**Sub-Saharan AgriTech Integration Model**

**Digital Agriculture and Its Impact on Yield Stability**

Digital Agriculture (DA) is emerging as a transformative force in the dynamic field of agriculture, driving efficiency and stability in crop production. Integrating information technologies, ranging from mobile connectivity to advanced data analytics, can revolutionize agricultural practices, supporting farmers in achieving consistent and reliable yields despite the unpredictable nature of environmental and economic factors.

Digital Agriculture is the adoption and integration of information technologies within the agricultural sector, rapidly progressing following the dissemination of mobile phones and the Internet in Sub-Saharan Africa (von Bismarck-Osten, 2021). It involves the utilization of innovative tools such as IoT solutions for climate-smart agriculture (Dibal et al., 2022), digital platforms for investment and advisory (Akinwale et al., 2023), and the development of IoT cloud-based platforms for smart agriculture (Okoh et al., 2022).

The relevance of DA in Sub-Saharan Africa is underscored by its potential to address challenges such as food insecurity, a primary concern across the continent (Dibal et al., 2022). Leveraging IT innovations like drone technology and blockchain significantly impact agricultural practices, improving productivity and food security (Akinwale et al., 2023; Okoh et al.,2022). For instance, IoT is predicted to play a crucial role in feeding the rapidly increasing population by enhancing agricultural productivity (Dibal et al., 2022).

Moreover, the transformational potential of IT in agriculture extends to enhancing agricultural practices, such as the application of drone technology to improve crop health assessments and yield predictions, thus contributing to yield stability (McCarthy et al., 2023). However, adopting such technologies faces challenges, including financial constraints and the need for sophisticated management skills (Dibal et al., 2022; Von Bismarck-Osten, 2021).

**Mobile Technology Utilization**

The literature review for this research reveals that mobile technology has rapidly permeated agricultural sectors worldwide, significantly impacting market access and information dissemination. Mobile platforms facilitate real-time communication, provide access to market prices, and offer tailored agricultural advice, thereby promoting informed decision-making and reducing market asymmetries.

The adoption rate statistics of mobile technologies in agriculture underscore their crucial role in enhancing the sector. For instance, Von Bismarck-Osten highlights the rapid dissemination of mobile phones and the internet as critical drivers of this trend. Akinwale et al. demonstrate the user-friendly nature of mobile platforms like ThriveAgric, which utilize skilled agricultural extension agents to provide advice and market information via mobile technology. These platforms not only improve market access for farmers but also enable crowd farming, an innovative solution to agricultural investment and production challenges (Akinwale et al., 2023).

In Sub-Saharan Africa, the adoption of mobile technology has played a pivotal role in transforming the agricultural landscape. While not as widespread as mobile phones, drones show potential for enhancing crop health assessments and yield predictions, which are critical for market stability and access (McCarthy et al., 2023).

Moreover, IoT solutions integrated through mobile technology are revolutionizing how farmers receive and utilize information. Dibal et al. discuss how IoT and mobile technologies provide farmers with real-time data, essential for making informed decisions that align with market demands.

These examples illustrate that mobile technology's role in agriculture extends beyond essential communication—it enables sophisticated data-driven farming practices. This trend is expected to continue, shaping the future of agricultural market access and information systems (Dibal et al., 2022; McCarthy et al., 2023; Okoh et al., 2022).

**IoT Device Adoption**

The Internet of Things (IoT) has brought about a new era of precision in agriculture. According to the literature, IoT solutions enable real-time monitoring of crop health, soil conditions, and micro-climates, thus facilitating proactive management of agricultural resources. The deployment of sensors and devices leads to data-rich farming environments where informed interventions can be made to enhance crop yields and predict potential issues before they affect production.

Recent studies demonstrate the significant contributions of IoT to precision farming. For instance, Dibal et al. highlight using livestock sensors as an IoT solution, allowing real-time animal health monitoring, leading to timely veterinary interventions and improved livestock management. Additionally, Okoh et al. discuss the development of IoT cloud-based platforms tailored explicitly for smart agriculture, enabling precision farming by integrating soil sensors, weather stations, and crop health monitoring tools into a centralized system.

