

## REVIEW

# Fintech as a Catalyst for Sustainable Development in Food Systems

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**Abstract:** As global food systems face increasing pressures from climate change, resource scarcity, and financial exclusion, fintech has emerged as a transformative force with the potential to drive sustainable development. Production, processing, distribution, and consumption of food have become increasingly unsustainable, with severe environmental, social, and economic implications. This threatens the fulfillment of UN Sustainable Development Goals (SDGs), particularly the ambitious target of ending hunger and malnutrition by 2030. Current trajectories reveal the urgency with which we need to address emerging and existing challenges, such as climate change, inefficiencies that lead to the wastage of nearly one-third of all food produced, and problems that perpetuate deep-rooted inequalities, leaving billions without access to adequate nutrition. This paper adopts a narrative review approach, synthesizing existing literature and case studies to explore the role of financial technologies (fintech) in addressing challenges within global food systems in improving supply chain transparency and strengthening the resilience of smallholders and agribusinesses. By bridging gaps in credit, risk management, and market connectivity, fintech offers innovative pathways to support inclusive, efficient, and climate-resilient food systems. By combining an analysis of fintech's current applications with a call for greater awareness and action, this review underscores the critical role of financial innovation in building sustainable food systems and achieving the SDGs by 2030.

**Keywords:** fintech, sustainable development, food system, climate resilience, agriculture, value chain

## 1. Overview of Global Food System Challenges

Climate change is one of the most pressing challenges of our time. Agriculture is unique in the sense that while food production contributes significantly to greenhouse gas emissions, it is the most vulnerable to climate change impacts. The scale is eye-opening. Agriculture production is responsible for 39% of the total food system emissions, followed by land-use changes at 32%, and supply chain activities contributing another 29% [1]. It is also estimated that if the current consumption and production patterns remain unchanged, food system emissions could escalate to 30 GtCO<sub>2</sub>e per year by 2050, representing a 67% increase from current levels. Climate change is disrupting agricultural and fishery productivity, jeopardizing food availability, compromising nutritional quality, and increasing risks of hunger and diet-linked mortality [2]. Agricultural productivity has also slowed down significantly, particularly in developing countries [3]. Climate change has worsened this by reducing global agricultural productivity by 21% since 1961, equivalent to losing an entire decade of progress [4]. The regional disparities in climate impacts are also stark and concerning. Tropical regions, which house many of the world's most vulnerable populations, face productivity losses exceeding 40%, intensifying food insecurity in critical areas of Africa, Central America, South Asia, and the Middle East. Long-term projections paint a grim picture, suggesting that without significant intervention, climate change will reduce per capita agricultural production by 5–10% globally by

2050, with sub-Saharan Africa potentially experiencing declines of up to 10% [5].

Beyond climate change, several systemic inefficiencies plague the food systems. One of them is food loss and waste (FLW), which is one of the most urgent yet under-addressed challenges in contemporary food systems. An estimated 30% of global food production is lost or wasted annually, with 13% lost during post-harvest handling and storage and an additional 17% wasted at the consumer and retail levels [6]. The economic costs of this waste are astronomical. Food loss and waste costs nearly \$1 trillion annually and is responsible for 8–10% of global greenhouse gas emissions. The irony lies in the fact that despite producing enough food for 8 billion people, over 821 million people go to bed hungry each night, and one in three suffers from some form of malnutrition. The patterns of food loss vary. In developing countries, food loss is primarily driven by inadequate logistics, insufficient storage infrastructure, and limited market access, while food waste is more prevalent in high-income countries, though increasingly common in developing economies as well. Sub-Saharan Africa and other low-income regions suffer the highest food loss rates, exceeding 20%, while developed regions report losses below 10%. These FLW also reflect systemic failures since most of the global food system relies on government support, and evidently, these practices have been perpetuating unsustainable practices, resulting in inefficiencies. Despite decades of innovation and past successes, substantial technological advancement remains essential to develop climate-resilient, sustainable practices that can support healthy diets for a growing global population.

The third pillar of food system challenges then becomes the access crisis, where inequalities persist in food access, nutrition,

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and economic opportunities. These manifest in caloric sufficiency to micronutrient adequacy, and from rural-urban disparities to gender-based discrimination. Over 700 million people are estimated to face hunger globally, and an additional 3 billion people cannot afford nutritious diets, suffering from various forms of micronutrient deficiencies [7]. The concept of “hidden hunger” helps articulate the inequalities in food access and realization and is said to affect approximately 3 billion people, mainly in sub-Saharan Africa and South Asia, who lack access to healthy diets rich in essential micronutrients. This form of malnutrition is particularly insidious because it often coexists with adequate caloric intake, reflecting the complex relationship between food security and nutritional quality. Projections suggest that by 2030, more than one-third of the global population will likely still face this dietary inadequacy, underscoring the persistence of economic barriers to proper nutrition. While many suffer from undernutrition, some parts of the world also suffer from overnutrition in the form of obesity. Overall, diet-related diseases contribute to 20% of premature deaths globally, highlighting the urgent need for a fundamental shift toward healthier, more sustainable dietary patterns. Gender inequality aggravates the situation. Systemic disadvantages mean that women smallholders produce less per hectare than men, not due to differences in ability, but due to structural barriers including limited access to quality land, credit, and labor [8]. Macroeconomic vulnerabilities and systemic shocks amplify vulnerability. Economic slowdowns and macroeconomic instability have worsened food insecurity in many low-income countries. Economic constraints limit public investment in agriculture, nutrition, and health sectors that are critical for addressing hunger and inequality [9]. Recent crises like COVID-19 and the Ukraine war exposed food systems’ fragility, driving up prices and worsening access for vulnerable groups. About 150 million more people fell into poverty, with landless rural households facing higher risks of child wasting [10].

