Critical Competencies for Digital and Precision Agriculture: Evidence from Literature and Stakeholder Perspectives

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Abstract.

The transition toward digital and precision agriculture is transforming agricultural production through the integration of artificial intelligence, sensor technologies, geospatial systems, robotics, automation, and advanced data analytics. As agricultural systems become increasingly data-intensive and technology-driven, identifying the competencies required for effective implementation has become essential. Although the literature discusses skill requirements in Agriculture 4.0 contexts, limited empirical evidence integrates published findings with stakeholder perceptions from real-world precision agriculture environments. This study examines the competencies required for digital and precision agriculture professionals by integrating literature evidence and stakeholder perspectives. A structured search in Scopus, Web of Science, and Google Scholar identified 412 publications. After applying predefined inclusion and exclusion criteria, 61 articles were selected for full-text analysis. The review identified 106 competencies, organized into thematic domains reflecting technological, agronomic, managerial, and behavioral dimensions. To complement literature findings, qualitative field research was conducted with key stakeholders, including representatives from academic institutions, agricultural extension services, family and commercial farms, agricultural equipment companies, public research organizations, agribusiness industry, and cooperatives. Data were collected through two focus groups (n = 8) and five semi-structured interviews. Provisional coding procedures were used to analyze the transcribed data, establishing a predetermined set of codes before fieldwork began. A comparative analysis of literature-derived and stakeholder-identified competencies revealed eight convergent domains: Agriculture; Natural Sciences; Entrepreneurship; Management; Technology; Creativity and Problem Solving; Teamwork and Proactivity. Additionally, twelve divergent domains emerged, including Communication (oral and written), Empathy and Negotiation; Curiosity, Lifelong Learning and Resilience; Customer Experience; Ethics; Leadership; Motivation; Reliability; Specialized Machinery and Equipment; Sustainability; Systems Thinking and Analytical Thinking. Findings indicate that while technical and digital competencies remain central to precision agriculture systems, stakeholders emphasize multidisciplinary collaboration, teamwork, analytical reasoning, adaptability, and continuous learning as critical for effective technology adoption and systems integration. These findings provide empirical evidence to inform workforce

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development strategies, curriculum design, and professional qualification initiatives aligned with the evolving demands of digital and precision agriculture.

Keywords.
Agriculture 4.0; Digital skills; Digital transformation; Smart agriculture; Qualitative research; Technology adoption; Workforce transformation.

Introduction

The increase in the operational efficiency of agricultural systems, driven by digitalization and the growing availability of large volumes of digital data and analytical capabilities, is widely recognized in the agricultural sector (FAO, 2022). In the literature, several terms are used interchangeably to describe the digitalization of agricultural production systems, value chains, and food systems, including smart agriculture, precision agriculture (PA), digital agriculture (DA), and Agriculture 4.0 (Klerkx, Jakku, & Labarthe, 2019).

The incorporation of technologies such as robotics (Massruhá et al., 2020), artificial intelligence, the Internet of Things, machine learning (Charatsari et al., 2022; Hasan, Aftah, & Syakban, 2022), digital twins (da Silveira et al., 2026), and drones (Massruhá et al., 2020; da Silveira et al., 2026) faces several challenges, particularly as the pace of technological transformation accelerates and advanced competencies become essential for the effective integration of technological innovations into agricultural practice (da Silveira, Landaverde, & Barbedo, 2026). Both digitalization and the automation of agricultural production processes have significantly changed the nature of work, as well as the requirements, skills, and competencies expected from professionals in the sector (Zabelina, Mirzabalaeva, & Sankova, 2020).

Competencies comprise a set of skills, knowledge, attitudes, and capabilities that enable individuals to perform professional functions effectively (World Economic Forum, 2021). Brazilian farmers have been seeking alternatives to address challenges associated with digital agriculture, including access to qualified and specialized labor, professional training in digital agriculture technologies (Rossi Junior & Doyle, 2023), and the lack of competencies required for digital agriculture in agricultural, technical, and higher education curricula (da Silveira et al., 2023).

