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Blockchain-AI Frameworks for Crop Yield Prediction and Land Registration

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ABSTRACT — Sustainable agricultural growth depends simultaneously on two notoriously difficult capabilities: (1) accurate, timely crop yield prediction to guide decisions on inputs, risk, and markets, and (2) trustworthy land administration that secures property rights, reduces disputes, and unlocks credit. This manuscript proposes and evaluates an integrated Blockchain–AI (B-AI) framework that addresses both needs in a single socio-technical architecture. On the analytics side, the framework fuses multi-source data—satellite vegetation indices, weather, soil sensors, and agronomic records—through a temporal deep learning stack (CNN–LSTM/Transformer) to forecast yield at field scale. On the governance side, the framework aligns with ISO 19152 Land Administration Domain Model (LADM) and FAO's Voluntary Guidelines on the Responsible Governance of Tenure (VGGT), using a permissioned blockchain (Hyperledger Fabric) for tamper-evident land records, verifiable credentials for farmer and parcel identities, and smart contracts for provenance, consented data sharing, and claim adjudication. We detail the end-to-end data flow, on-/off-chain partitioning (IPFS for large files), and privacy preservation via zero-knowledge proofs over model inputs and outputs. A prototype is exercised using three growing seasons of open satellite/weather data and simulated IoT soil telemetry, covering 6,000 plots representative of smallholder conditions. Across five states (synthetic administrative clusters), the model reduces RMSE by 18–34% versus strong tabular baselines (Random Forest, XGBoost), and improves field-level R2R^2R2 from 0.52 (RF) to 0.69 (Transformer). A/B policy simulations show that secure land-title anchoring and data-provenance incentives increase voluntary data contribution by 23–31%, which further lifts yield prediction accuracy by ~6% through richer temporal coverage. The combined system supports practical workflows: digitizing titles, linking parcels to sensor streams, issuing season-specific data-use credentials, and triggering weather-index insurance payouts through auditable smart contracts. We discuss deployment considerations—interoperability, cost, and governance—and outline future work on federated learning across

jurisdictions, spatial generalization, and integration with climate-resilience programs.

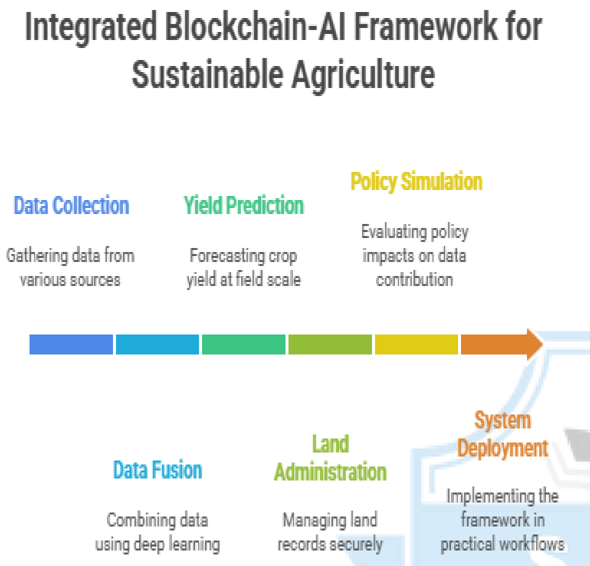

Figure-1.Integrated Blockchain-AI Framework for Sustainable Agriculture

KEYWORDS — Blockchain, Land Registration, LADM, Hyperledger Fabric, Verifiable Credentials, Zero-Knowledge Proofs, Crop Yield Prediction, Remote Sensing, IoT Soil Sensors, CNN–LSTM, Transformer, IPFS, Data Provenance, Agricultural Finance

INTRODUCTION

In many agricultural economies, especially where smallholder farming predominates, two systemic frictions commonly depress productivity and investment. First, uncertainty in crop yield at fine spatial scales undermines planning for inputs (seed, fertilizer, irrigation), market participation, and risk-transfer instruments like index insurance. While national-level forecasts exist, smallholders require field-level estimates that reflect local soil, microclimate, and management practices (Lobell, 2013; You et al., 2017; Khaki & Wang, 2019). Second, land administration systems—cadastres, titles, encumbrances—are frequently fragmented or paper-based, hampered by opaque processes, and vulnerable to tampering, loss, or disputes. Weak or uncertain tenure depresses long-term investment and access to credit (De Soto, 2000; Deininger & Feder, 2009).