The current trends indicate that the world is moving further away from, rather than closer to, achieving Sustainable Development Goal 2. Global undernourishment has risen from 564 million in 2015 to 735 million in 2022, driven by the intersection of conflict, climate shocks, and recent global crises [11]. Even in hypothetical scenarios without major disruptions between now and 2030, hunger levels are projected to remain above 2015 levels, affecting at least 570 million people. The trajectory underscores the need for transformation beyond incremental improvements. One has to aim for fundamental changes in how food is produced, distributed, and consumed.

## 2. Understanding Fintech and Its Core Tools – Relevance to Agriculture and Food Systems

Fintech subsumes a comprehensive range of financial services, including mobile payments, peer-to-peer (P2P) lending, cryptocurrency, insurance, and credit aggregators that have transitioned from traditional human capital-intensive models to technology-driven solutions [12]. Its intersection with agriculture can serve as a transformative force in addressing financial inclusion that has plagued food systems worldwide. This is evidenced by estimates that suggest that about 84% of farms globally are operated by smallholder farmers who face persistent barriers to accessing formal financial services. There are several other unique challenges that only fintech can solve, including remoteness, fragmentation of rural client populations, weakness of brick-and-mortar banking networks in rural areas, scarce data availability, lack of conventional collateral among farmers, and absence of credit histories [13]. Digitalizing these services is expected to improve agriculture’s contribution to economic

**Figure 1**  
**Traditional products of fintech [29]**



growth and poverty reduction since fintech offers unprecedented possibilities to target and price credit, share risk, and harness information technology to expand agricultural productivity. Fintech’s key role in agricultural transformation is also noted by the Asian Development Bank’s 2017 report, which finds that fintech could address 40% of the unmet need for payment services and 20% of the need for credit in Asia [14]. This revolution is needed for ensuring food security and economic growth, especially in developing countries where smallholder farmers contribute significantly to meeting increasing food demand.

### 2.1. Traditional products

Within the traditional products of fintech, mobile banking, digital wallets, InsurTech, and P2P lending are some that come naturally to our mind (see Figure 1). These have revolutionized financial access in rural areas, streamlined agricultural transactions, improved agricultural risk management, and democratized agricultural finance. For instance, mobile banking has revamped the way in which farmers access financial services. The growth of mobile banking, fueled by foundational digital infrastructure, policy support, and swift mobile penetration, has simplified payment systems. This swiftness has also been due to falling smartphone and data costs, biometric-based fraud detection, and simplified payment systems. It has reduced transaction times and expanded access, especially in rural areas. It has also altered the ways in which farmers access price information, search for buyers, and build brands as and when they try to move up the value chain. This is, however, not without challenges. The success of mobile-based financial services depends heavily on the presence of a strong enabling ecosystem, including digital infrastructure, mobile penetration, appropriate regulation, literacy levels, and consumer protection mechanisms. Without substantial public investment, it can become difficult for many regions to achieve conditions that allow for successful mobile deployment.

Mobile platforms [15] have also enabled the development and wide use of digital wallets, which offer farmers and other agricultural value chain actors efficient, secure, and transparent payment solutions. Digital wallets have been famous in replacing slow, risky informal payment systems with faster, cheaper, and safer digital transactions. Services like M-PESA in Kenya, Tanzania, and other SSA countries and various bank-fintech partnerships have demonstrated the potential for expanding financial access through mobile platforms. Kampani, a blended finance initiative in Peru, provides collateral-free equity investments to agricultural Small and Medium-sized Enterprise (SMEs) and cooperatives, like a Peruvian ginger facility and Nicaragua’s COOSEMPODA, partnering with Non Government Organizations (NGOs) like Rikolto. Integration of digital wallets within the agricultural value chain has enabled farmers to receive payments directly from buyers, improving market linkages and price transparency. It also helps eliminate intermediaries who exploit information asymmetries. Digital wal-