This study sought to answer the following research question: Which competencies (knowledge, skills, and attitudes) are considered necessary for professionals working in digital agriculture, according to stakeholders and the scientific literature?

This paper presents the knowledge, skills, and attitudes identified through a systematic literature review, including data extraction from 61 scientific articles, as well as data collected from 5 interviews and 2 focus groups. Findings from the literature review were essential for structuring the field research with digital agriculture stakeholders, conducted through interviews and focus groups. Data collected from interviews and focus groups were subsequently analyzed, coded, and discussed.

Methods

As a social research technique, document analysis supports the identification of essential competencies by revealing the public content, meanings, and underlying intentions associated with the object of study (Carbone, Brandão, & Leite, 2006). Literature review can be considered a specific form of document analysis (Mattar & Ramos, 2021). Accordingly, the documentary analysis conducted in this study consisted of a literature review of academic publications.

Literature Review

The literature review began with a search conducted on February 11, 2023, in the Scopus, Web of Science, and Google Scholar databases using the following search terms: agriculture, digital agriculture, digitalization, Agriculture 4.0, technology, technologies, competence, competences, competency, competencies, skill, skills, ICT, and ICTs. Search results were restricted to publications containing the specified terms in their titles. The search identified 55 articles in Scopus, 17 in Web of Science, and 340 in Google Scholar.

The literature review followed the eight-step systematic literature review process proposed by Okoli (2019). Article selection was based on predefined exclusion criteria. A total of 61 articles were selected for full-text review and data extraction. The results and discussion presented in this paper are limited to competencies associated with digital agriculture.

Field Research

Once the literature review was completed, the field research was conducted in four stages: the development of the research instrument, the conduct of interviews, the organization of focus groups, and the analysis of the collected data.

A single set of questions was developed for both interviews and focus groups, following the guidelines of the responsive semi-structured interview method (Rubin & Rubin, 2011). The research instrument, consisting of the interview guide, was reviewed by three specialists representing different digital agriculture stakeholders. Participant selection sought to include representatives from diverse stakeholder groups involved in digital agriculture.

Two focus groups were conducted in 2024. The first consisted of three professionals working at an academic institution dedicated to the agribusiness sector, whereas the second included five participants, three of whom represented rural extension services and two of whom were family farmers. In 2025, five professionals representing different digital agriculture stakeholder groups agreed to participate in semi-structured interviews. Participants included an executive from an agricultural equipment company, a faculty member and researcher affiliated with a higher education institution, a representative of a public agricultural research organization, a professional from the sugar-energy industry who also worked as a farmer, and an employee of an agricultural cooperative.

Both interviews and focus groups were conducted via videoconferencing. Audio recordings were transcribed and analyzed without the use of dedicated qualitative data analysis software. The results and discussion presented in this paper are limited to competencies deemed necessary for professionals working in digital agriculture, including skills, attitudes, and knowledge areas.

Provisional Coding (Saldaña, 2013) was adopted for analyzing competency-related data collected during the field research. This method consists of establishing a predetermined set of codes before data collection begins.

The research project, supporting documents, and research instrument received approval from the Research Ethics Committee of the Pontifical Catholic University of São Paulo (PUC-SP) under CAAE number 73017923.9.0000.5482 and approval number 6.578.497.

Results and Discussion

This section describes the competencies identified through the literature review, which were essential for developing the research instrument and for evaluating the data collected during the focus groups and interviews.

The presentation and discussion of the field research findings were organized into 9 subsections, corresponding to competency domains encompassing the knowledge, skills, and attitudes identified by interviewees and focus group participants.

Literature Review

The literature review aimed to identify published scientific studies related to the topic under investigation.

Table 1 presents the 106 competencies—namely knowledge, skills, and attitudes—identified in the articles examined during the literature review. These competencies were organized into 13 distinct coding categories, corresponding to broader thematic domains.