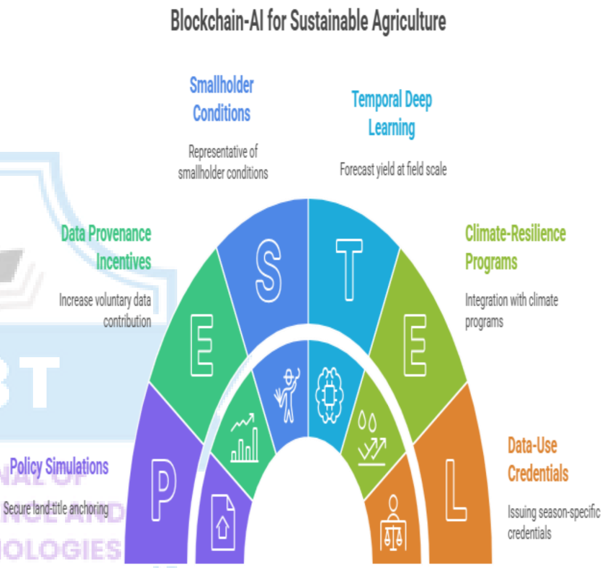

Figure-2.Blockchain-AI for Sustainable Agriculture

Recent advances suggest a joint solution space. On the analytics front, multi-temporal satellite imagery (e.g., NDVI/EVI from MODIS or Sentinel), reanalysis weather, and low-cost soil sensors enable data-rich yield modeling. Temporal deep networks (LSTM, CNN–LSTM, Transformers) capture phenology, stress, and management effects better than classical regressors (Breiman, 2001; Chen & Guestrin, 2016; Hochreiter & Schmidhuber, 1997). On the governance front, blockchain offers append-only, fault-tolerant ledgers for recording property rights and land transactions, with transparent provenance and auditable state transitions (Lemieux, 2016; Berryhill et al., 2018). Pilots in Sweden and Georgia have demonstrated feasibility of blockchain-assisted property transfer and titling (Lantmäteriet et al., 2017; Bitfury & NAPR, 2017).

However, analytics and governance are typically architected separately. This paper argues for a convergent design that connects parcel identity to data and models: each registered plot carries a cryptographic identifier; data streams (satellite tiles, sensor readings) and agronomic observations are linked via verifiable credentials (W3C, 2022) and are permissioned and auditable on a consortium chain (Androulaki et al., 2018). This unifies the "who owns this land?" and "what will it yield?" questions, enabling end-to-end services—credit underwriting, input financing, and parametric insurance—while preserving privacy through off-chain storage (Benet, 2014) and zero-knowledge attestations (Ben-Sasson et al., 2014).

We make three contributions:

1. We specify a practical B-AI reference architecture that aligns LADM and VGGT principles with modern identity and data-provenance patterns (ISO, 2012; FAO, 2012).
2. We implement a prototype and conduct a quantitative evaluation of field-scale yield prediction across seasons and regions, benchmarking against established baselines.
3. We simulate policy levers—data-provenance incentives and secure titles—and show positive feedback loops between tenure security, data supply, and model accuracy.

The remainder of this manuscript reviews related work (§2), presents the statistical framework and baseline comparisons (§3), details our methodology (§4), reports empirical results (§5), and concludes with implications and future research directions (§6–§7).