These IoT innovations enable the collection and analysis of vast amounts of agricultural data, facilitating precise application of water, fertilizers, and pesticides, which optimizes resource use and reduces environmental impact (Okoh et al., 2022). Furthermore, IoT devices empower farmers with detailed insights into their operations, enabling them to forecast yields and manage crops more efficiently and accurately.

The case studies presented by Dibal et al. and Okoh et al. within Sub-Saharan Africa provide concrete examples of how IoT technology is being implemented to overcome traditional farming challenges. Integrating this technology within the agricultural sector signals a shift towards more scientific farming practices, where decisions are data-driven, and results can be more predictable and sustainable.

**Precision Farming Tools:**

The role of GPS technology and drones in precision agriculture has been extensively documented in the literature. These tools help accurately map fields, efficiently allocate resources, and precisely apply inputs such as water and fertilizers, reducing waste, optimizing input usage, and potentially improving yields. Empirical studies also support these benefits. For instance, smart agripreneurship, which involves technologies like greenhouse technology, drones, and precision agriculture, has enhanced crop yield and quality. Moreover, digital agriculture policies and strategies have been linked to increased efficiency and productivity, with agricultural employment making up a significant portion of the workforce in regions such as South Africa. In Sub-Saharan Africa, agriculture accounts for a quarter of the GDP, highlighting the sector's pivotal economic role. Specifically, adopting agricultural technologies, including drones and sensors, has been shown to cause fluctuations in maize production in certain regions, impacting food security and economic stability. Furthermore, the integration of digital technologies in agriculture has resulted in increased cereal production in places like Burkina Faso (Gouly, 2019), and innovation platforms have been identified as instrumental in improving rice yields in Ghana (Amengor et al. 2017).

**Data Analytics:**

The application of advanced data analytics in agriculture has been identified as a critical component of contemporary farming practices. By analyzing extensive datasets, farmers can gain predictive insights into crop yields, pest outbreaks, and weather events, enhancing their ability to plan and make informed decisions. This proactive approach to decision-making is essential for achieving yield stability, as it allows for anticipatory measures rather than reactive ones. Integrating conventional farming knowledge with advanced data analytics, as smart agripreneurship demonstrates, can significantly enhance crop yields and quality. In sub-Saharan Africa, where over 70% of farms are small-scale, digital tools can substantially benefit these farms by facilitating better decision-making and increased productivity (McKinsey, 2023). Studies have also shown that information and communication technologies can contribute to a rise in the food production index in West African countries (Anser et al. 2021), while the utilization of big data can support smallholder farmers by providing insights for enhanced agricultural practices (Protopop et al., 2016). In summary, data analytics drives agricultural transformation, enabling farmers to make smarter, data-driven decisions that underpin farm sustainability and productivity.

**Direct Relationship Between DA and YS:**

The theoretical relationship between adopting digital technologies (DA) and yield stability (YS) is supported by empirical evidence. Numerous studies have demonstrated that higher levels of DA enable smallholder farmers to access timely and relevant information on weather patterns, diseases, pests, inputs, and markets, allowing them to make informed decisions and mitigate risks, thus reducing variability in yields (Kombat et al., 2021; Mhlanga & Ndhlovu, 2023; Daum et al., 2022). For instance, a multi-channel ICT campaign significantly increased smallholder maize farmers' knowledge of monitoring and sustainable management practices for the invasive Fall Armyworm pest by 15-20% in Uganda, which stimulated the adoption of integrated pest management practices and enhanced productivity (Tambo et al., 2019).

Overall, empirical evidence indicates that higher DA leads to improved crop management and planning practices among smallholder farmers. This enables them to respond dynamically to challenges and reduce yield instability over seasons (Kombat et al., 2021; Mugwagwa et al., 2010). The direct relationship posited by our framework suggests that as DA increases, YS is expected to improve, offering a buffer against the inherent volatility in agriculture.

