

Prospective analysis of the adoption of digital technologies in agriculture

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Abstract

Open innovation emerges when knowledge, experience, and capabilities are distributed across various organizations, enabling innovative activities inside and outside research institutions within a collaborative system. In the agricultural sector, this phenomenon is manifested through innovation ecosystems that involve multiple stakeholders, including universities, governments, research institutes, companies, cooperatives, and financial markets. However, one of the main challenges is measuring an innovation's success, especially in the early stages of developing technology-based products. Given this context, this paper proposes a methodological model for developing indicators that measure the level of success in adopting digital technology in the field, from the initial stages of technological product development. Five stages and the results obtained in the benchmarking phase are presented.

Keywords: prospective evaluation; technological innovation; digital agriculture

1. Introduction

Digital Agriculture is an emerging field that aims to integrate the use of digital technologies in the agricultural sector to improve resource efficiency, increase productivity, and promote the sustainability of the entire production chain. Remote sensors, drones, big data, and artificial intelligence are examples of tools that enable the collection and analysis of data in real-time, allowing farmers to make more assertive and informed decisions.

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Nevertheless, the adoption of these technologies in the field faces several challenges, such as the high cost of adoption, maintenance, and management, the lack of adequate infrastructure and connectivity, and the need for farmer training (Silveira et al., 2021; Dibbern et al., 2024). In this scenario, the following research question arises: *“How to measure or evaluate the level of success of an innovation, especially at the beginning of the development of technology-based products, considering the context of Digital Agriculture?”*.

Evaluating the innovative potential of technology in its early stages of development is challenging, primarily due to the difficulty of predicting how it will be adopted in various contexts. Several factors can be highlighted as elements that influence this evaluation, including user acceptance, the need for training, socioeconomic and environmental impacts, and potential barriers associated with the lack of infrastructure for implementation. These factors reinforce the need to develop approaches that capture the perception of potential adopters, ensuring a comprehensive and contextualized prospective technological assessment of the context in which it will be adopted. Measuring the level of success in adopting technology is, therefore, a crucial step in identifying the critical factors that contribute to its effectiveness and sustainability in various contexts and scenarios. Thus, this research aims to present the methodological procedures for constructing indicators that measure the level of success in adopting digital technologies in the field, as well as the results related to the benchmarking step.

2. Methods

The development process of these indicators involves several interconnected steps, structured based on the context we want to monitor and/or evaluate. To develop a methodology integrated into the context of Digital Agriculture, five steps were considered.

The **first step**, known as “bibliometric analysis,” employed a mixed-methods approach, combining bibliometric research techniques with the selection and analysis of case studies. This phase aimed to identify and examine the primary barriers and factors influencing the adoption of Digital Agriculture, to determine the essential requirements for incorporating and utilizing digital technologies in the agricultural sector. To understand the dynamics of technology adoption, a bibliographic search was conducted in the Scopus and Web of Science databases using a set of relevant keywords. This search covered

research published between 2014 and October 2023, the period during which the first part of the research was conducted. Subsequently, based on the most cited publications, 20 case studies were selected for more detailed analysis to categorize the main barriers and factors in the adoption of such technologies.

The **second step** of the proposal is linked to mapping for “benchmarking” purposes, utilizing the Snowball Sampling technique (Vogt, 1999; Clements et al., 2017). Adapted to the study's context, this technique involves a method for identifying subjects or, in this case, objects of study (metrics and indicators used by various national and international institutions), through a process in which one element leads to the identification of another. In this sense, in addition to the previous step, an exploratory search for indicators related to topics concerning Digital Agriculture was carried out, using a variety of data sources, such as the database of the Brazilian Agricultural Research Company (Embrapa), and Data centers of the United Nations (UN), among others. From the identified materials, we extracted the relevant metrics and indicators that could compose the proposal of this study.

The **third step**, called “analysis and proposition”, aimed to develop a system capable of assessing the level of success in adopting a given digital technology in the field. For this, an integrated analysis of the results obtained in the previous steps (1 and 2) was conducted, considering the identified barriers, adoption factors, and metrics and indicators. Based on the integrated analysis of the results, two sets of indicators were developed that meet the specific needs of Digital Agriculture and can be applied in the Brazilian context, and by extension, adapted for use in other countries. The first set of indicators (Profile 1) establishes the basic criteria and requirements that developers of agricultural digital technologies must consider to ensure their solutions meet the needs of the sector and the producer. The second set of indicators (Profile 2) gathers the requirements considered by potential users/adopters (such as rural extension agents, technicians, researchers, and producers) when choosing and adopting a new digital technology for their property, involving elements that involve both the digital training of the producer, as well as other elements related to the availability of infrastructure.

To attest to the validity of the proposed sets of indicators, the **fourth step** involved the voluntary participation of specialists from the broad field of Exact and Earth Sciences. The definition of these specialists was conducted to obtain respondents with training in various areas of study, such as agronomists, engineers, and computer scientists, who had

completed at least a master's level. The specialists were selected both internally within the Center for Science for Development in Digital Agriculture (CCD-AD/Semear Digital) and from external reference institutions, including both Brazilian and foreign institutions. Each requirement of both profiles had at least five specialists who validated it, assigning weights to them. In total, 13 different specialists validated each of the profiles, resulting in a total of 26 expert participants. The parameterization of the weight was achieved through the mode, which is the most frequent value in the set of weights assigned by the specialist participants in the study.