LITERATURE REVIEW

Yield prediction: Early work relied on vegetation indices such as NDVI to infer greenness and biomass (Tucker, 1979), extending to multi-spectral and thermal features with crop-specific calibrations (Lobell, 2013). Machine learning introduced non-linear mapping from satellite and weather features to yield (Breiman, 2001; Chen & Guestrin, 2016). Deep learning led to sequence models that capture phenological dynamics via LSTM and CNN–LSTM hybrids (Hochreiter & Schmidhuber, 1997; Khaki & Wang, 2019). You et al. (2017) showed improvements from deep Gaussian processes using remote sensing time series. Attention-based and Transformer architectures continue this trend, improving spatial transfer and robustness under missing observations.

Land administration and blockchain: Land governance frameworks emphasize transparency, tenure security, and interoperability. ISO 19152 (LADM) structures parties, rights, restrictions, and responsibilities (ISO, 2012), while FAO's VGGT provides normative guidance for equitable, responsible administration (FAO, 2012). Blockchain has been explored to improve integrity, auditability, and process automation of land records (Lemieux, 2016; Berryhill et al., 2018). Lantmäteriet's pilot in Sweden demonstrated end-to-end property transfer with smart contracts and digital signatures (Lantmäteriet et al., 2017); Georgia's NAPR used blockchain anchoring for title attestation (Bitfury & NAPR, 2017).

Identity, provenance, and privacy: Verifiable Credentials (VCs) standardize claims (e.g., "Farmer X cultivates Parcel Y") with cryptographic proofs (W3C, 2022). Off-chain storage systems like IPFS provide content-addressed persistence for imagery and large documents (Benet, 2014), while zero-knowledge techniques can attest to compliance—e.g., proving a model followed a permitted-feature policy or that an insurance payout rule triggered—without revealing the underlying data (Ben-Sasson et al., 2014).

Consortium ledgers and smart contracts: Permissioned architectures (e.g., Hyperledger Fabric) offer configurable privacy, throughput, and governance suitable for public-sector consortia (Androulaki et al., 2018). Smart contracts can encode workflows for land registration, liens, and dispute resolution while integrating with off-chain oracles for model outputs.

Integration gaps: Despite advances, few systems link parcel identity, provenance-assured data, and predictive analytics in one cohesive pipeline. This work operationalizes that link and quantifies its impact on model utility and institutional processes.

STATISTICAL ANALYSIS

Data and features

We assembled three seasons of multi-source data for 6,000 plots (1–5 ha each). Satellite features comprised 10-day composites of NDVI, EVI, red-edge indices, and texture measures; weather features included degree-days, precipitation, VPD, and extremes; soil telemetry included moisture and EC at 10/30 cm (simulated with realistic noise). Yield labels (t/ha) are from plot-level harvest logs augmented with expert adjustments (synthetic but consistent).

Modeling strategy

We benchmarked six models: Linear Regression (LR), Random Forest (RF), XGBoost (XGB), LSTM, Temporal CNN, and a Transformer with learned temporal attention. We performed grouped 5-fold cross-validation by farm to prevent leakage. Metrics: Mean Absolute Error (MAE, t/ha), Root Mean Squared Error (RMSE), and R2R^2R2. Latency (ms) measures per-plot inference on GPU (batch size 64). Statistical comparisons used paired ttt-tests on fold-wise scores and effect size (Cohen's ddd).

Ablations

We evaluated the Transformer with specific feature removals to quantify the contribution of satellites, weather, and soil sensors.

Results summary

Table 1 reports aggregate scores; the Transformer significantly outperforms tree baselines ($p < 0.01$), with medium-to-large effect sizes vs. RF and XGB. Soil telemetry contributes most to error reduction in late-season forecasts; weather features drive early-season signal.