**Indirect Relationship Between DA and YS:**

Our theoretical framework proposes a mediated relationship between da (direct assistance) and ys (yield shocks) variables. Specifically, we suggest that this relationship is indirect and occurs through the intermediate variables of agricultural productivity and access to inputs and services. The results of empirical studies support this hypothesis by demonstrating that da enhances these intermediary variables, which positively impact ys.

**Scenario Analysis: Modeling the Future of Agriculture**

To assess Digital Agriculture's (DA) effect on yield stability, we propose a scenario analysis approach comprising the Current Trends Scenario and the Accelerated Adoption Scenario. The former reflects the trajectory of yield stability based on the existing DA levels among smallholder farmers in sub-Saharan Africa. According to this scenario, only 33% of smallholder farmers currently use digital technologies, primarily basic mobile phones. The lack of smartphones, poor rural connectivity, high costs of data, and limited digital literacy hinder widespread adoption. This scenario expects that yield stability will continue to be impacted by unpredictable weather, climate change, pests, and diseases, with modest improvements expected but overall yield instability persisting.

On the other hand, the Accelerated Adoption Scenario projects the impact on yield stability if DA rates increase to 60% of smallholder farmers in 5 years and reach 90% adoption in 10 years. This is facilitated by policies promoting digital agriculture, investments in rural broadband infrastructure, and public-private partnerships to develop locally relevant, user-friendly technologies. It predicts that higher access to precision agriculture technologies, digital advisory services, mobile payments, and market linkages will enable farmers to improve their practices, manage risks better, increase productivity, and reduce yield variability across seasons.

**Conclusion and Policy Implications**

The convergence of information technology (IT) and agriculture presents an opportunity for a data-driven, resource-efficient, and resilient agricultural future. This is supported by the evidence and theoretical concepts discussed, emphasizing the strategic importance of decision analytics in safeguarding crop yields and strengthening the agricultural sector against uncertainties. To achieve this future, developing and implementing policies that encourage the adoption of DA, enhance rural IT infrastructure, and provide farmer training in digital tools is crucial. The scenario analysis highlights the potential benefits of accelerated DA adoption in terms of improved yield stability. However, realizing this future will require collaboration among policymakers, technologists, agribusinesses, and farmers.

**Resilience Index - Bolstering Agriculture Against External Shocks**

**Building Agricultural Resilience Through IT Innovation**

The ability of agricultural systems to withstand and recover from external disturbances, including climate fluctuations, pests, and economic turmoil, is called agricultural resilience (Sennuga et al., 2022). Creating a Resilience Index (RI) is crucial for quantifying this capacity and establishing a standard for advancements. It is hypothesized that incorporating information technology into farming practices can bolster resilience, providing farmers with a robust safeguard against the unpredictability of external factors.

**Components of the Resilience Index:**

**Diversification of Crops and Income:**

Diversification is a well-established risk management approach that has been extensively studied and validated (Kombat et al., 2021). By leveraging mobile-based digital advisory services, smallholder farmers can access vital market intelligence on crop prices and demand trends, facilitating more informed decision-making regarding crop selection and alternative income sources.

**Soil and Water Management Technologies:**

Efficient management of soil and water resources is essential for maintaining agricultural productivity in the face of climate change, as highlighted by Onyango et al. (2019). Precision agriculture technologies, such as IoT sensors, satellite imagery, and drones, enable data-driven decision-making regarding irrigation, fertilizer use, and land-use planning that is customized to local conditions, as demonstrated by Ayim et al. (2022).

**Access to Real-Time Market and Climate Data:**

Recent research suggests that prompt access to market trends and localized weather forecasts can significantly diminish the susceptibility of agricultural systems to fluctuations and environmental pressures (Sennuga et al., 2022). Various studies have emphasized the importance of mobile applications, online platforms, and SMS services to disseminate such crucial information (Kombat et al., 2021).

**The Buffering Effect of RI Against External Factors:**

It is hypothesized that a higher resilience index, particularly one supported by information technology innovations, can mitigate the negative impacts of external shocks. For instance, precision techniques can reduce the adverse effects of drought by ensuring efficient water usage. At the same time, early pest warning systems enabled by artificial intelligence can alert farmers before infestations escalate (McCarthy et al., 2022).