Finally, the **fifth step** involves consolidating and testing indicator baskets. After validation with the specialists, the requirements were consolidated in a spreadsheet file, along with their respective assigned weights. At the end of the spreadsheet, the weighted average of the analyzed technology is generated. The result varies from 1 to 5, with a score closer to 1 indicating a lower level of success in adopting a specific technology, and a score closer to 5 indicating a higher level of adoption success. To test the indicator baskets, they were validated using two technologies: software and hardware, both of which were employed in the context of the DATs (Agrotechnological districts) at the Semear Digital Center.

3. Results and Discussion

Based on the data collected from the various databases identified in the benchmarking stage, a process of filtering and extracting metrics and indicators related to the topic of Digital Agriculture was performed. In this regard, to complement the results obtained through stage 1 (Dibbern et al., 2024, 2025), ten indicators/indices were identified, to be detailed in Table 1.

Table 1. Indicators and indices identified during the benchmarking stage.

Indicators / Metrics / Index	Description
Digital Agriculture Level	Purpose: To measure the growth of digital agriculture in China. Indicators: Technological infrastructure and penetration, R&D activity, innovation capacity, etc.
Agricultural Modernization Index	Purpose: To compare levels of agricultural modernization over time. Indicators: Mechanization, inputs, practices, and economic performance.
Technology Adoption Propensity	Purpose: To predict the likelihood of consumers adopting new technologies. Indicators: Four dimensions related to technology adoption (optimism, proficiency, dependency, and vulnerability)
Agriculture Digitalization Index	Purpose: To predict the likelihood of consumers adopting new technologies. Indicators: Four dimensions related to technology adoption (optimism, proficiency, dependency, and vulnerability)
Cisco Digital Readiness Index	Purpose: To measure a country's digital readiness. Indicators: Infrastructure, economy, and human capital.
Rural Significant Connectivity Index	Purpose: To measure significant connectivity in Latin America and the Caribbean. Indicators: Internet access, equipment, broadband services, and 4G coverage.
GSMA Mobile Connectivity Index	Purpose: To measure the factors enabling mobile internet connectivity. Indicators: Network infrastructure, affordability, literacy, and digital skills.
Inteli.gente Platform	Purpose: To assess the maturity of Brazilian cities in digital transformation and sustainable development. Indicators: ICT, economy, and socio-environmental factors.
Ambitec-Agro	Purpose: To evaluate the performance of technological innovations and management practices adopted in rural activities. Indicators: Use of Inputs and Resources, Environmental Quality, Employment.
Technological Innovation Impact Assessment System	Purpose: To provide recommendations for the management of agricultural biotechnology Indicators: Economic, environmental, social, and institutional impacts of the technology.

It is essential to emphasize that the understanding and study of these metrics and indicators were crucial to the formulation of the proposal presented in this abstract, highlighting paths of analysis that were incorporated within the scope of the proposed prospective assessment. These evaluation instruments, from various organizations and initiatives, offer a comprehensive and complementary perspective on the adoption of digital technologies, connectivity, and digital transformation in the field. Each one reflects the standpoint of its creating entity, encompassing elements linked to the factors and barriers to the adoption of digital technologies in the field. Although robust, these indicators do not refer to the proposal presented here. Therefore, even though they offer

specific cuts and local diagnoses, these instruments do not measure the level of success in adopting a particular digital technology in a specific location within the field.

Due to the lack of space, this abstract focuses only on the results obtained from the benchmarking process. In summary, based on the consolidation of the results, two baskets of indicators were formulated: one aimed at technology developers, and the other at potential adopters, represented by rural extension workers, researchers, and rural producers.

4. Conclusion

The methodological path presented throughout this summary highlights the importance of a structured and well-founded process for creating indicators that assess the level of success in adopting digital technologies in the field. The practical testing and application of these baskets demonstrate the flexibility and relevance of the proposed requirements, reinforcing their ability to identify the critical success factors for adopting a given digital technology in the field, which can help improve it and inform decisions for its implementation.

Finally, the need for a continuous process of refining and updating the indicators is emphasized, given the technological advances and changes in demand associated with the sector's actors. Instruments such as this represent a relevant contribution to the prospective evaluation and monitoring of the results and impact of digital technologies in the field, fostering innovation and sustainability in Agriculture.

Considering this context, it is important to note that the proposal presented in this study is still in the development and improvement phase. Therefore, as this is an instrument under construction, there is room for improvement, such as conducting a second validation stage linked to the other requirements/variables indicated by the experts participating in the study: environmental impact linked to the disposal of electronic devices, such as hardware (electronic waste); access/adoption of technology indirectly via contracting services, association, union or cooperative; impact on animal welfare; among others..

Validation of the indicator baskets should also take place in real situations of use through other case studies and pilot projects in different regions. This approach could be adapted to other countries. It will allow us to identify and overcome specific challenges, ensuring that these baskets are adapted to users' needs.

Acknowledgments

The authors would like to thank FAPESP (Proc. 2022/09319-9; Proc. 2023/08686-0) for the funding.

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