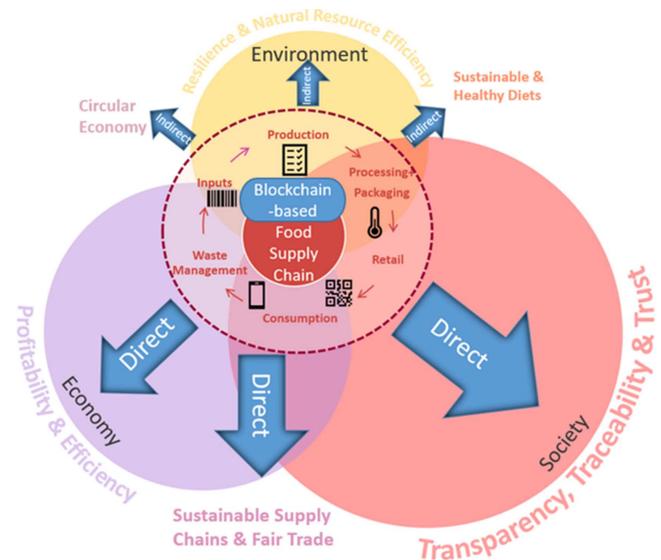
lets have also facilitated the bundling of services, allowing farmers to access credit, insurance, and market linkages through single platforms. However, the widespread adoption of digital wallets also raises important concerns about data privacy and protection, as these platforms depend on sharing large quantities of different types of data across various services and service providers.

- 1) InsurTech, or the use of digital technology to develop innovative and sustainable insurance solutions, is a growing niche within fintech. It addresses one of the most persistent problems in agricultural finance: the difficulty of providing affordable, accessible insurance coverage to smallholder farmers who face significant risks from drought, floods, hail, and hurricanes. It utilizes basic cellphones or smartphones to deliver insurance services, which enables centralization and more effective data management, significantly reducing operational costs and dramatically expanding outreach by allowing providers to reach large populations of small farmers in rural areas. Mobile-based insurance solutions also reduce the time required to apply for policies, settle claims, and communicate with clients, while enabling the rapid provision of payouts following extreme natural events. They have a huge market to serve. Currently, only 19% of the target population of 268 million smallholder farmers globally has access to insurance coverage. Closing this coverage gap would require USD 60–80 billion in insured value coverage and USD 1.4–2.5 billion annually just to cover subsistence farmers, who represent 60% of all smallholders. InsurTech, however, also faces barriers such as systemic risk in agriculture, consisting of a lack of awareness and familiarity among farmers, a tendency to underestimate the likelihood of extreme natural events, a scarcity of reliable data, insurers’ limited expertise in agricultural value chains, weak infrastructure, and the absence of enabling legal frameworks. The sector also grapples with the challenge that recent innovations in risk sharing, such as index insurance, have largely failed due to a lack of demand.
- 2) P2P lending, also known as crowd-lending, represents an alternative financing mechanism that enables large numbers of retail investors to pool small amounts of funding and channel the resulting sum as loans toward specific agricultural projects. These platforms help connect a diverse population of investors driven by motivations and goals that are not strictly financial in nature and combine social and environmental impact with economic returns. It, however, also faces unique challenges in the form of belonging to a sector with substantial and varied risks. Individual retail investors sometimes may lack the skills necessary to evaluate the range of factors that might impair a project’s capacity to meet its goals. Their success depends heavily on maintaining high-quality standards for sponsored projects and keeping loan default rates to a minimum to ensure continued investor confidence. Platforms must set and comply with very high-quality standards regarding the agricultural investment projects they sponsor, as reputation damage from supporting projects with negative environmental spillovers can result in the complete loss of investor confidence.

## 2.2. Blockchain and other emerging services

Besides the traditional products offered by Fintech platforms, a fundamental restructuring of the agricultural space is being carried out by the fintech ecosystem. This is done by the introduction of blockchain technology (see Figure 2), emerging agritech, modifications in the value chain dynamics, the launch

**Figure 2**  
**Blockchain and food system [30]**

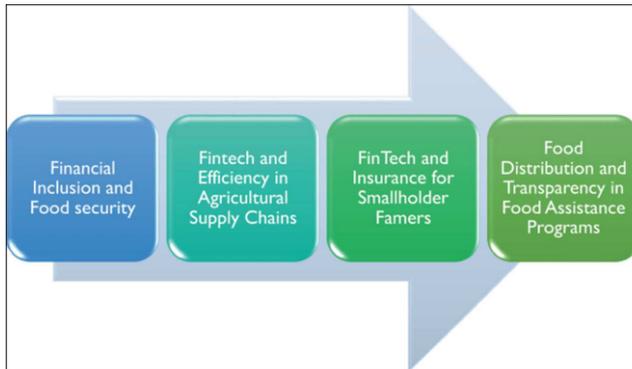


of multiservice platforms and big data, and automated credit risk management. Although the practical application of many of these technologies is unproven in countries, the technologies’ potential lies in their ability to create immutable, transparent records of transactions and data, integration across agricultural value chains, tackling value chain dynamics, and offering comprehensive agricultural financial solutions. Blockchain applications in agriculture, for instance, focus on enhancing traceability and transparency in supply chains, enabling better tracking of products from farm to consumer. This enhanced transparency can help address issues of food safety, quality assurance, and fair trade practices. It can also serve in land record management, solving the documentation problem that hinders loan disbursement. Despite its theoretical promise, the technology requires substantial digital infrastructure and technical expertise, which may be limited in many agricultural regions. Furthermore, the energy requirements and complexity of blockchain systems may make them less suitable for resource-constrained agricultural contexts.

