures explicitly designed for rural or low-connectivity environments - precisely the niche addressed by the ABAF-RE framework.

Relevance of Each Study for the ABAF-RE Architecture

The specific contribution of each article to the five layers of the ABAF-RE architecture is synthesized in Table *4*, invoked below.

No.	Study	Applicable components	Contribution level	ABAF-RE layers supported	Verifiable evidence	Practical implications for rural entrepreneurship
1	**(Wang et al., 2024)**	**Environmental ledger; multisource reconciliation; green-GDP accounting**	**High**	**Layer 1 (Distributed Ledger); Layer 4 (Verifiable ESG Reporting)**	**ANN/ML experiments using environmental-economic datasets**	**Enables consistent environmental–economic traceability under asynchronous data capture.**
2	(Poppe et al., 2024)	Farm-level reporting structures; operational accounting in agriculture	Medium	Layer 4 (Verifiable ESG Reporting)	Empirical farm-office evidence (EU agriculture)	Transferable baseline for structured, auditable ESG reporting in rural enterprises.
3	(Hong and Xiao, 2024)	Digital-economy infrastructure; sustainability information flows (AI/blockchain as enablers)	Medium	Layer 5 (Algorithmic Governance)	Digital-infrastructure modeling with validated datasets	Supports the case for digital accounting infrastructure as a prerequisite for rural assurance ecosystems.
4	(Liu et al., 2024)	Blockchain-accounting axes: transparency; smart contracts; continuous auditing	High	Layers 1–4 (Core layers)	Bibliometric mapping (2013–2023) with verified clusters/co-occurrence structures	Provides a state-of-the-art scaffold to align ABAF-RE with the main DLT-accounting trajectories.
5	(Ali et al., 2024)	Fraud-detection principles; forensic indicators; anomaly-identification logic	Medium	Layer 2 (ML/DL Analytics); Layer 3 (Programmatic Validation)	Forensic-accounting frameworks grounded on digital-evidence practices	Strengthens anomaly-detection design and evidentiary logic for rural microentrepreneurship auditing.

6	(Malhotra et al., 2023)	Authenticity proofs for XAI; hashing; timestamp-based verification	High	Layer 2 (ML/DL Analytics); Layer 5 (Algorithmic Governance)	Integrity/authenticity protocols (hashing, time anchoring)	Critical for explainability and model-traceability in low-connectivity environments.
7	(Handoyo, 2024)	Green supply-chain metrics; sustainability indicators	Low	Layer 4 (Verifiable ESG Reporting)	Bibliometric/thematic structures in the field	Helps define ESG indicator families relevant to rural value chains (what to report and why).
8	(Rahman et al., 2024)	Transparency and record-integrity mechanisms in DLT banking	Medium	Layer 1 (Distributed Ledger)	Systematic-review evidence base	Supports rural microfinance traceability and integrity constraints for local credit/account ledgers.
9	(Madkhali and Sithole, 2023)	Sustainability governance; institutional digitalization challenges	Medium	Layer 5 (Algorithmic Governance)	Case-based organizational evidence	Highlights adoption barriers and governance constraints likely to appear in rural deployments.
10	(Ouyang et al., 2022)	Smart-contract coordination; rule-as-code execution among AI agents	High	Layer 3 (Programmatic Validation); Layer 5 (Algorithmic Governance)	Conceptual/architectural framework validated via simulations	Provides rule-as-code logic adaptable to accounting controls and ESG validation in rural workflows.
11	(Gusc et al., 2022)	True-cost accounting; hybrid AI–DLT logic	Medium	Layer 4 (Verifiable ESG Reporting)	Applied examples in energy-transition contexts	Enables extended-cost accounting logic for rural environmental and social impacts.

12	(Remondino and Zanin, 2022)	Agri-food digitalization; documentary traceability in supply chains	High	Layer 4 (Verifiable ESG Reporting)	Verified evidence/case-based discussion in agri-food logistics	Provides directly transferable rural traceability requirements and constraints for ABAF-RE.
13	(Cazazian, 2022)	Smart-contract roles in accounting information systems; auditing enablement	High	Layer 3 (Programmatic Validation)	Structured theoretical model of smart-contract logic	Supports rule-based accounting controls and automated ESG-validation constraints.
14	(Wang et al., 2022)	Blockchain-enabled SAGIN; intermittent-connectivity operation	High	Layer 1 (Distributed Ledger); Layer 5 (Algorithmic Governance)	Architecture assessed against heterogeneous-network scenarios	Justifies asynchronous, offline-first and delay-tolerant ledger operations in rural areas.
15	(Liu, 2023)	Blockchain-based audit-synchronization algorithms	Medium	Layer 1 (Distributed Ledger); Layer 3 (Programmatic Validation)	Algorithmic auditing demonstrations	Strengthens continuous-auditing and evidence-synchronization capabilities for rural accountability.

TABLE 4: Relevance of each study to ABAF-RE architectural layers

Source: Authors' elaboration. ABAF-RE = AI-Blockchain Accounting Framework for Rural Entrepreneurship; AI = artificial intelligence; DLT = distributed ledger technology; ESG = environmental, social, and governance; ML = machine learning; GDP = Gross Domestic Product; DL = deep-learning.

The analysis indicates that all studies contribute to at least one architectural layer, while a smaller subset functions as structural pillars for ABAF-RE. In particular, Malhotra et al. (Malhotra et al., 2023) consolidate authenticity and explainability requirements; Liu et al. (Liu et al., 2024) provide the state-of-the-art structure of blockchain accounting; Remondino and Zanin (Remondino and Zanin, 2022) ground rural supply-chain traceability constraints; Wang et al. (Wang et al., 2024) support sustainability-oriented reconciliation through integrity-constrained modeling; and Wang et al. (Wang et al., 2022) justify offline-first, delay-tolerant operation under intermittent connectivity. Complementarily, Ouyang et al. (Ouyang et al., 2022) and Cazazian (Cazazian, 2022) inform rule-as-code and smart-contract validation logics that enable programmable assurance.

