An Analytical Framework for Examining Agriculture 4.0 Adoption in Rural Education and Smallholder Farming

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Abstract*– Rural education systems and smallholder farming communities in Colombia and across Latin America face parallel challenges related to agricultural sustainability, technological renewal, and long-term generational continuity. In rural schools, limited opportunities for applied technological engagement weaken students' capacity to connect agricultural education with future career pathways, while among small and medium-scale producers, the adoption of Agriculture 4.0 technologies remains limited. Although tools such as Internet of Things, drone-based sensing, and augmented reality offer benefits for productivity and environmental management, their lack of a significant presence in rural contexts underscores the need to better understand how such technologies are perceived, interpreted, and evaluated within everyday educational and farming practices. In response, this paper defines an adoption-oriented analytical framework for examining how Agriculture 4.0 technologies are introduced and assessed across rural agricultural education and smallholder farming settings. The framework is structured around a two-phase process that first examines perception formation following contextualized technological exposure and subsequently analyses evaluative judgment emerging through applied interaction in settings that approximate real agricultural decision-making. The department of Meta, Colombia, is designated as the intended application context for the framework, although full implementation is beyond the scope of the present study. Preliminary results draw on baseline surveys, interviews, and early qualitative observations to characterize initial adoption-related perceptions and to validate the readiness of the technological and pedagogical components supporting future framework execution. The proposed framework establishes a structured methodological basis for continued study and is intended to be transferable to other rural regions with comparable educational and socio-productive conditions.

Keywords—Agriculture 4.0, Precision agriculture, Technology adoption, Rural contexts, Emergent technologies

I. INTRODUCTION

Rural territories in Meta, Colombia, as well as in many regions across Latin America, face an interconnected structural crisis along three axes: agricultural sustainability, rural education, and technological innovation. Current dynamics show a growing disengagement of young people from rural life, driven by historical inequalities, precarious rural livelihoods, and limited opportunities for personal and professional development.

In Colombia, for example, between 2022 and 2024 the country recorded a net emigration of over one million people, according to estimates from the Banco de la República and the Mixed Migration Centre – 4Mi [1], [2]. A significant proportion of this population corresponds to rural youth aged 18–34, whose displacement reflects a sustained trend of disengagement from agricultural activities and rural livelihoods [3]. If this trend continues, Colombia may face a scenario in the coming decade in which there are insufficient young people to sustain agricultural production and food planting activities.

For decades, rural communities across Latin America have been marginalized from innovation agendas and public policy, consolidating productive models based on traditional practices, low levels of technification, and limited economic diversification. While emerging Agriculture 4.0 technologies offer substantial potential to address productivity and sustainability challenges, their adoption in rural contexts remains limited. Beyond structural and economic constraints, this limited uptake can be understood as a consequence of how potential users perceive the usefulness, usability, and relevance of these technologies within their local productive realities.

The department of Meta, Colombia, serves as a representative case for examining these challenges. Despite having more than four million hectares of agricultural land, only 32% of land classified as having agricultural aptitude is currently under cultivation. Rural technological infrastructure remains insufficient, restricting the effective use of Information and Communication Technologies (ICT) and constraining both farmers' and students' capacity and willingness to adopt tools such as Internet of Things (IoT) systems and drone-based sensing technologies [4].

Small and medium-scale producers in Meta also face difficulties in accessing technical assistance and long-term support, reinforcing uncertainty regarding the cost–benefit balance, usability, and reliability of precision agriculture technologies. These factors shape adoption intentions and constrain the diffusion of data monitoring systems in productive environments. Such adoption gaps directly limit progress toward key Sustainable Development Goals, including SDG 4 (Quality Education), SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action) [5].

To address these challenges, this research project articulates an adoption-oriented analytical framework for examining how Agriculture 4.0 technologies are introduced, perceived, and evaluated in rural education and smallholder farming contexts. The framework focuses on adoption-related processes, including perceived usefulness, usability, confidence, and intention to use among potential users. The proposed framework is designed to be transferable, offering a structured approach for studying technology adoption dynamics in other rural regions facing similar educational, infrastructural, and socio-productive constraints across Latin America.

II. Background and Motivation

A. *Technological and Educational Context.*

The integration of IoT, drone-based sensing, and augmented reality (AR) technologies into precision agriculture has been recognized as a driver of productivity, efficiency, and environmental sustainability. These technologies enable continuous data collection, real-time visualization of crop conditions, and data-informed decision-making. Empirical studies report efficiency gains of up to 40% and yield increases of approximately 30%, largely through optimized input use, early detection of pests and diseases, and improved water management [6], [7].

Despite this potential, adoption of Agriculture 4.0 technologies remains limited in developing agricultural contexts. In Colombia, only 15% to 31% of the agricultural sector currently employs modern digital tools such as sensors, data-driven monitoring systems, or aerial imaging platforms [7], [8].

In rural territories such as Meta, these adoption challenges are reinforced by educational and structural conditions, including an aging agricultural population, low youth participation in farming activities, and restricted access to continuous, context-sensitive technical training [3], [4], [9]. Weak alignment between rural education and productive realities reduces users' confidence in the applicability and operation of precision agricultural technologies, constraining their integration into everyday field decision-making.