The application of big data and automated credit assessment has repositioned the trajectory of agricultural credit. It has refined local assessment and has led to tailored and more affordable terms to farmers through the analysis of large datasets from financial and nonfinancial activities. These data sources include mobile money transactions, asset ownership records, remote sensing data, etc., and they are used to offer loans with five collateral requirements and better-suited repayment conditions. Here, too, significant barriers remain. The lack of regulatory frameworks raises concerns about data privacy, especially as rural populations with low digital and financial literacy adopt these services.

AgriTech represents a similar broader application of technology across agricultural value chains, wherein fintech is an enabler. The amplification of agritech within the food value chain is crucial, considering that the varied constraints of farmers are often inter-related and tend to amplify each other [16]. The combination of agricultural technology and financial innovation then creates synergies that address multiple constraints simultaneously. Agritech has made a significant contribution in propelling the 3Ds – data, digitalization, and demand – which has increased the lending capacity of banks [17]. The agritech ecosystem has developed sufficient depth

**Figure 3**  
**Fintech across food value chain [31]**



to deliver on these three dimensions for any crop or region, enabling institutional financing to reach millions of farmers and value chain actors, including dealers, traders, processors, and distributors. It must also be noted that a purely digital strategy is unlikely to succeed, particularly when elements like farmer onboarding and know-your-customer checks remain physical processes for the foreseeable future.

### 2.3. Across value chain changes

Lastly, fintech innovation plays a role in tackling agricultural value chain dynamics and providing comprehensive agricultural financial solutions through multiservice platforms (see Figure 3). It has provided new models of collaboration between different actors in the agricultural value chain, leveraging and altering the dynamics that link various segments. It is through digital technology brought by them, power imbalances are taken care of, and effective and equitable partnerships among different actors in both upstream (input providers, producers) and downstream (wholesalers, exporters) segments of agricultural value chains are encouraged.

This is also done through multiservice platforms that bundle a large section of both financial and nonfinancial services. These platforms generate substantial benefits by providing greater data flows on each client, constant refining of service efficiency, and considerable cost savings. From the client's perspective, multiservice platforms also offer the convenience of accessing multiple services through a single platform. For small farmers too, it becomes easy to obtain access to new market channels, inputs, insurance, and agronomic advice. This, however, also raises some significant concerns about ensuring that only relevant data is collected, that data is not shared outside the service network for unauthorized commercial purposes, and that users understand the risks associated with data sharing. In addition to this, there are significant concerns about fair competition among the fintech players. In agriculture, markets are characterized by strong information asymmetries and a lack of competition. A successful fintech company might leverage its dominant position to impose unfair terms on various parties dependent on its platform, including excessive fees, arbitrary prices, and unwarranted threats of exclusion from service.

### 3. Research Methodology

This review adopts a systematic literature review methodology to comprehensively examine the role of fintech in transforming global food systems toward sustainability, resilience, and inclusivity. The literature search was conducted across multiple aca-

demical and multidisciplinary databases to capture a broad range of sources, including institutional repositories such as those from the Food and Agriculture Organization, World Bank, and Organisation for Economic Co-operation and Development. These databases were selected for their extensive coverage of scholarly articles, conference proceedings, reports, and policy documents in fields like finance, agriculture, sustainability, and technology.

### 4. Mapping Food System Challenges and Fintech Solutions for the Agri-Food System

Each stage of the agri-food value chain faces systemic barriers that traditional financing mechanisms have proven inadequate to address. The convergence of fintech and agricultural innovation presents a transformative opportunity to reimagine how food systems operate and are financed. Even India, as the seventh largest agri-produce exporter globally and a self-sufficient country, grapples with escalating cultivation costs, declining soil fertility, climate change impacts, labor shortages, and uncompetitive market structures [18]. To note, these challenges are not limited to India but reflect global patterns where traditional agricultural financing has failed to meet the evolving needs of food system actors. Current estimates suggest that \$350 billion annually is needed by 2030 to align food systems with climate and sustainable development goals, yet existing funding mechanisms remain fragmented and inadequate. The potential returns from this transformation are substantial, with sustainable food transitions capable of generating a 15-fold societal return on investment [19].

Challenges in food system financing consist of structural financial barriers, risk profile and diversification issues, addressing access and affordability challenges at the input stage, overcoming productivity and risk management challenges at the production stage, and lastly but importantly, ensuring market access and price volatility post-harvest and marketing. The potential of value chain integration can help in financing the entire food system; however, credit assessment and risk management barriers still exist, with insurance and risk transfer questions still in the air.