Master Evidence Matrix

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To consolidate technical extraction, Table *5* synthesizes the data types, ML/DL models, blockchain mechanisms, and metrics reported in each study.

No.	Study	Type of data/empirical corpus	ML/DL models used	Type of blockchain/DLT	Evidence mechanisms (provenance, integrity, validation)	Key metrics reported
1	(Wang et al., 2024)	National environmental and economic datasets (China); green-GDP indicators	ANN; ML regression models	Conceptual permissioned ledger for environmental-economic reconciliation	Hash-linked reconciliation; cross-source consistency checks	R^2; MSE; environmental-economic consistency metrics
2	(Poppe et al., 2024)	Farm-level accounting records; sustainability indicators	None	None	Structured digital logs; internal traceability records	Farm KPIs; sustainability-reporting consistency measures
3	(Hong and Xiao, 2024)	Digital-economy indicators; macro-level sustainability variables	ML-based structural modeling	Digital infrastructure with optional blockchain nodes	Flow-consistency modeling; digital-environmental alignment metrics	Digital-economy indices; sustainability-impact coefficients
4	(Liu et al., 2024)	Bibliometric corpus (2013–2023): keywords, co-occurrences, citation networks	None	Multiple DLT families mapped at a conceptual level	Taxonomies; thematic clusters; transparency constructs	Co-occurrence frequencies; thematic clusters; network centrality measures
5	(Ali et al., 2024)	Fraud-case reports; forensic indicators	SVM; MLP; statistical detection models	None specified	Evidence-chain descriptions; anomaly-detection workflows	Accuracy; false-positive rate
6	(Malhotra et al., 2023)	XAI models and datasets in authenticity-proof contexts	CNNs; transformers; XAI explainers	Blockchain-based proof-of-authenticity frameworks	Hashing; timestamping; proof-of-integrity; model-lineage logging	Fidelity scores; explainability metrics

7	(Handoyo, 2024)	Global GSCM literature; sustainability-indicator corpora	None	None	Sustainability indicator mapping; thematic clustering	Sustainability indicator families; node criticality
8	(Rahman et al., 2024)	Banking-sector evidence base; systematic-review/bibliometric corpus	None	Multiple blockchain implementations in banking	Transaction-integrity schemes; DLT governance patterns	Record-integrity indicators; transparency metrics; reported transaction-cost implications
9	(Madkhali and Sithole, 2023)	Institutional digital-governance evidence; sustainability reports	None	None	IT governance evidence; documented sustainability workflows	Institutional readiness; reliability/consistency of sustainability indicators
10	(Ouyang et al., 2022)	AI-agent interaction logs; conceptual architecture	RL/ML for agent collaboration	Smart-contract-enabled blockchain	Verifiable interactions; contract rule enforcement; event logs	Response time; coordination efficiency metrics
11	(Gusc et al., 2022)	Energy-transition evidence; cost-accounting indicators	ML for cost estimation	DLT-enabled true-cost accounting	Cost provenance; environmental-cost internalization mechanisms	Emission factors; true-cost indices
12	(Remondino and Zanin, 2022)	Agri-food logistics indicators; case-study evidence	None	Indirect/optional DLT references	Document-lineage tracking; supply-chain traceability	Logistics KPIs; environmental traceability indicators
13	(Cazazian, 2022)	Theoretical corpus on accounting information systems and smart contracts	None	Smart-contract DLT (conceptual)	Rule formalization; auditability logic; contract-governed workflows	Conceptual taxonomies; validation-flow structures
14	(Wang et al., 2022)	Network datasets for	DL models in heterogeneous-network	Lightweight blockchain for	Distributed integrity proofs; multi-domain	Latency; availability;

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		SAGIN topologies	contexts (as reported)	heterogeneous networks	consensus mechanisms	packet-integrity metrics
15	(Liu, 2023)	Auditing processes; conceptual algorithmic proposals	ML-enhanced audit routines	Permissioned blockchain (conceptual)	Evidence synchronization; audit-trail traceability	Audit consistency; evidence-alignment metrics

TABLE 5: Technical evidence extraction matrix

Source: Authors' elaboration. ANN = artificial neural network; DLT = distributed ledger technology; ESG = environmental, social, and governance; ML = machine learning; KPI = Key Performance Indicator; DL = deep-learning XAI = explainable artificial intelligence.

Finally, Table *6* maps technical patterns across the corpus to the architectural structures that support the ABAF-RE model.

Architectural pattern	Description	Articles providing evidence (Nº)	Application within the ABAF-RE architecture
Asynchronous Distributed Ledger	**Distributed records that function under intermittent connectivity, allowing delayed notarization and resilient multi-source reconciliation.**	**1, 4, 11, 15, 14**	**Supports Layer 1: Distributed Ledger, enabling offline-first accounting and environmental/financial integrity in rural contexts.**
Explainable Machine Learning (XAI)	ML/DL models incorporating interpretable mechanisms, audit trails, anomaly detection and risk scoring with transparent decision pathways.	5, 6, 10, 11	Supports Layer 2: Explainable ML/DL, ensuring transparent anomaly detection, auditable decisions and bias control.
Rule-as-Code Validation (Smart Contracts)	Formalization of accounting, ESG and operational rules into programmable logic deployed on smart contracts or contract-governed workflows.	10, 11, 13	Supports Layer 3: Programmable Validation, enabling automated rule enforcement and verifiable ESG assurance.
Verifiable ESG Reporting	Mechanisms that ensure audit-ready sustainability indicators, environmental metrics and supply-chain traceability using structured evidentiary artifacts.	1, 2, 7, 11, 12, 14	Supports Layer 4: Verifiable ESG Reporting, integrating traceable KPIs from rural agri-food and environmental contexts.
Algorithmic Governance	Systems enabling oversight, performance monitoring, model-risk management and oversight of distributed actors (human and algorithmic).	3, 4, 11, 15	Supports Layer 5: Algorithmic Governance, ensuring supervisory transparency and role segregation in digital-accounting ecosystems.
Agri-Food Traceability & Rural Lineage	Document lineage, logistics tracking, environmental indicators and multi-node supply-chain validation relevant for rural producers.	2, 7, 12, 14	Cross-layer: informs the design of rural workflows, providing evidence structures for farmer-level value chains.
Hybrid AI–DLT Provenance Models	Integration of ML pipelines with blockchain as a trust substrate for datasets, model states and temporal proofs.	1, 6, 11	Reinforces Layers 1–2, supporting model provenance, dataset integrity and multi-actor notarization.
Incentivized Verification Mechanisms	Token-based or incentive-compatible validation structures to enhance participation of distributed	6, 12	Enables future extensions of Layer 3 and Layer 4, motivating accurate ESG submissions and rural participation.