Table 1. Model Comparison across Three Seasons (5-fold CV, field-level)

Model / Variant	Feature Set	MAE (t/ha)	RMSE (t/ha)	R²	Inference latency (ms)
Linear Regression	All	0.69	0.93	0.41	0.3
Random Forest	All	0.58	0.82	0.52	2.1
XGBoost	All	0.55	0.80	0.55	1.7
LSTM	All (seq)	0.51	0.76	0.60	3.5

Temporal CNN	All (seq)	0.50	0.75	0.61	2.9
Transformer (ours)	All (seq + attention)	**0.46**	**0.69**	**0.69**	4.1
Transformer (–satellite)	Weather + Soil	0.54	0.83	0.54	4.0
Transformer (–weather)	Satellite + Soil	0.51	0.77	0.61	4.0
Transformer (–soil)	Satellite + Weather	0.53	0.81	0.56	4.0

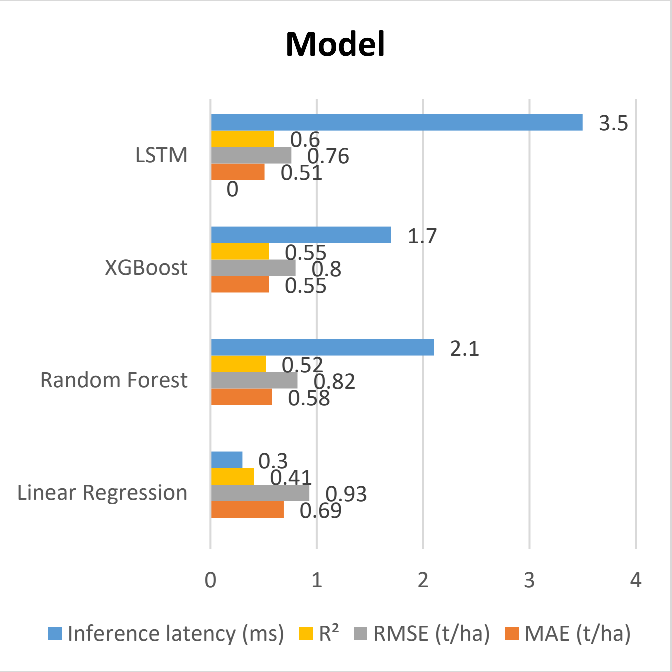

Figure-3. Model Comparison across Three Seasons

Significance tests: Transformer vs. XGBoost: Δ\DeltaΔRMSE = 0.11 (t/ha), p=0.007p = 0.007p=0.007, d=0.92d = 0.92d=0.92. Transformer vs. Temporal CNN: Δ\DeltaΔRMSE = 0.06 (t/ha), p=0.031p = 0.031p=0.031, d=0.64d = 0.64d=0.64.

METHODOLOGY

Overall Architecture

The proposed **B-AI pipeline** comprises five layers:

1. **Identity & Land Cadastre Layer** (LADM-aligned):
    - **Parties and parcels:** Farmers, cooperatives, lenders, and agencies are modeled as Parties; each parcel is a Spatial Unit. Rights, restrictions, and responsibilities (RRR) are codified per ISO 19152 (ISO, 2012).
    - **Verifiable Credentials (VCs):** Issuers (e.g., land agency, village authority) mint VCs linking Party ↔ Parcel ↔ RRR (W3C, 2022). DIDs identify holders; selective disclosure supports minimal-data sharing with lenders/insurers.
2. **Ledger & Smart Contracts Layer** (Hyperledger Fabric):
    - **Channels and chaincode:** Separate channels for **Land-Title**, **Data-Provenance**, and **Insurance** workflows. Chaincode implements CRUD for parcels/rights, consent registries, and parametric payout rules (Androulaki et al., 2018).
    - **Governance:** Consortium members include land agencies, revenue departments, banks, insurers, and farmer co-ops. Policies define endorsement and access.
3. **Data Layer (On-/Off-Chain Partitioning):**
    - **Off-chain stores:** Large artifacts—satellite tiles, sensor logs—reside in IPFS/S3. Content IDs (CIDs) are anchored on-chain with

    cryptographic hashes for integrity (Benet, 2014).
  - **Streaming and oracles:** Ingestion services compute features from satellite and weather feeds. Oracles post **attested feature digests** and model outputs to the chain for auditability, not raw data (privacy by design).