Adoption remains low among small and medium-scale producers. Fewer than 10% of farms employ precision agriculture tools such as drones, sensors, or IoT-based monitoring systems, with use concentrated in large-scale agribusiness operations [10]. Limited access to technical assistance and support can increase perceptions of complexity and uncertainty regarding practical benefits. At the same time, environmental challenges such as high water consumption, intensive agrochemical use, and insufficient monitoring of hydrological and soil variables are precisely the types of problems that digital agricultural technologies are designed to address, yet most small and medium-scale producers lack the capacity to implement these solutions in practice [11], [12].

III. Objectives

The primary objective of this Work-in-Progress contribution is to define an adoption-oriented analytical framework for examining how Agriculture 4.0 technologies are perceived and considered for adoption in rural agricultural education and smallholder farming contexts.

Beyond the scope of this Work-in-Progress paper, the broader study applies this framework within the department of Meta, Colombia, to systematically examine adoption dynamics through structured exposure to emerging agricultural technologies. Rural students and small and medium-scale producers in this region are introduced to Agriculture 4.0 tools under controlled yet contextually realistic conditions, and the framework is used to analyze how adoption-related perceptions and intentions evolve following this exposure. This extended application enables assessment of how different forms of engagement, contextual relevance, and interpretability of technological outputs influence adoption-related judgments across educational and productive settings.

IV. Adoption-Oriented Framework

This section presents how the adoption-oriented analytical framework is applied to examine how Agriculture 4.0 technologies are perceived in rural contexts. The framework establishes structured exposure and engagement conditions that allow rural students and small and medium-scale producers to interact with digital agricultural technologies within educational and agricultural settings.

The framework is organized into two sequential phases: an initial phase focused on perception formation following contextualized exposure, and a second phase examining evaluative judgments after applied interaction in real productive environments.

A. *Contextualized Exposure and Initial Perception*

The first phase examines the formation of user perceptions following structured exposure to Agriculture 4.0 technologies. This phase focuses on early interpretive responses, emphasizing how technologies are understood, contextualized, and evaluated by users with varying levels of prior experience.

Exposure settings are defined in coordination with educational institutions, local communities, and agricultural associations to ensure that they reflect representative local productive realities. These settings function as analytical contexts, ensuring that exposure conditions remain comparable across participant groups while remaining grounded in territorial constraints.

Exposure activities enable participants to observe and interact with core components of Agriculture 4.0 systems, including IoT-based environmental monitoring, drone-assisted data capture, and AR-based visualization of agricultural information. Interactions are intentionally designed to foreground system purpose, interpretability of outputs, and relevance to local agricultural practices.

Baseline adoption-related perceptions are studied through a pre-exposure ICT and technology acceptance survey. This instrument collects self-reported information on technological familiarity, perceived complexity, confidence in digital tool use, and initial expectations regarding the usefulness of precision agriculture technologies. The survey is complemented by short open-ended prompts that elicit qualitative insights into participants' prior experiences, concerns, and perceived barriers to adoption.

Participatory sessions with students and producers are conducted to identify priority crops, locally salient production challenges, and monitoring variables of interest. These sessions both contextualize exposure activities and generate qualitative data on user expectations and interpretive frameworks. Observational field notes are recorded to document user questions, engagement patterns, and non-verbal indicators of hesitation or interest.

This phase establishes a baseline reference point for perceived usability, familiarity, and confidence, against which subsequent adoption-oriented assessments within the framework are compared.

B. Applied Interaction and Adoption Evaluation

The second phase examines how potential users interpret, assess, and reflect on Agriculture 4.0 technologies when engagement occurs in contexts resembling real agricultural decision-making environments. While Phase one focuses on perception formation, this phase captures evaluative judgments shaped by practical relevance, interpretability of outputs, and compatibility with existing productive practices.

Applied interaction is situated within diverse crop systems and production contexts representative of small and medium-scale agriculture. These contexts function as analytical environments through which users encounter technological outputs related to crop health, water management, and risk identification, allowing adoption-related judgments to form under conditions of increased contextual realism.

During this phase, interaction with drone-generated visual outputs, environmental monitoring data, and AR-based representations provides the basis for examining perceived usefulness, trust in system outputs, and ease of interpretation. Emphasis is placed on how users make sense of technological information and whether such information is perceived as actionable and relevant within decision-making processes.

Adoption-related evaluation in this phase is captured through post-exposure survey instruments designed to measure shifts in perceived usefulness, confidence in technology operation, and intention to use Agriculture 4.0 tools under comparable conditions in the future. These instruments support comparative analysis across framework phases by examining changes relative to baseline perceptions established during phase one.

Qualitative reflection is incorporated through semi-structured group discussions and short individual testimonials, which provide contextual depth regarding perceived benefits, limitations, and the conditions under which participants would consider adopting or rejecting the technologies encountered. These reflections complement structured survey indicators by capturing interpretive nuances not fully expressed through quantitative measures.