	actors in reporting and assurance.		
Interoperability & Oracle-Aware Design	Bridging on-chain and off-chain data sources through trusted gateways, essential for ESG reporting and rural IoT devices.	1, 3, 6, 15	Supports cross-layer interoperability, ensuring rural-data ingestion and trusted sensor-to-ledger integration.

TABLE 6: Architectural patterns supporting the ABAF-RE framework

Source: Authors' elaboration. ABAF-RE = AI-Blockchain Accounting Framework for Rural Entrepreneurship; AI = artificial intelligence; DLT = distributed ledger technology; ESG = environmental, social, and governance; ML = machine learning; IoT, Internet-of-Things

To preserve direct correspondence between results and the research questions, the patterns in Table *6* are interpreted as design conditions (not as effects). With respect to P1 (technical patterns required to preserve end-to-end auditability when synchronization is non-continuous: verifiable provenance, deferred notarization, XAI, and oracle design), the patterns "Asynchronous Distributed Ledger", "Interoperability & Oracle-Aware Design", and "Hybrid AI-DLT Provenance Models" support an offline-first capture specification, deferred notarization, and explicit lineage preservation, including the oracle boundary as a first-class design requirement. With respect to P2 (interoperability and governance mechanisms enabling ESG indicators and financial records to maintain semantic coherence and multi-actor traceability across heterogeneous rural workflows), the patterns "Rule-as-Code Validation", "Algorithmic Governance", and "Verifiable ESG Reporting" justify the need for semantic interoperability controls, version control, and role segregation to sustain coherence, traceability, and accountability across accounting and ESG information flows. This methodological bridge clarifies that the manuscript's central "result" is a traceable architectural specification grounded in synthesized evidence, rather than an empirical claim about operational performance impacts.

Synthesis and Implications for the ABAF-RE Model

Across semantic, bibliometric, methodological, and architectural views of the corpus, the synthesis suggests convergence around hybrid systems that integrate immutable ledgers, explainable analytics, and programmable validation to support verifiable accounting processes. This is reported as a corpus-level trend, not as a universal performance claim.

The ABAF-RE architecture synthesizes these insights into a modular, multi-layer framework suitable for rural entrepreneurship: offline-first data capture, asynchronous notarization, transparent ML-driven assurance, and rule-as-code validation.

An integrated reading of the results reveals a field moving steadily toward the convergence of distributed accounting, explainable analytics, and verifiable ESG reporting mechanisms. Although the 15 reviewed studies approach the problem from different angles, their overlap exposes a stable underlying pattern: the need for hybrid infrastructures in which documentary integrity, algorithmic traceability, and programmatic validation operate as a single system. The ABAF-RE model builds on these contributions and directs them toward an underexplored context - rural entrepreneurship under intermittent connectivity - where failures in recording, synchronization, and verification often translate into severe barriers to markets and financing. Beyond the PRISMA corpus (15 studies), external sources are cited only to frame readiness/risk-management frameworks (e.g., TRL-IRL-SRL, MLTRL, ISO/NIST) or to contextualize deployment considerations. These sources are not used to derive Table *6* patterns nor to support corpus-based conclusions; substantive design inferences are anchored exclusively in the included studies.

Conceptual Convergences and Interdisciplinary Stability

Recent literature on green-GDP accounting reports measurable gains when artificial neural networks are combined with distributed-ledger logics. In the Chinese context, ANN/ML models used to reconcile environmental and economic indicators are reported with reduced prediction error and higher cross-series consistency in the evaluated setting, supporting more stable green-GDP estimations (Wang et al., 2024). Although the study does not provide a single percentage improvement versus traditional approaches, it reports quantitative results (e.g., error and consistency metrics) suggesting that blockchain-ML coupling can enhance eco-accounting coherence under heterogeneous data conditions.

Evidence from ESG disclosure research follows a similar direction. Blockchain-enabled reporting and assurance architectures are commonly framed as mechanisms intended to mitigate information asymmetries and strengthen verifiability; however, effect sizes are rarely reported through a single standardized indicator across studies. In several cases, percentage figures - when present - refer to illustrative calculations or network-level measures rather than directly observed changes in information-asymmetry constructs, limiting cross-study comparability (Zhu and Liu, 2024). In agri-food and rural supply-chain contexts, digitalization and traceability architectures - including IoT-linked designs discussed alongside DLT - are reported to strengthen document lineage, tamper-evidence, and multi-actor reconciliation. Nevertheless, quantified improvements remain study-specific and method-dependent, and they are not sufficiently standardized to justify a transferable performance range in this synthesis (Ellahi et al., 2024; Sri Vigna Hema and Manickavasagan, 2024).