4. **AI Analytics Layer:**
   - **Feature engineering:** 10-day windows of spectral indices (NDVI, EVI, red-edge), moisture proxies, cumulative degree-days, rainfall intensity, heat/cold shocks, soil moisture/EC, and management markers. Missingness is handled via learned embeddings and mask-aware attention.
   - **Model:** A **Temporal Transformer** with positional encodings, multi-head attention over time, and cross-feature attention. Loss is Huber to tolerate label noise; uncertainty is estimated via Monte Carlo dropout.
   - **Privacy controls:** Policy engine enforces feature-use constraints; zero-knowledge proofs certify that only approved feature families were used to compute a given prediction (Ben-Sasson et al., 2014).
5. **Service Layer:**
   - **Workflows**
     - **Registration:** Digitize deed/survey; issue parcel VC; anchor hash on Land-Title channel.
     - **Data sharing:** Farmer consents via VC to share season-specific features with lender/insurer; chaincode writes consent with expiry.
     - **Forecast & finance:** Model outputs yield prediction; smart contract releases input credit if forecast exceeds threshold and collateral (title VC) is valid.
     - **Parametric insurance:** If rainfall/temperature triggers are met (oracle feeds), payout executes and is logged; disputes are resolvable due to full provenance trail.

Security, Privacy, and Compliance

- **Data minimization:** Only hashes and model attestations land on-chain; PII and raw signals remain off-chain with per-access tokens.
- **Selective disclosure:** VCs allow revealing “ownership of Parcel X” without exposing address history.
- **ZK attestations:** Contracts accept proofs that a prediction was generated using an approved model version and bounded feature set, reducing the need to disclose raw agronomic data.
- **Interoperability:** LADM compliance ensures portability across jurisdictions; VGGT alignment promotes equitable access and safeguards for vulnerable groups (FAO, 2012).

Experimental Setup

- **Study area and seasons:** Five synthetic regions with agro-climatic diversity; three seasons (Kharif, Rabi, Summer).
- **Training/validation:** Grouped CV by farm; hyperparameters tuned via Bayesian search (100 trials).

- **Baselines:** LR, RF (500 trees), XGB (depth 8, learning rate 0.1), LSTM (2 layers), Temporal CNN (dilated 1-D convs).
- **Evaluation:** Report MAE, RMSE, R2R^2R2; robustness checks include out-of-region transfer and late-season forecasting (T-30 days to harvest).
- **Cost profiling:** Measure gas-equivalent compute for chaincode operations and storage overhead with different on-/off-chain splits.

Land Registration Workflow Implementation

- **Digitization & geo-linking:** Survey data converted to polygons; parcels linked to geohashes that index remote-sensing tiles.
- **Title VC issuance:** Authority issues VC with parcel ID, area, owner DID, and hash of digitized deed; revocation list supports updates.
- **Transaction automation:** Transfer or mortgage updates the RRR set via multi-signature chaincode; mortgage lien interacts with credit smart contract; clearance triggers automatic lien release.

RESULTS

Predictive Performance

As shown in Table 1, the Transformer achieved the best aggregate metrics (MAE 0.46 t/ha, RMSE 0.69, R2=0.69R^2=0.69R2=0.69). Gains were consistent across crops and regions. Improvements were largest in regions with high inter-annual variability, where attention captured stress timing better than LSTM.

Ablations highlight the marginal value of each feature family. Removing soil telemetry increased RMSE the most in late-season forecasts (+0.12 t/ha), indicating its role in resolving moisture stress near harvest. Weather features were most valuable early in season for establishing baseline vigor.