Structural financial barriers stem from high sector-specific risks, poor data availability, mismatched capital supply relative to farmers' needs, and prohibitive transaction costs and result in limited investable and bankable projects, particularly in rural areas, creating a systematic deterrent for financial institutions. The financial exclusion of agricultural actors is particularly pronounced among small and marginal farmers. Approximately 80% (120 million) of farmers in India are classified as small and marginal, comprising about 70% of the agricultural workforce. These farmers generally have limited or no access to formal credit sources, often relying on informal intermediaries or input suppliers for financing, which leads to challenges like low productivity and distress selling [20].

This exclusion perpetuates a cycle where banks provided agriculture credit worth \$168 billion in fiscal year 2018–19, yet 50% of this credit was concentrated among medium and large farmers, leaving the most vulnerable producers underserved. The reluctance of traditional lenders comes from high costs of servicing remote areas, combined with elevated acquisition and servicing costs for small-scale operations, creating economic disincentives. The perceived high risk of default, amplified by policy uncertainties such as farm loan waivers by state governments, further discourages formal lending. Additionally, the difficulty in gathering and verifying farm-level and farmer-level data, coupled with limited visibility into cash flows and credit histories, creates information asymmetries that increase lending risks.

Another problem is that agricultural incomes are dominated by correlated weather and price shocks that cannot be diversified locally. This risk concentration shapes the entire financial ecosystem. When farmers bear these risks, they under-invest in productivity improvements; when banks, local or global, absorb them, they curtail credit availability. This leaves the sector highly vulnerable and systematically under-capitalized.

#### 4.1. Stage-wise intervention

- 1) At the input stage, farmers are still facing traditional input barriers related to access, affordability, and quality assurance. Small and marginal farmers often lack the capital required to purchase high-quality seeds, fertilizers, pesticides, and equipment at optimal timing, which forces them to rely on inferior inputs or delay purchases, both of which negatively impact productivity and profitability. Traditional input financing mechanisms tend to be exploitative due to middlemen who charge excessive interest rates on loans or force farmers to sell their produce at below-market prices as collateral for input advances. This system perpetuates farmer indebtedness and limits their ability to invest in yield-enhancing technologies. Information and communication technology has helped transform agriculture from a labor-intensive to a knowledge-intensive profession, enabling faster, wider, and real-time outreach. This has been done through digital input marketplaces that facilitate direct-to-farm delivery of agricultural inputs and leverage data analytics to provide advisory-driven recommendations and maintain channel-agnostic distribution networks that ensure last-mile delivery to remote farmers. Input-linked credit systems, along with technology-enabled supply chain financing, have proven effective in reducing transaction costs, improving repayment rates by linking credit to productive investments, and providing farmers with timely access to essential inputs.
- 2) At the production stage, fintech can play a role in fulfilling the complex financing needs that traditional systems struggle to address. In agriculture, working capital requirements tend to vary seasonally, often being subject to weather-related uncertainties that make cash flow planning extremely challenging. Over this, more than 22.5% of farmers in India live below the poverty line, with large tracts of land remaining infertile due to unscientific agricultural practices. This poverty trap prevents farmers from investing in soil improvement, modern cultivation techniques, or climate-resilient crops that could enhance long-term productivity. Fintech-enabled farm management and data analytics can help provide comprehensive farm management solutions, which help in predictive modeling, crop monitoring, and traceability throughout the production process. It also encourages precision agriculture financing and data transparency, which reduces information asymmetries and enables more accurate risk assessment [21].
- 3) Fintech also has a role to play in post-harvest operations and marketing. The post-harvest stage presents numerous challenges related to storage, processing, and market access. Limited storage facilities force farmers to sell immediately after harvest at low prices, and the complex network of intermediaries between farmers and final consumers often results in farmers receiving a disproportionately small share of the final product price. Small-scale farmers face higher costs for handling, combining, and shipping their goods due to limited surpluses, and such high transaction costs, combined with limited market information,

prevent farmers from receiving fair prices for their produce. For marketing and market access, digital output marketplaces that facilitate direct connections and provide procurement mechanisms through farmers and Farmer Producer Organizations (FPOs) for both staples and fresh produce are popular. Warehouse receipt systems permit farmers to borrow against stored grains, allowing them time after harvest to strategize their sale. Fintech platforms have also been crucial in price discovery and market information, providing farmers with real-time market information, price forecasts, and demand projections to enable informed decisions about crop selection, harvesting timing, and market participation.

#### 4.2. Value chain integration

The interconnected nature of food systems requires integrated financing approaches that address the entire value chain from production to consumption. Livestock management, mechanization, and novel farming techniques such as vertical farming and hydroponics require specialized financing mechanisms that traditional lenders are often reluctant to provide. This problem can be solved through integrated fintech solutions such as value chain financing, which connected farmers, input suppliers, processors, and retailers through integrated financial products; FPO financing, which would help to reduce transaction costs, improve market access, and enable collective bargaining power that individual farmers lack; and equipment and technology financing, which can provide creative financing through leasing arrangements and farming-as-a-service models.

