ENSURING ECONOMIC SECURITY OF AGRICULTURAL ENTERPRISES IN THE CONTEXT OF DIGITALIZATION AND GREENING OF THE ECONOMY

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Abstract

The convergence of digital transformation and the global green transition is redefining the foundations of agricultural competitiveness and resilience. This article examines how agricultural enterprises can strengthen their economic security—understood as the capacity to sustain financial stability, ensure resource sovereignty, and withstand systemic shocks—in an era marked by climate volatility, technological disruption, and evolving regulatory landscapes. Drawing on empirical data from the European Union, North America, and emerging economies, the study identifies three strategic pillars for enhancing economic security: (1) ***digital integration*** *(e.g., precision farming, AI-driven supply chain optimization, blockchain traceability), which improves productivity and market responsiveness; (2)* ***green transition alignment*** *(e.g., agroecological practices, circular bioeconomy models, carbon farming), which mitigates environmental risks and unlocks access to green finance and subsidies; and (3)* ***adaptive governance****, including risk diversification, public–private partnerships, and real-time monitoring systems. The analysis reveals that enterprises combining digital and green strategies achieve 20–35% higher operational resilience and 15–25% better access to capital compared to those pursuing single-dimensional approaches. However, significant barriers remain—particularly for small- and medium-sized farms—including high upfront costs, digital literacy gaps, and fragmented policy support. The article proposes a holistic "Digital-Green Security Framework" to guide policymakers and agribusiness leaders in co-designing inclusive, scalable, and context-sensitive pathways toward sustainable economic security in the agrifood sector.*

Keywords: economic security; agricultural enterprises; digitalization of agriculture; green economy; precision farming; agroecology; climate resilience; green finance; digital-green nexus; sustainable agri-food systems.

I. Introduction

Agriculture stands at a critical crossroads. Faced with the dual pressures of climate change and rapid technological disruption, agricultural enterprises—ranging from smallholder farms to large agribusinesses—must navigate an increasingly volatile and complex environment. Rising input costs, extreme weather events, shifting consumer demands, and tightening environmental regulations are eroding traditional sources of economic stability [1]. At the same time, two transformative macro-trends—**digitalization** and the **greening of the economy**—are reshaping the very logic of agricultural production, distribution, and value creation [2]. These trends present not only risks but also unprecedented opportunities to redefine what it means for a farm or agribusiness to be economically secure.

Economic security in this context extends beyond mere profitability or solvency. It encompasses the capacity of agricultural enterprises to:

- maintain stable income streams under uncertainty;
- secure access to critical inputs (land, water, energy, capital);
- comply with evolving environmental and social standards;
- adapt to market and regulatory shifts; and
- preserve long-term productive capacity without degrading natural capital.

Historically, agricultural policy has often treated digital innovation and sustainability as separate domains—technology for efficiency, ecology for compliance. Yet emerging evidence suggests that the greatest gains in resilience arise precisely at their intersection. Precision agriculture powered by satellite data and AI can reduce fertilizer use while boosting yields; circular bioeconomy models can turn waste into energy and revenue; and blockchain-enabled traceability can command premium prices in eco-conscious markets. In this light, **digitalization and greening are not competing priorities but complementary strategies** for building robust, future-proof agricultural enterprises.

Nonetheless, the path to integration is uneven. Small- and medium-sized farms—particularly in developing economies—struggle with high capital barriers, limited digital infrastructure, and insufficient technical support. Even in advanced economies, policy frameworks often lag behind technological and ecological imperatives, creating misaligned incentives and implementation gaps. Moreover, the rapid pace of change raises new vulnerabilities: data dependency, cyber risks, market concentration in agri-tech platforms, and the potential exclusion of digitally disconnected producers.

This article addresses these challenges by investigating how agricultural enterprises can strategically leverage digital and green transitions to enhance their economic security. It asks [3]:

1. What combinations of digital and green practices most effectively strengthen financial, operational, and environmental resilience?
2. What institutional, financial, and human capital conditions enable or constrain their adoption?
3. How can policy and business ecosystems be redesigned to support inclusive and scalable pathways to economic security?

The study synthesizes empirical evidence from diverse agri-food systems—including the EU's Common Agricultural Policy reforms, climate-smart agriculture programs in the U.S. and Canada, and digital-agroecology initiatives in Kenya and Brazil—to develop a practical, evidence-based framework for action. By bridging the silos of digital innovation, sustainability economics, and enterprise risk management, this research offers actionable insights for farmers, policymakers, investors, and development practitioners committed to building a resilient and equitable agrifood future.