In ML-assisted auditing, anomaly- and fraud-detection pipelines often report task-specific classification performance for the specific tasks, feature sets, and datasets evaluated. Yet, comparability across studies is constrained by heterogeneity in data access, class prevalence, labeling strategies, and evaluation protocols. Likewise, explainability interventions - frequently operationalized through SHAP- and LIME-type explanation families - do not translate into a single universal “percentage improvement” metric. Instead, explainability is typically assessed through proxies such as fidelity, user trust, usability, and decision consistency, which vary by task and audience. For this reason, this review treats explainability gains as context-dependent outcomes that must be reported together with the measurement instrument and target population (Han et al., 2023), (Hur et al., 2025), and (Zhang et al., 2022).

Discussion

Figure *7* conceptualizes the interaction among these mechanisms as an iterative evidentiary cycle: the ledger anchors integrity and provenance; explainable analytics generate justifiable outputs; smart contracts encode and enforce accounting and environmental constraints; and the ESG layer structures auditable disclosure. Across the evidence base, some studies report quantitative outcomes that are task- and context-specific - such as detection performance metrics or observed differences under particular disclosure/assurance settings - but these values do not constitute uniform benchmarks transferable across domains. Accordingly, ABAF-RE is positioned as an evidence-informed design synthesis rather than as a fully validated field system, and any performance targets are framed as pilot hypotheses to be tested under pre-registered metrics and explicit governance assumptions (Coli et al., 2021), (Compagnino et al., 2025), (Ellahi et al., 2024), (Han et al., 2023), and (Wang et al., 2024).

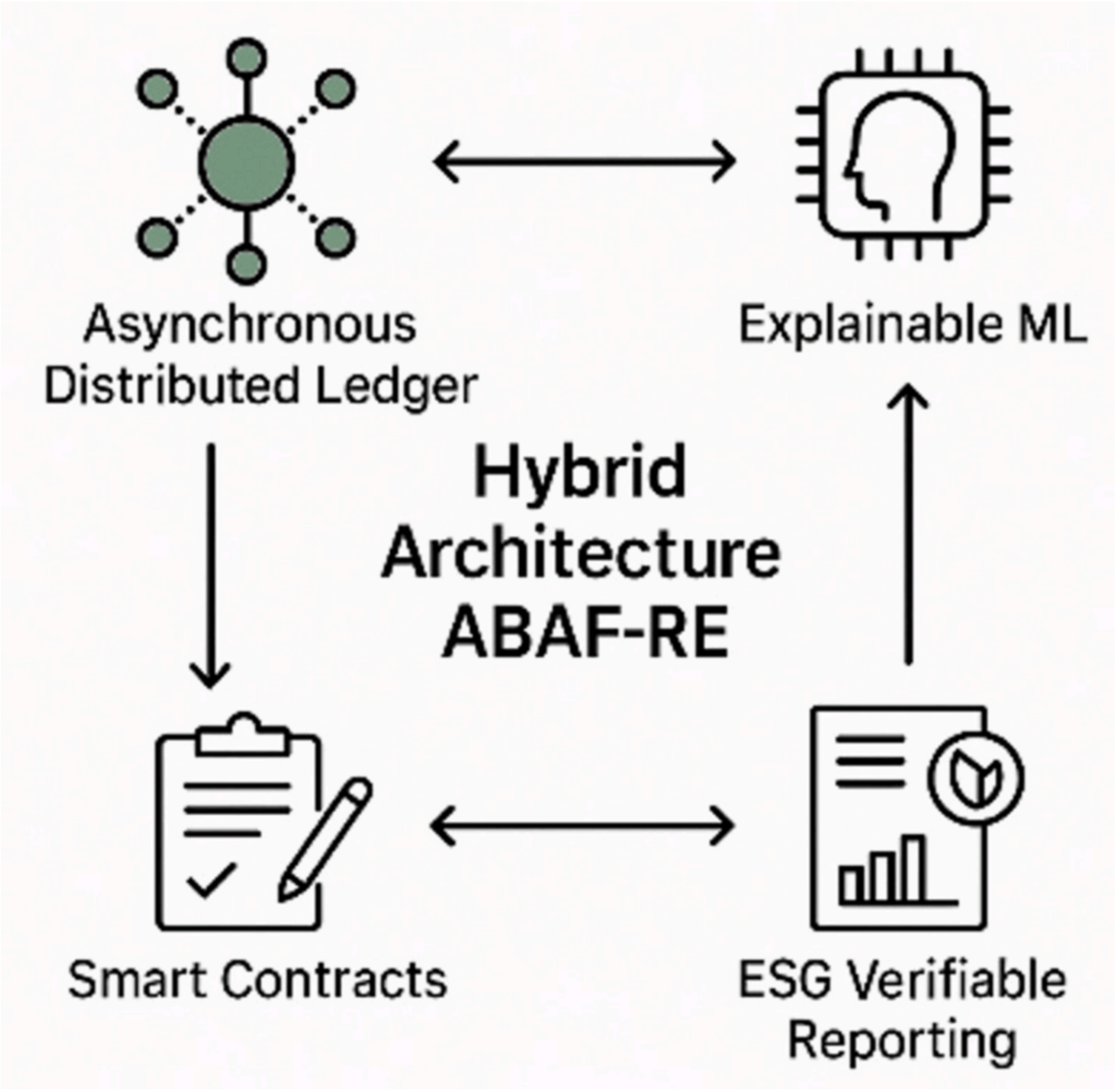

FIGURE 7: Hybrid Architecture ABAF-RE: interaction between asynchronous ledger, explainable ML, smart contracts, and verifiable ESG reporting

Source: Authors' elaboration. ABAF-RE = AI-Blockchain Accounting Framework for Rural Entrepreneurship; ESG = environmental, social, and governance; ML = machine learning

Microfinance Pilots

Microfinance-oriented pilot reports are used here to illustrate feasibility, governance constraints, and operational considerations for blockchain-enabled recordkeeping and reconciliation in resource-constrained contexts; accordingly, this manuscript does not infer specific percentage KPI effects unless they are explicitly reported as results in the source document (Coli et al., 2021).