**Measuring the Interaction Between RI and External Factors:**

The relationship between IT interventions and external factors can be examined through scenario analysis. This approach involves evaluating the effectiveness of IT interventions in different situations, including varying levels of IT adoption and varying degrees of external shocks. A codebook can inform scenario analysis, which provides a framework for simulating resilience outcomes in response to different conditions.

**Policy Implications for Enhancing RI:**

Investment in rural information technology infrastructure to promote the extensive adoption of technologies that enhance resilience.

Implementation of digital literacy programs aimed at equipping farmers with the necessary skills to utilize information technology tools for soil, water, and pest management.

Provision of research and development incentives to encourage the creation of locally adapted innovations that directly bolster agricultural resilience.

**Combined Effect of Digital Agriculture and Resilience on Yield Stability**

**Harnessing IT for Resilient and Stable Agricultural Yields**

The dual forces of Digital Agriculture and agricultural resilience, as quantified by the Resilience Index (RI), are central to achieving and maintaining YS in the face of external challenges. The synergy between DA and RI suggests that integrating IT directly supports agricultural productivity and fortifies the system against shocks, leading to a more stable agricultural output. For instance, digital agriculture platforms optimize farming operations and decision-making, enhancing productivity and resilience to environmental variations (von Bismarck-Osten, 2021).

**Interplay Between DA and RI:**

**IT as an Enabler of Resilience:** IT innovations such as skilled agricultural extension services supported by IT platforms like ThriveAgric can enhance RI by providing tools and information that help adaptive management practices (Akinwale et al. 2023). Furthermore, integrating IoT solutions in agriculture supports climate-smart methods, thus enhancing resilience against environmental stressors (Dibal et al., 2022). For example, predictive analytics informed by IoT can guide crop rotation decisions that maintain soil health and reduce disease incidence, contributing to increased RI.

**Resilience as a Reinforcer of Yield Stability:** A high RI, underpinned by IT innovations like drone technology, contributes to YS by enabling agricultural systems to withstand and quickly recover from adverse events like drought or floods (McCarthy et al., 2022). This is particularly critical in regions prone to environmental stressors.

**Scenario Analysis for Combined Impact:**

**Baseline Resilience Scenario (BRS):** This scenario reflects the current state of resilience and yield stability without additional IT interventions. It serves as a control to assess the potential gains from enhancing DA.

**Enhanced Resilience through IT Scenario:** Under this scenario, we explore the impact of increased IT integration on resilience and yield stability. This includes the adoption of innovative farming technologies and the use of big data for real-time decision-making.

**Stress Test Resilience Scenario:** This scenario introduces significant external stressors to evaluate the robustness of the enhanced resilience provided by IT. It tests how well IT-supported agricultural systems can maintain yield stability compared to systems with lower levels of IT integration.

**Policy Implications for Combined Strategy:**

**Coordinated IT and Resilience Policy:** Developed policies promoting IT adoption and targeting agriculture's resilience aspects, ensuring that IT solutions addressed key vulnerability points.

**Support Systems for Risk Management:** Establishing support systems that use IT to deliver risk management services, such as insurance and emergency response, which are vital for maintaining yield stability in the face of shocks.

**Framework for Continuous Improvement:** Creating a feedback loop within the policy framework that allows for the continuous monitoring of IT and resilience impacts on yield stability, ensuring that interventions are adaptive and responsive to emerging challenges.

**Policy Recommendations:**

Infrastructure Investment: Ensure that the necessary IT infrastructure, such as internet connectivity and access to technology, is available, especially in rural and underserved areas. This can be achieved through public-private partnerships, government subsidies, or direct investment in IT infrastructure development. Von Bismarck-Osten (2021) emphasizes the rapid dissemination of mobile phones and the internet as crucial for IT-based agricultural advice.

Education and Extension Services: Expand extension services to include IT training for farmers and agricultural workers. Educational initiatives should focus on the benefits of IT adoption and practical training in using IT tools and platforms. Akinwale et al. (2023) discuss the role of digital platforms like ThriveAgric in providing user-friendly services that support farmers.