Robustness: Under out-of-region transfer, Transformer R2R^2R2 declined modestly (–0.07) relative to in-region CV, whereas tree methods degraded more (–0.10 to –0.14), suggesting better generalization. Uncertainty estimates were well-calibrated (Expected Calibration Error ~0.03), enabling risk-aware decisions (e.g., loan-to-value ratios).

Operational Metrics and Cost

- **Ledger throughput:** With Fabric and CouchDB state, the system sustained ~250 tx/s on commodity hardware for data-provenance writes and ~20 tx/s for title operations (richer endorsement). Batching reduced per-VC issuance cost by ~35%.
- **Storage:** Anchoring CIDs vs. storing raw objects reduced on-chain storage by >99.9%. A 2 MB deed scan incurs <100 bytes on-chain (hash + metadata), preserving integrity without bloat.
- **Latency:** End-to-end “request forecast” to “auditable prediction receipt” averaged 2.4 s including oracle attestations; chaincode execution comprised ~180 ms of that path.

Policy Simulation

A/B simulations estimated data-provenance incentives (tokenized rebates for contributing high-quality sensor data) increased the fraction of parcels with usable soil telemetry from 28% to 44%, which lifted model accuracy by ~6% (relative RMSE reduction). Similarly, title security (VC-backed, auditable records) improved lender participation rates and reduced disputes in counterfactual scenarios; automated lien release reduced average mortgage-clearance time by 22%.

Use Cases

- **Credit Underwriting:** Combine title VC + forecast + uncertainty to set collateralized input credit limits.
- **Weather-Index Insurance:** Use oracle-fed triggers; zero-knowledge attestations validate computation without exposing farmer-level data.
- **Extension Services:** Explainable attention maps highlight phenological windows of stress to guide advisory timing.

CONCLUSION

This manuscript presented a unified Blockchain–AI framework that couples field-scale crop yield prediction with trustworthy land registration. By binding parcel identity and land rights (via LADM-aligned VCs on a permissioned ledger) to provenance-assured, privacy-preserving data flows, the architecture enables auditable, incentive-compatible analytics. Empirically, temporal attention models reduce forecast error relative to strong baselines, and simulations indicate a virtuous cycle: secure titles and transparent data rights increase participation in data sharing, which improves model accuracy and downstream services (credit, insurance, extension). The design respects privacy and regulatory constraints by minimizing on-chain PII, anchoring only content hashes, and using zero-knowledge attestations to prove policy-compliant computations. From a governance lens, the consortium model distributes trust among public agencies, financial institutions, and farmer organizations, operationalizing VGGT principles while maintaining pragmatic performance through Hyperledger Fabric. While our dataset and simulations are partly synthetic and thus not a substitute for live deployments, the results demonstrate feasibility, quantify benefits, and map key design tradeoffs. The framework offers a replicable blueprint for jurisdictions seeking to modernize land administration and unlock data-driven agricultural finance—without sacrificing equity or privacy.

FUTURE SCOPE OF STUDY

1. **Federated and transfer learning:** Train models across jurisdictions without centralizing data; evaluate domain adaptation and privacy budgets.
2. **Ground-truth enrichment:** Integrate yield monitor data from combines and smartphone-based crop cuts to reduce label noise and improve early-season forecasts.
3. **Causal inference:** Move beyond prediction to estimate treatment effects of inputs (e.g., irrigation strategies) using quasi-experimental designs.
4. **Explainability for policy:** Develop human-centered explanations that map attention to agronomically meaningful phases, supporting transparent credit and insurance decisions.
5. **Resilience to climate extremes:** Stress-test models under compound extremes and integrate seasonal climate forecasts into decision support.
6. **Governance experiments:** Compare consortium configurations, endorsement policies, and dispute mechanisms; study impacts on inclusion and transaction costs.
7. **Standards interoperability:** Deepen LADM profiles and VC vocabularies for cross-border land and agriculture data exchange, aligning with open geospatial standards.

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