Fintech is using more creative tools to check a farmer's creditworthiness such as by analyzing everything from how close they are to markets and their historical crop performance to weather forecasts and soil quality. Something as simple as mobile phone usage patterns is also now used to predict whether someone will default on a loan. Real-time monitoring systems now track crop health and estimate yields continuously, giving lenders ongoing insight into how their loans are being used and whether problems lie. There has been a historic misalignment with farmers' actual risk management needs, and newer fintech platforms have been addressing these limitations through denser satellite data, automated trigger mechanisms, and mobile money payout systems that reduce risk. Traditional index-based micro-insurance has seen extremely low uptake rates. Fewer than 10% of farmers have purchased policies at market premiums and have required subsidies of about 60% to achieve only 50% adoption. More promising alternatives involve institutional risk transfer through index contracts for lenders and catastrophe bond structures for governments, providing more efficient risk transfer mechanisms. Savings and investment have also been addressed. Agricultural households face unique challenges in accumulating savings due to irregular income patterns, limited access to formal financial institutions, and immediate consumption needs, which constrain their ability to invest in productivity improvements. Technology-enabled solutions are emerging through mobile money platforms that enable micro-savings, automated savings mechanisms, and goal-based products specifically designed for agricultural households.

Besides offering material benefits, fintech has also significantly increased financial literacy and inclusion, enhancing the uptake of fintech tools crucial for saving, consumption, and agricultural investment. However, a gender dimension exists wherein

women have demonstrated lower knowledge levels, highlighting the need for gender-sensitive fintech education.

### 4.3. Barriers and risks

As seen above, the digital divide serves as a fundamental barrier in almost all fintech and agritech technology implementations. Low digital literacy prevalent in rural areas remains despite government efforts to bridge the gap. This is compounded by infrastructure limitations, where poor internet connectivity and limited smartphone penetration restrict their ability to participate in digital financial ecosystems. The infrastructure gap becomes evident in the case of India's emerging technology in the drone ecosystem, which faces a shortage of trained personnel. With minimal margins from agriculture, many farmers find the inflated costs due to import duties difficult to pay. The price sensitivity among farmers also creates difficulties for fintech providers trying to build sustainable revenue models, as many smallholders cannot afford market-priced products.

The lack of data governance and protection frameworks poses a fundamental risk to fintech adoption in agriculture. Current regulatory structures create vulnerabilities for malicious actors or service providers to misuse. The absence of clear policies and coordination frameworks exacerbates concerns among other government institutions and private players looking to enter the market. There are a number of cybersecurity vulnerabilities too that have been created through increased digitalization. Financial transactions, particularly those involving money and digital payments, have been rendered susceptible to fraud and cybercrime. This is especially concerning given the limited cybersecurity awareness among rural users, who may be more susceptible to phishing attacks, identity theft, and other forms of digital fraud. The interconnected nature of modern fintech systems leads to cascading effects across the ecosystem in the case of a breach. Such a systemic breach can result in huge losses for farmers who depend on seasonal profits for their livelihood.

Market and institutional barriers also prevent scalability and effectiveness. Fragmented market structures significantly raise the cost of traceability and digital integration, particularly in domestic supply chains that lack stringent standards or consumer demand for transparency, which makes it difficult to implement standardized digital solutions as well. Resistance to new technology is visible in the reliance of farmers on traditional laboratory testing for grading services due to the non-accreditation of newer methods. This creates barriers to innovation and limits the potential for efficiency gains through digitization. Multiple regulatory authorities without harmonized standards increase compliance costs for producers and service providers, and the complexity creates a patchwork of requirements that are difficult to navigate. Key regulatory issues include determining which institutions are required to share information, the exact nature of information to be shared, the circumstances under which financial institutions can query borrower credit, and recourse mechanisms for incorrect information.

Finance and economic barriers such as income uncertainty and seasonality create challenges for digital financial services. The cyclical nature of agricultural income makes it difficult for farmers to meet rigid repayment schedules or insurance premium deadlines. This seasonal nature of agricultural production also affects cash flow patterns, creating periods of high liquidity followed by extended periods of limited income. There is also limited access to credit and capital. Around half of farming households do not borrow at all, and only 13% of the gross loan portfolio from banks was allocated to agriculture in 2019, mostly benefiting larger agribusinesses<sup>XIII</sup>. The technological implementation challenges, as mentioned before, remain such as data quality and availability, integration and interoperability issues [22], lack of standardized interfaces and protocols, and social and behavioral barriers such as preference for face-to-face interactions rather than impersonal digital interfaces. Such trust and adoption challenges, along with cultural and social factors such as age, gender, perceived utility, and existing financial habits, all affect willingness to adopt new technologies.

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## 5. Case Studies from India

India's agricultural sector has come a long way. A number of innovative fintech solutions have been used to transform traditional farming practices and financial inclusion. The current landscape has been characterized by structural inefficiencies, with close to 90% of farm holdings being small and marginal by size, resulting in poor technological investment and limited economies of scale. Some fintech initiatives such as the Unified Payment Interface (UPI), Kisan Credit Card (KCC) digitization, and the electronic National Agricultural Market (eNAM) have emerged as big names in the market access landscape. They also embody a shift in the government's approach to agricultural development, moving "from production centric to income centric approach."