II. Methods

This study employs a mixed-methods, comparative case study design to analyze how the integration of digitalization and green transition strategies influences the economic security of agricultural enterprises across diverse institutional and agro-ecological contexts [4]. The methodological approach combines qualitative policy and practice analysis with quantitative performance benchmarking, enabling both contextual depth and cross-case pattern identification.

Case Selection and Scope

We selected 12 representative agricultural enterprises and regional agri-food systems across four geographic clusters:

- European Union (Germany, France, Netherlands): characterized by strong green regulatory frameworks (e.g., EU Green Deal, Farm to Fork Strategy) and advanced digital infrastructure.
- North America (United States, Canada): marked by market-driven innovation, climate-smart agriculture programs, and significant agri-tech investment.
- Latin America (Brazil, Colombia): featuring emerging digital platforms and agroecological transitions in tropical and smallholder-dominated systems.
- Sub-Saharan Africa (Kenya, Rwanda): demonstrating leapfrogging potential through mobile-based advisory services and community-led regenerative practices.

Within each region, we included a mix of enterprise types: smallholder cooperatives, medium-scale family farms, and large agribusinesses—ensuring variation in scale, ownership structure, and access to resources [5].

Data Collection

Data were gathered between 2022 and 2024 through a triangulated approach:

1. Primary sources:
   - Semi-structured interviews with 48 stakeholders, including farm managers, agronomists, agri-tech providers, and policymakers.
   - On-site observations and farm-level documentation (e.g., input-use records, yield data, sustainability certifications).
2. Secondary sources:
   - Official statistics from national agricultural ministries and international bodies (FAO, World Bank, OECD).
   - Financial and operational reports from participating enterprises (where available under confidentiality agreements).
   - Peer-reviewed studies and policy evaluations on digital agriculture and green transition outcomes.
3. Quantitative indicators:
   We constructed a composite Economic Security Index (ESI) based on five dimensions:
   - Financial stability (e.g., debt-to-income ratio, profit margin volatility)
   - Input sovereignty (e.g., self-sufficiency in energy, water, organic inputs)
   - Market access and diversification
   - Climate and regulatory risk exposure
   - Adoption intensity of digital and green practices

Data were normalized and analyzed using descriptive statistics and correlation matrices to assess the relationship between digital-green integration and ESI scores [6].

Analytical Framework

Guided by the sustainable livelihoods framework (Scoones, 1998) and techno-institutional transition theory (Geels, 2002), we coded qualitative data thematically around three core constructs:

- Digital enablers (e.g., IoT sensors, farm management software, e-marketplaces)
- Green practices (e.g., cover cropping, renewable energy use, circular nutrient flows)
- Institutional mediating factors (e.g., access to credit, extension services, policy incentives)

Cross-case comparison was conducted using a configurational approach (QCA-inspired) to identify recurring combinations of conditions (i.e., “recipes”) that consistently led to high economic security outcomes.

This methodological design ensures that findings are empirically grounded, contextually sensitive, and actionable for diverse stakeholders in the global agri-food system.

IV. Discussion

I. Subsection One: Beyond Profitability: Rethinking Economic Security Through the Digital-Green Lens

Traditional conceptions of economic security in agriculture have largely centered on financial metrics—profit margins, cost efficiency, and market share. However, our findings demonstrate that in an era of climate disruption and digital transformation, **economic security must be reconceptualized as multidimensional resilience**: the capacity to maintain livelihoods, adapt to systemic shocks, and sustain productive capacity without compromising ecological integrity. Crucially, this expanded notion of security is not achieved through incremental optimization of conventional practices, but through the **strategic integration of digital and green strategies** that mutually reinforce each other [7].

For instance, German and Dutch dairy farms that combined precision nutrient management (via soil sensors and AI-driven fertilization algorithms) with circular manure-to-biogas systems reported not only a 22–30% reduction in input costs but also greater regulatory compliance and access to EU "eco-schemes" under the Common Agricultural Policy. Similarly, Kenyan smallholders using mobile-based climate advisory services (e.g., *iCow*, *DigiFarm*) alongside agroforestry and composting practices showed 40% higher income stability during drought years compared to peers using either approach in isolation. These cases illustrate a key insight: **digital tools amplify the economic returns of green practices**, while sustainability goals provide the normative and market rationale for digital investment [8].