Visual Schemata and their Integrative Function

The analysis now turns to Figure *8*, which develops the territorial dimension of the model:

FIGURE 8: Adaptive sustainability ledger for ESG and rural IoT integration

Source: Authors' elaboration. ESG = environmental, social, and governance; IoT = Internet-of-Things.

Figure *8* illustrates how asynchronous, offline-first architectures can enable local data capture in rural environments where connectivity is intermittent and synchronization cannot be assumed. In agri-food supply chains, IoT-enabled traceability solutions - when coupled with integrity-preserving mechanisms such as tamper-evident logging, provenance metadata, and deferred notarization - are frequently discussed as mechanisms intended to strengthen documentary integrity and limit risks of evidence loss or post hoc alteration. However, reported effects are highly dependent on the baseline configuration, sectoral constraints, and implementation context, and therefore should not be interpreted as transferable benchmarks across settings (Ellahi et al., 2024) (Sri Vigna Hema and Manickavasagan, 2024). Complementarily, empirical evidence from farm-office digitalization indicates improvements in the accuracy and consistency of sustainability-reporting routines under real operational conditions, supporting the practical relevance of adaptive digital infrastructures in rural accounting workflows (Poppe et al., 2024).

The discussion progresses to Figure *9*, associated with the environmental-to-carbon verification pipeline.

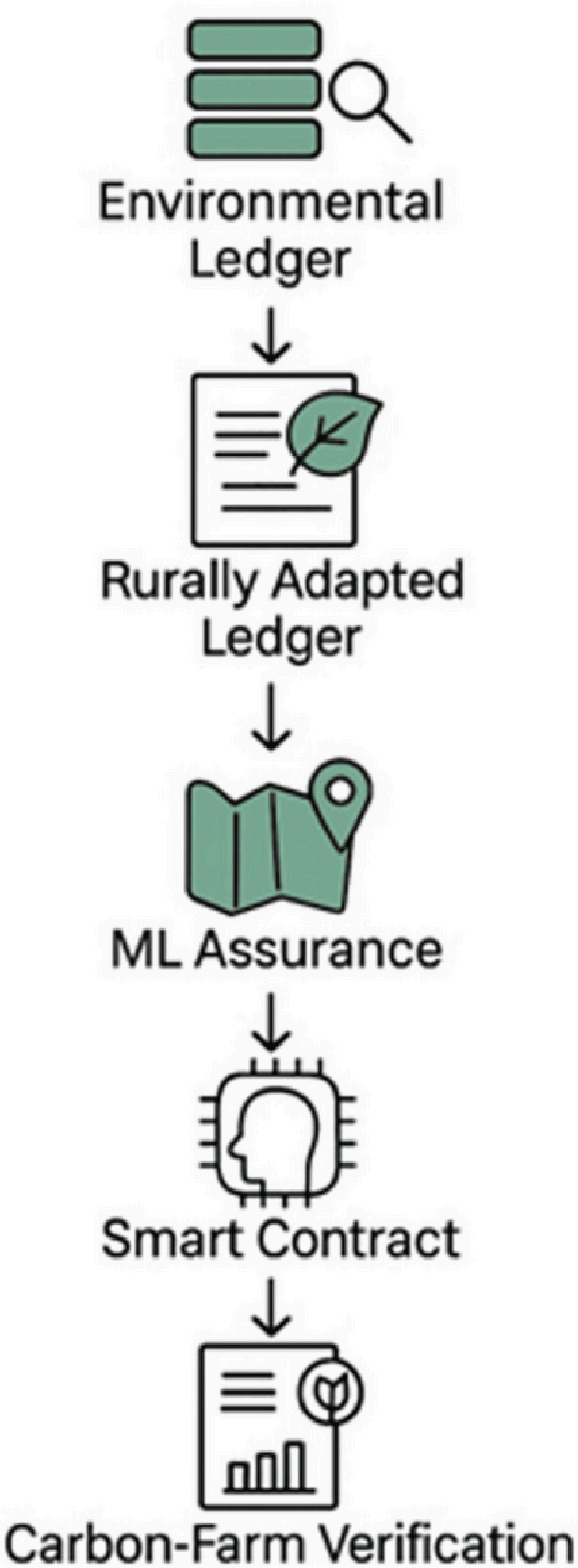

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FIGURE 9: Environmental-to-carbon verification pipeline for rural chains

Source: Authors' elaboration. ML = machine learning.

This sequence-environmental ledger → rural ledger → ML-based assurance → smart-contract validation → carbon verification-integrates core principles of true-cost accounting and environmental accountability. Prior studies indicate that standardized emission factors and harmonized measurement rules can improve the precision with which sustainable and non-sustainable practices are differentiated, even in contexts with high spatial variability, provided that measurement assumptions, data lineage, and validation rules remain auditable throughout the pipeline (Gusc et al., 2022) (Patil et al., 2025).

Implications for Rurality and Distributed Governance

The reviewed evidence suggests that distributed technologies may help mitigate structural challenges in rural territories - information loss, buyer-side asymmetries, the absence of verifiable records, and barriers to certification - by supporting evidentiary continuity, facilitating reconciliation across actors, and enabling auditable governance over both data and rules when implemented with explicit baselines and governance assumptions. Nevertheless, reported performance effects are typically derived from heterogeneous tasks, datasets, and evaluation protocols, which limits cross-study comparability and discourages the use of fixed "universal" percentages as field-level benchmarks. Accordingly, ABAF-RE treats the literature as an evidence base for design decisions and risk-aware hypotheses, while reserving quantitative claims for pilot evaluation against pre-registered metrics and explicitly defined baselines (Coli et al., 2021), (Compagnino et al., 2025), (Ellahi et al., 2024), (Han et al., 2023), and (Wang et al., 2024).