Research and Development Support: Incentivize R&D in agricultural IT innovations directly contributing to resilience and yield stability. Support could take the form of grants, tax incentives, or the creation of innovation hubs that foster collaboration between researchers, technologists, and farmers. Dibal et al. (2022) highlight IoT solutions as critical for improving livestock management and productivity.

Risk Management Systems: Develop and implement risk management systems that leverage IT for better forecasting, insurance solutions, and emergency response. These systems can help mitigate the impact of external shocks on agricultural productivity. McCarthy et al. (2023) demonstrate how drone technology can improve agricultural risk management.

Regulatory Frameworks: Create regulatory environments that support the adoption and integration of IT in agriculture. This includes data protection laws, standards for technology use in farming, and guidelines for the ethical use of data. Okoh et al. (2022) present the development of an IoT Cloud-based platform that can benefit from such regulatory frameworks.

**Operational Strategies:**

Pilot Programs: Launch pilot programs to test and refine IT-based interventions in different agricultural settings. These programs can serve as case studies for broader implementation and help to identify best practices. Von Bismarck-Osten (2021) provides case studies of digital platforms that can serve as valuable references for pilot program designs.

Stakeholder Engagement: Engage with all stakeholders, including farmers, technology providers, researchers, and policymakers, to ensure that IT solutions are relevant and adapted to local contexts. As Akinwale et al. (2023) demonstrated, engaging stakeholders is critical for the success of IT platforms in agriculture.

Monitoring and Evaluation: Establish robust monitoring and evaluation (M&E) mechanisms to track the impact of IT interventions on agricultural resilience and yield stability. Use the M&E findings to inform policy adjustments and scale successful interventions. The work of McCarthy et al. (2023) supports the need for M&E to understand the benefits of new technologies like drones.

Adaptive Management: Implement an adaptive management approach that allows for the flexible adjustment of policies and strategies in response to new information, technological advancements, or changing environmental conditions. Okoh et al. (2022) advocate for the convenience of smart farming solutions, which require an adaptive management framework to be fully realized.

These recommendations are supported by a range of studies that showcase successful IT integration in agricultural practices across different contexts and countries, particularly in areas where food insecurity is prevalent. These integrations address immediate agricultural challenges and can significantly alleviate food insecurity by improving productivity and resilience in the face of climatic and economic variability.​

**Continuous Learning and Adaptation Mechanisms**

To enable continuous improvement in the IT-agriculture framework, the following mechanisms can be implemented:

Baseline Assessment and Benchmarking: Conduct a baseline assessment of current agricultural IT services and outcomes as a reference point for improvement—benchmark practices against other contexts to identify opportunities. Establish a regular review cycle to re-evaluate services and refresh benchmarks.

Monitoring and Evaluation (M&E) System: Develop an M&E system guided by COBIT's Monitor, Evaluate, and Assess (MEA) processes to track progress against defined KPIs and framework objectives. Designed the M&E plan, implemented data collection, monitored indicators, and continuously reviewed system effectiveness.

Adaptive Management Strategy: Using year-on-year performance data, formulate and implement adaptive management strategies annually that respond to emerging challenges and priorities. Establish dynamic agricultural productivity and food security metrics to inform decisions.

Stakeholder Feedback Loop: Incorporate formal mechanisms to gather farmer and community feedback, regularly analyze insights, integrate feedback into strategy and operations, communicate actions taken, and evaluate feedback loop efficacy.

Technology Update Plan: Guided by ITIL change management practices, systematically assess, and integrate new digital innovations into the framework to harness emerging tools. This involves technology scouting, proof-of-concept testing, update rationale analysis, and change management.

Stakeholder Engagement: Adopt COBIT's Enable, Direct, and Monitor (EDM) processes to engage stakeholders in framework governance through consultation, capacity building, and collaborative participation.

Integrating these continuous learning practices will enable the framework to respond dynamically to the evolving IT-agriculture landscape and remain locally attuned, ultimately driving sustained advancement.