Complementing these qualitative insights, structured survey instruments are employed to systematically capture adoption-related constructs across participants. Survey instruments employed across both phases are composed of adapted item sets drawn from established technology acceptance and ICT competency instruments. Specifically, perceived usefulness and perceived ease of use items are adapted from the original Technology Acceptance Model proposed by [15], intention-to-use items are adapted from the Unified Theory of Acceptance and Use of Technology framework [16], and user confidence items are informed by ICT self-efficacy and digital competence questionnaires. All items are selectively adapted and contextually simplified to ensure relevance and comprehensibility in rural agricultural settings, consistent with prior adoption research in smallholder and developing-world contexts [17].

V. CASE STUDY POPULATION

The first participant group consists of secondary-level students (grades 9–11) enrolled in technical agricultural education programs in three rural public institutions. Approximately 120 students are expected to participate. This population represents prospective future users of Agriculture 4.0 technologies at a critical transition point between formal education and entry into productive, vocational, or higher-education pathways. Applying the framework to this group allows examination of early-stage adoption-related perceptions.

The second participant group comprises small and medium-scale agricultural producers operating in municipalities across the central and eastern plains of Meta. These producers are active decision-makers responsible for crop management and resource allocation in productive environments. Participating farms include systems dedicated to rice, cassava, plantain, maize, cocoa, fruit trees, and mixed crop–livestock production, reflecting the heterogeneous and smallholder-dominated structure of regional agriculture. This group provides a practical context for applying the framework to examine technology acceptance, usability perceptions, and adoption intentions associated with precision agriculture tools under operational, economic, and environmental conditions.

VI. PRELIMINARY RESULTS

Preliminary results reflect baseline adoption-related perceptions. These results are derived from initial qualitative data collection and from the preparation and validation of the technological and pedagogical components used within the framework.

Baseline perceptual insights were obtained through semi-structured interviews and informal conversations with 20 small and medium-scale agricultural producers, as well as with local stakeholders, prior to applied engagement activities. In parallel, interviews were conducted with school principals and academic coordinators from two rural public institutions located in Cumaral and Villanueva, Meta, focusing on the structure, scope, and limitations of existing technical agricultural education programs.

Across interviews with producers, limited access to sustained, hands-on training emerged as a central barrier to the adoption of Agriculture 4.0 technologies. While general awareness of tools such as drones, sensors, and monitoring platforms was common, participants expressed uncertainty regarding practical usefulness, cost–benefit balance, and compatibility with everyday farming routines. Previous exposure to short-term pilot initiatives without continuity or follow-up was frequently cited, contributing to skepticism toward externally introduced technologies.

Water management and pest and disease control emerged as the most important priority areas across producer interviews, particularly in rice and mixed-crop systems. Participants emphasized a preference for technologies capable of delivering clear, interpretable, and valuable information over complex or abstract data outputs. These findings reinforce the importance of perceived usability, trust in system outputs, and contextual relevance as central factors shaping early adoption-related judgments.

Educational stakeholders highlighted structural constraints affecting technology integration in rural schools, including limited access to updated equipment, restricted instructional time for applied technological content, and weak articulation between curricular activities and local productive realities. These conditions were identified as limiting students' opportunities to develop confidence and practical familiarity with digital agricultural tools prior to entering productive or vocational pathways.

Alongside baseline data collection, the project has completed the development and functional validation of key technological and instructional components used to support framework application. Structured training workshops aligned with the two framework phases have been designed and prepared. A modular IoT-based water management kit has been developed and tested, integrating soil moisture sensors, ambient humidity sensors, water flow monitoring, and remotely controlled irrigation valves to support real-time data capture and basic automated water control under field-relevant conditions.

The drone-based data acquisition component has been fully implemented and validated for agricultural monitoring tasks, including aerial image capture and field-scale visualization. However, the AR component remains under active development, with current efforts focused on interface design and visualization workflows intended for use in upcoming educational workshops in 2026.

Together, these preliminary results indicate an initial perceptual baseline and confirm the technical readiness required for continued application of the adoption-oriented framework.

VII. Conclusion

This paper presented an adoption-oriented analytical framework for examining how Agriculture 4.0 technologies are perceived and evaluated in rural agricultural education and smallholder farming contexts. The framework focuses on key adoption-related dimensions, including perceived usefulness, usability, confidence, and intention to use, under real educational and productive conditions.

Preliminary results highlight the importance of interpretability of technological outputs, sustained hands-on engagement, and alignment with local productive realities. The availability of operational drone-based monitoring systems, a modular IoT water management kit, and an AR component under development provides a functional basis for application of the framework proposed in this paper.

Beyond Meta, Colombia, the framework offers a transferable methodological tool for studying Agriculture 4.0 adoption processes in rural regions facing similar educational, infrastructural, and socio-productive constraints.

Acknowledgment

The authors gratefully acknowledge the institutional support of the Universidad de los Llanos in the development of this research under the project "Training and Application of IoT Technologies, Drones, and Augmented Reality to Strengthen Agricultural Education and Sustainable Agriculture in Meta," Project Code 401002626.

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