The ABAF-RE model responds to these constraints by incorporating three essential components: offline-first architectures (to preserve integrity under deferred synchronization), explainable analytics (to make risk signals defensible in assurance settings), and programmatic validation (to encode accounting/ESG constraints into auditable checks). Together, these elements are designed to reduce operational friction and increase verifiability in rural chains where informational flows are fragmented and enforcement capacity is uneven.

Scientific Contribution

The literature reveals a recurring gap: while conceptual models and urban-oriented pilots are prevalent, reproducible architectures designed explicitly for rural constraints - intermittent connectivity, heterogeneous devices, and multi-actor evidence reconciliation - remain scarce. ABAF-RE addresses this gap by synthesizing asynchronous ledgers, explainable ML, and programmatic validation into a cohesive architecture whose components are consistent with mechanisms documented in recent accounting, auditing, sustainability, and traceability research. Importantly, the model is presented as an evidence-informed design synthesis, not as a demonstrated field intervention; therefore, expected benefits are operationalized as pilot targets to be empirically tested rather than asserted as transferable outcomes. The implementation strategy for this model is detailed in Table *7*, invoked here.

Horizon	Implementation focus (strategic actions)	Literature-reported evidence (from reviewed studies)	Evaluation targets for ABAF-RE pilots (to be empirically validated)	Key sources
Short term (0–12 months)	Pilot offline-first evidence capture; local sealing (hash + timestamp); initial asynchronous anchoring; baseline XAI configuration; minimal rule-as-code checks for accounting/ESG.	Traceability and auditability studies report context-specific gains in documentary integrity and reconciliation when workflows define clear provenance and tamper-evidence mechanisms; ML-based detection performance is typically task- and dataset-dependent; explainability is usually operationalized through proxies (e.g., fidelity, usability, trust, decision consistency) rather than a universal percentage metric. Therefore, these findings are treated as design-relevant evidence, not transferable benchmarks.	(i) Maintain deferred synchronization within an a priori specified operational window for the pilot, justified by contextual constraints; (ii) define operationalizable traceability KPIs (e.g., rate of records without complete lineage, reconciliation time, proportion of evidence with verifiable local sealing) and evaluate changes against a recorded baseline using pre-registered metrics; (iii) establish and apply an explanation acceptability criterion agreed with assurance stakeholders (e.g., a completeness-and-utility rubric), documenting assumptions and limits.	(Ellahi et al., 2024); (Han et al., 2023); (Sri Vigna Hema and Manickavasagan, 2024); (Zhang et al., 2022).
Medium term (1–3 years)	Add edge gateway; synchronization queues; permissioned ledger node(s); oracle service; expanded ESG/accounting validation module; governance (roles, access control, audit logs); iterative ML retraining.	Work on blockchain-enabled disclosure and pilot deployments suggests potential reductions in reconciliation frictions and stronger verifiability through rule formalization and auditability-by-design. However, effect sizes are heterogeneous and are not consistently reported in directly comparable KPI formats; impacts are better framed as pilot	(i) Validate integration/interface maturity (IRL): no traceability breaks under windowed sync and queue replay; (ii) demonstrate end-to-end audit-trail completeness (lineage from capture → anchoring → validation → reporting); (iii) demonstrate measurable reductions vs. local baselines using pre-registered metrics (e.g., reconciliation	(Coli et al., 2021); (Wang et al., 2024); (Zhu and Liu, 2024).

		hypotheses evaluated against local baselines and pre-registered metrics.	time, exception resolution time, unverifiable-record rate).	
Long term (3–5 years)	Operational scaling: monitoring + assurance dashboard; rule/contract version control; identity management; MLTRL-aligned ML lifecycle; carbon-verification workflow where feasible; interoperability with external registries/markets only if governance allows.	The reviewed corpus does not establish long-run adoption rates or scalable performance as transferable benchmarks; long-term evidence is primarily expressed through governance, assurance mechanisms, and control architectures rather than uniform quantitative effects.	(i) Sustain auditability under change control (rules/models) with verifiable versioning and rollback; (ii) maintain continuous monitoring (drift/incident response) against pre-specified thresholds; (iii) demonstrate identity and access management with role segregation and auditable authorization trails; (iv) validate carbon/ESG verification workflows where the external assurance context permits.	(Gusc et al., 2022); (Patil et al., 2025); (Stanescu et al., 2025).

TABLE 7: Evidence-informed implementation roadmap for ABAF-RE: staged actions, literature-reported benchmarks, and pilot evaluation targets

Source: Authors' elaboration. ABAF-RE = AI-Blockchain Accounting Framework for Rural Entrepreneurship; ESG = environmental, social, and governance; ML = machine learning; XAI = explainable artificial intelligence; KPI = Key Performance Indicator; MLTRL = Machine Learning Technology Readiness Level.

Readiness Roadmap (TRL-IRL-SRL) and Staged Implementation in Rural Settings

To make ABAF-RE technologically implementable rather than purely conceptual, a layered readiness approach is proposed by combining TRL (component maturity), IRL (interface/integration maturity), and SRL (system-level readiness). This combined lens is particularly relevant in rural deployments, where failures are frequently driven by interfaces and dependencies - intermittent connectivity, deferred synchronization, device heterogeneity, and multi-actor coordination - rather than isolated component malfunction. Accordingly, progress should be assessed at the component level and at the integration/system level, with explicit criteria for data flow continuity, interface robustness, and traceable operational controls (International Organization for Standardization, 2013) (Sauser et al., 2010). For the analytics layer, MLTRL is additionally incorporated to define ML-specific readiness gates (data quality, validation, robustness, deployment, and in-operation monitoring), reducing the risk of prototypes that do not withstand real-world operation (Lavin et al., 2022).