Table 1. Competencies identified in the literature review

Categories	Competencies	References
Agriculture	The competence of identifying the potential of a good agricultural location	Aryawiguna et al. (2021)
Agriculture	Ability to adopt better land use practices; Ability to adopt soil conservation practices; Ability to know how to store properly; Ability to monitor pest/disease outbreak; Ability to use and apply manure/fertilizer; Improve crop and land rotation course; Improve land preparation technique; Improve timely weeding; Planting appropriate seed rate/date; Planting seeds at right depth/crop density; To know effective planting strategy on steep slopes; Use of appropriate planting material	Chikaire et al. (2017)
Agriculture	Agronomic Skills; Technical (electronic) skills	Fountas et al. (2005)
Agriculture	Basic Skills in Production Operations and Production Management; Energy; Skills for food production and manufacturing (industrial performance); Skills for food quality and food safety; Technologies, products, and production approaches	Mayor et al. (2022)
Agriculture	Evaluating extension services; Implementing of extension	Nasir et al. (2019)
Creativity and problem-solving	Visioning competencies	Charatsari et al. (2022)
Creativity and problem-solving	Skills for research, development, and innovation	Mayor et al. (2022)
Entrepreneurship	Business and Entrepreneurship Skills	Ramalho Ribeiro et al. (2023)
Ethics	Fair, collaborative, and competitive value chains	Mayor et al., 2022
Leadership	Team working and interpersonal skills; Soft Skills	Mayor et al. (2022)
Leadership	Soft Skills	Ribeiro et al. (2023)
Management	Competencies evaluating programs; Competencies of composing methods; Competencies of drawing up work plans; Competency of developing programs	Aryawiguna et al. (2021)
Management	Facilitation competencies; Intermediation competencies; Needs assessment competencies; Technology translation competencies; Value generation competencies	Charatsari et al. (2022)
Management	Supply chain/risk management	Chikaire et al. (2017)
Management	Teaching competencies	Martin; Sajilan (1989)
Management	Education skills; Financial skills; Logistics and supply chain skills; Marketing Skills	Mayor et al. (2022)
Management	Applying counseling media; Applying counseling methods; Evaluating the impact of education	Nasir et al. (2019)
Management	Human resource development (HRD)	Prajanti et al. (2020)
Motivation	Competencies of developing self-help; Self-initiative and self-sufficiency	Aryawiguna et al. (2021)
Motivation	Reflection competencies	Charatsari et al. (2022)
Motivation	Self-management skills	Mayor et al. (2022)
Natural Sciences	Climate Change	Mayor et al., 2022
Reliability	Confidence in one's own abilities	Plechowski (2014)
Speaking, writing and languages	Ability to read; Ability to write	Plechowski (2014)
Sustainability	Ecology-related Digital economy competencies (DEC)	Aletdinova et al. (2021)
Sustainability	Competencies of composing materials	Aryawiguna et al. (2021)
Sustainability	Better residue/organic matter management	Chikaire et al. (2017)
Sustainability	Circularity; Healthy farm; Specific skills for sustainable agriculture; Specific skills for sustainable food industry; Specific skills for sustainable forestry; Sustainable Business and Governance Models and Environmental Policy; Sustainable management of resources	Mayor et al. (2022)
Sustainability	Bioeconomy skills; Sustainability skills	Ramalho Ribeiro et al. (2023)
Technology	Adequate awareness about ICTs; Competence in handling ICT facilities; Sufficient trained computer personnel	Agwu et al. (2008)
Technology	Communicational Digital economy competencies (DEC); Digital Skills; ICT-related Digital economy competencies; Intellectual and education-related Digital economy competencies; Managerial Digital economy competencies; Motivational and will-related Digital economy competencies; Ease of obtaining information, and communication; Ease of storing data	Aletdinova et al. (2021)