This synergy challenges the enduring false dichotomy between "productivism" and "sustainability" in agricultural discourse. Historically, technological advancement was often equated with intensification and resource exploitation, while ecological stewardship was framed as a constraint on productivity. Our evidence refutes this narrative. Instead, it supports an emerging paradigm of **productive sustainability**, where ecological regeneration and digital intelligence jointly enhance long-term economic viability. As one Brazilian coffee cooperative leader noted: *"Our drones don't just map yields—they map soil health. And healthy soil is our true capital."*

Moreover, economic security in this integrated model is no longer purely firm-level; it becomes **relational and systemic**. Blockchain traceability in Rwandan coffee cooperatives, for example, doesn't just reduce fraud—it builds trust with premium buyers, enabling multi-year contracts that buffer against price volatility. In the U.S. Midwest, farmer networks sharing anonymized yield and weather data via cooperative platforms have collectively improved insurance pricing and reduced systemic risk. Thus, digital-green integration fosters not only enterprise resilience but also **collaborative security** across value chains.

This redefinition carries profound policy implications. Support mechanisms must move beyond siloed subsidies—for either "technology adoption" or "environmental compliance"—toward **co-designed incentive systems** that reward synergistic outcomes. For example, linking green finance eligibility to demonstrable use of digital monitoring tools can ensure both transparency and impact. Likewise, public investment in rural broadband should be coupled with agroecological extension services to prevent digital tools from reinforcing extractive models [9].

In sum, Subsection One argues that the convergence of digitalization and greening is not merely a tactical shift but a **strategic reorientation of agricultural value creation**—one in which economic security is rooted in ecological health, data-driven adaptability, and shared risk governance. The enterprises thriving in today's volatile landscape are those that see data and soil not as separate assets, but as interconnected foundations of enduring prosperity.

II. Subsection Two: Inclusive Transitions or New Divides? Equity, Access, and Power in the Digital-Green Agricultural Landscape

While the integration of digital and green strategies offers a compelling pathway to enhanced economic security, our cross-case analysis reveals a critical paradox: **the very tools designed to build resilience can also deepen existing inequalities** if deployed without deliberate equity safeguards. The risk of a "dual-track agriculture" is real—where large, well-connected enterprises accelerate into a high-tech, low-carbon future, while smallholders and marginalized producers face exclusion due to financial, infrastructural, and cognitive barriers [10].

A recurring pattern across regions is the **high upfront cost of integrated solutions**. Precision irrigation systems paired with renewable energy pumps may yield long-term savings, but the initial investment often exceeds the annual revenue of small farms in Kenya or Colombia. Similarly, EU eco-schemes require digital record-keeping and verification systems that many aging or digitally inexperienced farmers find burdensome. In the U.S., access to federal climate-smart programs disproportionately favors operations with dedicated compliance staff, leaving mid-sized and socially disadvantaged farmers underrepresented.

Beyond capital, **digital literacy and data sovereignty** emerge as pivotal yet often overlooked dimensions of economic security. In Brazil, agri-tech platforms offer free yield prediction tools—but retain ownership of farm-generated data, which can later be monetized or used to shape input pricing. Kenyan smallholders using mobile advisory services frequently lack control over how their behavioral and agronomic data are aggregated or shared with input suppliers. This raises concerns about a new form of **digital dependency**, where farmers become passive users of opaque algorithmic systems rather than empowered agents of their own production decisions [11].

Furthermore, **gender disparities** persist. In Rwanda and Colombia, women farmers—who often manage agroecological practices like composting or seed saving—frequently lack access to smartphones, formal credit, or training in digital tools. As a result, they are excluded from the synergistic benefits of integrated approaches, even when they are central to ecological resilience on the ground. This points to a broader gap: green initiatives often recognize women's environmental roles, while digital programs remain gender-blind, missing opportunities for co-creation.

These findings underscore that **technology and sustainability are not neutral**—they are embedded in power structures that shape who gets to innovate, who benefits, and who bears the risks. Without proactive intervention, the digital-green transition may replicate or even amplify historical inequities in land access, market power, and knowledge control.

However, promising counter-models exist. In the Netherlands, farmer-led cooperatives co-own regional data platforms, ensuring transparent governance and shared value from analytics. In India, the *Digital Green* initiative trains local women as "video mediators" who co-produce and disseminate agroecological content in local languages, blending digital reach with grassroots trust. Such examples demonstrate that **inclusive design is possible—but it requires intentional policy levers**:

- Subsidies tied to cooperative ownership or open-data standards;
- Public investment in rural digital infrastructure as a commons;
- Extension services that integrate digital literacy with agroecological training;
- Gender-responsive technology design and access programs.

Thus, Subsection Two concludes that ensuring economic security in the digital-green era demands more than technical solutions—it requires a **political commitment to democratic innovation**. Economic security must be understood not only as enterprise-level resilience but as

collective, equitable, and just transition. The true measure of success will not be how many farms adopt AI or solar pumps, but whether the transition strengthens the autonomy, agency, and dignity of all food producers—especially the most vulnerable.

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