Practically, rural implementation can be organized into three stages. In an initial stage (TRL 1-3), ABAF-RE is instantiated as a verifiable specification and proof of concept: minimal evidence artifacts, a data taxonomy, and ESG/accounting rules amenable to programmatic verification are defined, while preserving an offline-first logic with local sealing and a deferred channel for ledger anchoring. This logic is illustrated in Figure *10*, where the rural "local box" (mobile/PC and local storage) generates evidence (hashes and timestamps) prior to asynchronous transmission.

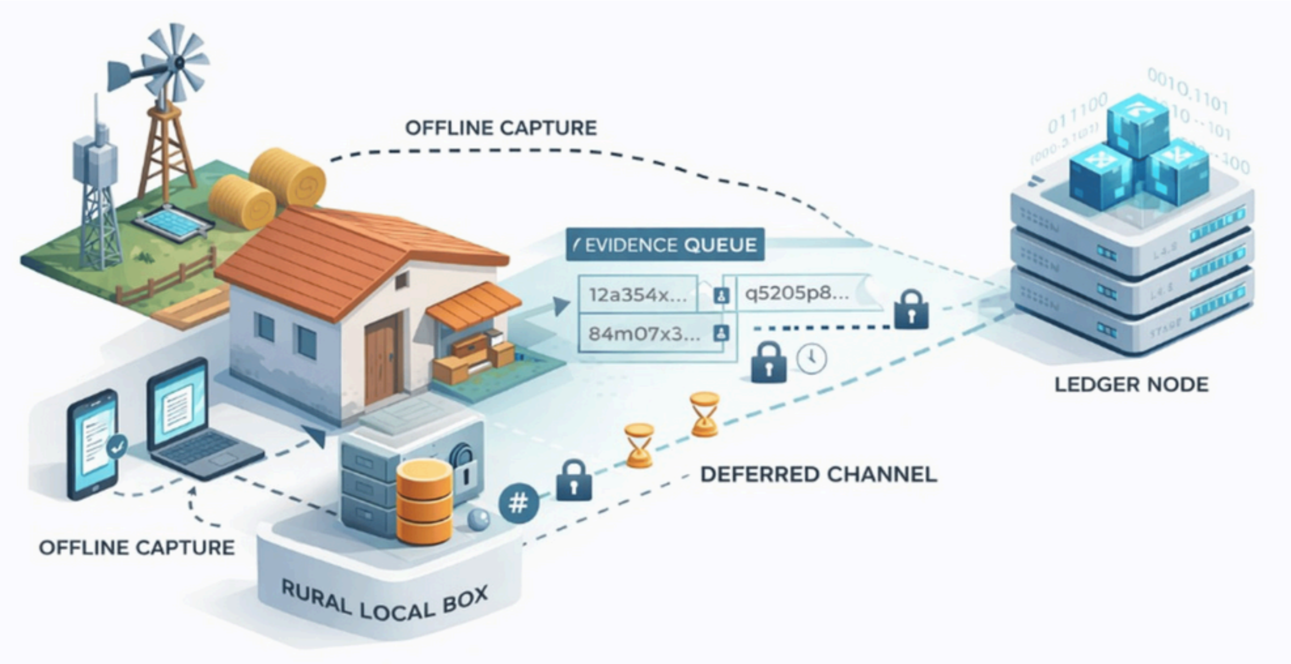

FIGURE 10: TRL 1–3 logical architecture (offline-first): rural local box (mobile/PC and local storage), evidence generation (hashing and timestamping), and a deferred channel for subsequent anchoring to the ledger node

Source: Authors' elaboration. TRL = Technology Readiness Level.

In a second stage (TRL 4-6), the focus shifts to validation in a relevant setting through integrated pilots: an edge gateway, synchronization queues, and a permissioned ledger are added, together with an oracle service and an ESG/accounting validation module translating rules and controls into auditable checks. Figure *11* depicts this stage, where the dominant challenge is no longer component existence but whether evidence flows remain intact under windowed synchronization and whether verification points (oracles and validation) avoid opacity and traceability loss.

FIGURE 11: TRL 4–6 integrated architecture: addition of an edge gateway, synchronization queues, a permissioned ledger node, an oracle service, and an ESG/accounting validation module enabling auditable checks

Source: Authors' elaboration. TRL = Technology Readiness Level.

In a third stage (TRL 7-9), the goal shifts to operationalization, scaling, and continuous assurance. Monitoring services, assurance dashboards, contract/rule version control, identity and access management, and an end-to-end ML lifecycle aligned with MLTRL (data → training → validation → deployment → monitoring/drift) are incorporated into routine operations. Figure *12* summarizes this operational state, where system maturity depends on robust change control, sustained technical auditability, and the ability to preserve verifiable evidence over time. This staged progression is consistent with work that explicitly distinguishes capability demonstration from real-world readiness in AI-enabled systems and emphasizes readiness gates across data, deployment, and in-operation monitoring (Lavin et al., 2022) (Martínez-Plumed et al., 2021).

FIGURE 12: TRL 7–9 operational architecture: monitoring and assurance dashboard, contract/rule version control, identity management, and an MLTRL-aligned ML lifecycle loop (data → training → validation → deployment → monitoring/drift)

Source: Authors' elaboration. TRL = Technology Readiness Level; MLTRL = Machine Learning Technology Readiness Level; ML = Machine Learning.