The UPI has fundamentally transformed how financial transactions occur in rural India. Launched in 2016 by the National Payments Corporation of India, UPI is a real-time payment system that enables instant money transfers between bank accounts through mobile devices. The success of UPI in rural areas has also been complemented by digital literacy programs by the government, including the National Digital Literacy Mission and DISHA, which trained 53.67 lakh beneficiaries between 2014 and 2016. The Payment Infrastructure Development Fund Scheme, developed by the Reserve Bank of India, has also been crucial in expanding UPI's reach to tier 3 to tier 6 centers, ensuring that even remote agricultural areas have access to digital payment infrastructure. This comes with the establishment of the National Automated Clearing House System for bulk transactions and the Bharat Bill Payment System for easy bill clearances, creating a digital payment ecosystem that supports the agricultural value chain.

KCC has also contributed to modernizing agricultural credit. Originally introduced in 1998, KCC represents one of India's most ambitious attempts to provide formal credit to farmers for the purchase of inputs such as seeds, fertilizers, and equipment while also providing flexibility for cash withdrawals. Some barriers, however, hinder its effectiveness and accessibility. The conventional KCC process was characterized by extensive documentation requirements, lengthy approval procedures, and multiple visits to the bank branches [23].

The Electronic National Agricultural Market (eNAM) was another initiative launched in 2016. It is a pan-Indian electronic trading portal that networks existing Agriculture Produce Market Committee mandis<sup>1</sup> to create a unified national market for agricultural commodities. It solves the problem of traditional marketplaces having limited geographical reach, price opacity, and multiple intermediaries that often capture significant value without adding proportional benefits to farmers. eNAM's expansion has been remarkable since its inception.<sup>2</sup> The platform's coverage further includes over 90 commodities, encompassing staple food grains, vegetables, and fruits, ensuring comprehensive market

<sup>1</sup>Traditional Indian marketplaces, primarily for agricultural produce and commodities.

<sup>2</sup>Comprising 1389 mandis, with more than 17.7 and 0.25 million registered farmers and traders, respectively.

access for diverse agricultural products. The financial scale of eNAM operations demonstrates its growing importance in India's agricultural economy.

There are a lot of startups that have been working on improving the overall value chain experience as well. Arya.ag is one of the many startups that is working to come up with solutions across the value chain, turning warehouses into financial assets. It has built an extensive warehouse-based financing model that spans across 25 states with a network of 10,000 warehouses. Their approach is particularly innovative because it allows farmers to use their stored agricultural produce as collateral for low-interest loans. They've facilitated ₹15,000 crore worth of storage space for commodities and provided ₹8,000 crore in financing through both their own lending and partnerships with financial institutions. This model addresses a critical gap in agricultural finance by recognizing that farmers often have valuable assets in the form of stored crops that can serve as security for loans [24]. DeHaat is another startup that has taken a holistic approach to farmer empowerment through what they call the "five A's": Access to Quality Input, Affordable Insurance, Formal Credit, Actionable Advisory, and Profitable Markets. Rather than focusing on just one aspect of agricultural finance, they recognize that farmers face interconnected challenges that require comprehensive solutions. This integrated approach acknowledges that successful farming depends on multiple factors working together effectively [25].

Samunnati, a non-banking financial company, has developed a value chain-centric approach that operates across 54 different agricultural value chains in 20 states. What sets them apart is their innovative approach to risk assessment – instead of relying on traditional collateral requirements, they evaluate creditworthiness based on transaction history and buyer–seller relationships. Their AMLA (Aggregation, Market Linkage, and Advisory) approach provides comprehensive support that extends well beyond simple financial services, helping farmers access markets and advisory services alongside credit [26].

These case studies demonstrate how strategic government intervention with robust digital infrastructure and targeted policy support can help provide better agricultural finance and market access. Agri-fintech in India presents a US\$600 billion opportunity however requires a depth of transformation that only technology can enable. Through systematic government support such as the IDEA or India Digital Ecosystem of Agriculture or DISHA (Digital Saksharta Abhiyan), the government can and must play a role in extending the digital financial services to all parts of the country.

## 6. The Future of Agri-Fintech in Sustainable Food Systems – Emerging Trends

The contemporary agricultural landscape is bound to undergo a profound transformation with emerging artificial intelligence (AI), Internet of Things (IoT), and climate-smart financial technologies. This technological revolution, commonly referred to as Agriculture 4.0, represents a paradigm shift that has the potential to reshape the entire agri-food system through innovative digital solutions and data-driven approaches. However, the implementation of these emerging technologies reveals a complex web of opportunities and challenges that vary significantly across different geographical and socioeconomic contexts.