Specific Recommendations for Policymakers

Based on the synthesized evidence and the governance requirements of the proposed architecture, ABAF-RE's practical value depends not only on technical design but also on enabling regulatory and policy conditions. First, policymakers should promote interoperability between financial reporting and sustainability disclosure, particularly by supporting disclosure regimes that link sustainability-related risks to decision-useful information for general-purpose reporting users (Castillo Delgadillo and Díaz-Peña, 2025) (Harahap et al., 2024). Second, assurance settings require explicit AI governance requirements, including minimum documentation, risk evaluation, data traceability, and in-operation monitoring aligned with recognized risk-management frameworks (International Organization for Standardization and International Electrotechnical Commission, 2023), (National Institute of Standards and Technology, 2023). Third, rural-oriented regulation should explicitly recognize offline-first and deferred synchronization architectures as legitimate evidence-preservation mechanisms under structural connectivity constraints, instead of implicitly assuming continuous online infrastructures that systematically exclude smallholders and microenterprises. Finally, piloted deployments should be incentivized under independent evaluation arrangements (e.g., audit bodies and academia) and innovation-oriented procurement mechanisms for verifiable traceability, in order to reduce vendor lock-in risk and to build transferable institutional learning.

Limitations and Potential Biases

This study has constraints that should be stated precisely to prevent inferences that exceed the underlying evidence base. First, restricting the corpus to peer-reviewed English-language journal articles within 2019-2025 was intended to maximize bibliographic traceability and cross-database comparability; however, the same restriction introduces a coverage bias that may under-represent regional contributions, applied literature published in other languages, or relevant technical evidence disseminated outside major indexing platforms. This does not undermine the synthesis, but it does bound its generalizability and its ability to fully capture locally embedded assurance and reporting practices in rural settings.

Second, the co-occurrence, thematic density, and lexical frequency analyses (Figures *2*-*6*) quantify semantic relations within the corpus and are used to describe conceptual convergence. By design, they do not establish causality or real-world effectiveness, and they should not be interpreted as direct indicators of technological maturity. For that reason, implementation readiness is addressed separately through an explicit maturity framework (TRL-IRL-SRL and MLTRL), while Figures *2*-*6* are interpreted as evidence of thematic structure supporting architectural design choices rather than as performance validation.

Third, the manuscript proposes an architecture and conducts internal consistency checks; without field deployment, the evidence remains literature-substantiated design synthesis rather than operational impact. Finally, publication bias is plausible: studies reporting positive outcomes, "successful" prototypes, or compelling conceptual frameworks tend to be over-represented relative to failed implementations or non-published evidence, potentially skewing the landscape toward proposals and pilots. Making these evidence gradients explicit strengthens the paper's credibility, bounds the scope of its claims, and clarifies which statements are directly supported by the corpus and which are offered as plausible architectural inference.

Conclusions

The synthesis presented in this review suggests that the field is moving beyond incremental "digitization" of accounting routines toward a redefinition of evidence conditions - that is, the operational and governance requirements under which financial and environmental information can be generated, preserved, and subjected to assurance. Across the examined corpus, three mechanism families recur as mutually reinforcing responses to a shared fragility: distributed-ledger anchoring (to maintain tamper-evident continuity), explainable ML/DL analytics (to produce audit-relevant signals that remain interpretable and contestable), and programmable validation (to express selected controls as executable, traceable checks). While reported outcomes vary by task, dataset, and institutional setting - and therefore do not support transferable effect-size claims - the direction of travel is consistent: verifiability is increasingly treated as a property that must be engineered into capture, synchronization, and control execution, rather than appended as a late-stage corrective.

On that basis, this article contributes an integrative design result: ABAF-RE, conceived as a modular architecture that organizes evidence preservation, analytical interpretation, and validation into an auditable cycle. Operationally, the framework treats an asynchronous ledger as a continuity substrate under deferred synchronization; it treats explainability as an assurance requirement, meaning that model outputs must be accompanied by inspectable traces (data lineage references, assumptions, and explanation artifacts) rather than functioning as opaque determinations; and it treats rule-as-code validation as the controlled translation of a subset of accounting/ESG constraints into executable checks whose inputs, versions, and outcomes are logged for later audit. This framing keeps accountability distributed and reviewable: the system can support verification, but it does not displace professional judgment, which remains necessary to interpret exceptions, contextualize indicators, and adjudicate disagreements across actors and documents.

The applied relevance of ABAF-RE becomes most visible in rural settings because the constraints there are structural, not incidental. Intermittent connectivity, heterogeneous devices, and uneven recordkeeping imply that the primary technical problem is not simply storage or transmission, but evidence continuity under discontinuous operation. In operational terms, this means preserving a defensible chain from event capture to later anchoring, minimizing opportunities for untraceable transformation at interfaces, and maintaining semantic coherence across records that may be produced by different actors under different routines. The framework's scientific value, in that context, is proportional and explicit: it offers a disciplined implementation logic that clarifies (i) what must be specified at design level to preserve integrity (artifacts, lineage, anchoring points), (ii) what must be integrated to sustain multi-actor traceability (interfaces, reconciliation rules, synchronization windows), and (iii) what must be governed as the system evolves (versioning of rules and models, access control, audit logging, and accountability assignments). This separation is not rhetorical; it functions as a boundary between design claims that can be defended by internal coherence and empirical claims that require field testing.

The next scientific step is therefore clear but methodologically demanding: pilot deployments and independent evaluation in rural scenarios under explicit baselines and pre-registered metrics. Evaluation should be structured to distinguish at least three dimensions: technical performance (e.g., lineage completeness, reconciliation time, exception rates), organizational feasibility (coordination costs, operational burden, and incentives for truthful reporting), and governance robustness (change control for rules/models, role segregation, and auditability under dispute). The present study establishes a coherent technical basis for distributed computational trust as an assurance infrastructure; its ultimate credibility will depend on whether that basis translates into resilient evidentiary practice in settings where connectivity constraints, heterogeneous actors, and evolving reporting requirements are not exceptions but the default operating condition.

Additional Information

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

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Data Availability Statements

The screening log (36 unique records after de-duplication), full-text eligibility decisions (21 assessed; 6 excluded with documented reasons), and the evidence extraction matrix for the 15 included studies are publicly available in a curated dataset deposited in Mendeley Data (V1): https://data.mendeley.com/datasets/m5y8trp9sw/1. The repository contains derived review data only and does not include copyrighted full-text articles.

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