Agriculture 4.0 – also known as "digital agriculture," "smart agriculture," and "farming 4.0" – requires more than just the adoption of new tools but demands a cultural and behavioral change to increase productivity and efficiency that supports a more sustainable agriculture through strategic decision-making using

precise and momentary information [27]. The core technologies driving this transformation include AI, IoT sensors, advanced data analytics, and automation systems – all of which are increasingly integrated with climate-smart fintech solutions designed to enhance agricultural sustainability and expand financial inclusion. The study indicates how financial inclusion significantly reduces the ecological footprint in BRICS-T nations, acting as a catalyst for environmental sustainability by enabling access to eco-friendly technologies and sustainable practices [28]. AI has emerged as a pivotal technology in modernizing agricultural practices, offering unprecedented capabilities for data processing and decision support. They are used for personalized advice through mobile applications and chatbot interfaces. They engage in precision agriculture by utilizing data from drones, remote sensing channels, etc., optimizing input usage and increasing productivity. These have also played an important role in building advanced algorithms that structure credit and risk assessment and aid remote loan monitoring for traditionally unbanked smallholder farmers. AI makes agricultural credit more accessible and affordable for small-scale producers who have historically been excluded from formal financial systems while also helping in other domains such as image recognition and deep learning algorithms that contribute to quality grading/assaying processes. Despite this, the complexity of agricultural systems and the diversity of local conditions mean that successful AI deployment requires "substantial boots on the ground" for effective scale-up, highlighting the need for comprehensive support systems beyond mere technology provision [29, 30, 31].

IoT is another crucial pillar of Agriculture 4.0 transformation, which envisions interconnected agricultural ecosystems. It facilitates real-time monitoring of soil conditions, weather patterns, crop health, and livestock welfare, providing farmers with unprecedented visibility into their operations. Sensor networks can collect vast amounts of environmental data, which AI algorithms then process to generate actionable insights and recommendations, enhancing agricultural decision-making. This can enable precision agriculture techniques, which can improve resource efficiency and crop yields while reducing environmental impact. IoT deployment, however, faces significant infrastructure challenges, particularly in developing regions. The technology requires reliable internet connectivity, adequate power supply, and technical support systems that may be lacking in rural areas. Additionally, the cost of IoT devices and the complexity of system integration can create barriers to adoption for smallholder farmers who represent the majority of agricultural producers globally.

Climate-smart fintech represents the convergence of financial technology with climate adaptation and mitigation strategies, creating innovative solutions that support both economic and environmental sustainability. Some critical enablers of the same are mobile money, biometric identification, and the blockchain along with financial literacy. The power of big data cannot be overstated in these systems. Data allows institutions to target better and expand access to uncollateralized credit. Emerging blockchain technology ensures transparency and trust through traceability, making it easy to address complex agricultural supply chain challenges while protecting data at every step. Its transformative potential lies primarily in its ability to create secure, transparent credit and asset registries. It can also provide more structure to the farm-to-folk model by creating an escrow-based, verified transaction system that can significantly mitigate trust deficits between producers and buyers. When combined with smart contracts, stakeholders can receive payments in a timely manner even with a change in the data. This can improve cash flow and reduce transaction costs and improve documentation significantly. Within smart farming, the practical implementation

of Agriculture 4.0 principles envisions integrating IoT, AI, and blockchain technologies into cohesive agricultural management systems. However, it also comes with its own problems. These include “privacy concerns and the unwillingness of institutions to share credit data,” along with structural barriers such as proprietary registry systems. Addressing these challenges is crucial for blockchain to realize its potential in expanding formal agricultural credit access. While developed regions like Europe and North America are adopting these tools rapidly, countries in the Global South, including India, continue to lag behind. India’s case is telling: despite a large smallholder population and growing interest from fintech and agritech sectors, adoption remains limited due to broader structural and contextual challenges. Realizing the potential of Agriculture 4.0 requires addressing the complex interplay of technological, economic, social, and institutional factors that influence adoption and effectiveness.

### Recommendations

Fintech holds transformative potential as a catalyst for sustainable development in food systems, offering innovative solutions to enhance efficiency, inclusivity, and resilience. To fully harness this potential, concerted efforts are required across multiple fronts. Investing in digital infrastructure and fostering robust agri-fintech ecosystems will enable scalable solutions tailored to the needs of diverse agricultural stakeholders. Promoting public–private partnerships can bridge resource and expertise gaps, driving collaborative innovation. Strengthening regulatory frameworks is essential to ensure fintech governance that balances innovation with consumer protection and systemic stability. Integrating fintech into food system resilience strategies will bolster adaptive capacities against climate and economic shocks. Furthermore, prioritizing inclusive design ensures that marginalized groups – such as women, youth, and smallholder farmers – are empowered through accessible financial tools. Finally, developing better metrics and rigorous impact evaluation frameworks is critical to measure fintech’s contributions to sustainability and guide evidence-based policymaking. By aligning these strategies through multistakeholder collaboration and robust policy governance, fintech can drive equitable and sustainable transformations in global food systems, paving the way for a more resilient and inclusive future.

### Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

### Conflicts of Interest

The author declares that she or he/she has no conflicts of interest to this work.

### Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

### Author Contribution Statement

**Shoba Suri:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

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