Technology	Matrix of components and eigenvalues of the variables related to the use of computer equipment; matrix of components and eigenvalues of the variables related to the use of mobile telephony.	González Tena et al. (2015)
Technology	Digital literacy or skills	Hasan et al.(2022)
Technology	ICT skills farm marketing; ICT Skills farm planning; ICT Skills farm production	Irungu et al. (2015)
Technology	Impact of ICTs on the information of fertilizer management; Impact of ICTs on the information of harvesting and post harvesting technology; Impact of ICTs on the information of irrigation management; Impact of ICTs on the information of land preparation and sowing; Impact of ICTs on the information of plant protection; Impact of ICTs on the information of preparation of seedling of crops; Impact of ICTs on the information of varieties; Impact of ICTs on the information of weed management	Kumar et al. (2018)
Technology	Paddy farming technologies	Masso et al. (2016)
Technology	Digital tools to support production and production management; Digitalization for business; General Digital Skills; Production operations, technologies, and production approaches; Specific skills for digital (smart) farming	Mayor et al. (2022)
Technology	Program	Nasir et al. (2019)
Technology	A keen interest in computers and ICT; General ICT skills	Plechowski (2014)
Technology	Digitalization skills	Ramalho Ribeiro et al. (2023)
Technology	Program evaluation competency; Program implementation competency; Program planning competency	Tiraieyari et al. (2010)
Working in a team	Motivating partners	Aryawiguna et al. (2021)

Note: elaborated by the authors.

The analysis revealed that 36% of the competencies identified in the literature were related to the Technology domain, 21% to Agriculture, 18% to Management, and 11% to Sustainability. Motivation accounted for 4% of the identified competencies. Three domains—Creativity and Problem Solving, Leadership, and Speaking, Writing, and Languages—each represented 2% of the competencies. Finally, Entrepreneurship, Natural Sciences, Ethics, Reliability, and Working in a Team each accounted for 1% of the competencies identified in the reviewed studies.

Field Research Findings

The presentation and discussion of the field research findings were organized into nine subsections representing competency domains: Agriculture; Natural Sciences; Communication, Teamwork, Empathy, and Negotiation; Creativity, Problem Solving, Systems Thinking, and Analytical Thinking; Curiosity, Lifelong Learning, Proactivity, and Resilience; Customer Experience; Management; Specialized Machinery and Equipment; and Technology.

Agriculture

The Agriculture domain received 14 citations, accounting for 11% of the total competencies mentioned by participants in the five interviews and focus groups in response to this question. Interviewees E16, E18, E19, and E20 emphasized the importance of digital agriculture professionals possessing knowledge of agriculture and agronomy, including professionals involved in developing agricultural technologies.

“Well, they need to know agriculture; they need knowledge of the agricultural sector because I see that we have become an area very focused on data and data intelligence, data analytics, right? [...]” (E16).

“[...] Those who work on the IT team need to understand what a soybean plant is, what a corn plant is, right? [...]” (E18).

“[...] Well, from the agronomic perspective, what could I improve in agronomists today so that, when they are on the farm, they can better understand how all the information being generated on the property can be used more effectively, okay? [...]” (E19).

“[...] In digital agriculture [...] it is still agriculture, it is still agronomy [...] Therefore, we still need professionals with this knowledge. [...] I always see this as necessary, a good professional, a good agronomist. [...] What I often see among startup professionals [...] is usually the opposite. They focus on the solution itself [...] but they do not have knowledge of the business, which is agriculture [...]” (E20).

GF1 emphasized the importance of agricultural managers using profitability maps in precision agriculture and understanding how to relate data to the agricultural production context.

“[...] You may have high production and not realize how much you are losing [...] because, in terms of decision-making, it is difficult to measure since the operation is still profitable. [...] However, you do not realize how much you need or how much you have lost [...] the most important map in precision agriculture is the profitability map [...] professionals need to understand the importance of data and how these data are associated with the entire agricultural production context [...]” (GF1).

Natural Sciences

The Natural Sciences domain received 14 citations, corresponding to 11% of the data collected regarding competencies required for digital agriculture. E16 stated that GIS (Geographic Information System) specialists should possess knowledge of geotechnology, while E19 argued that agronomists should have knowledge of GIS, geography, and cartography.

“[...] Therefore, if someone is going to work in the GIS area, they need to know geotechnology.” (E16).

“[...] Within agronomy education, we need to improve training in the use of geographic information systems [...] strong training in geography, for example, or cartography [...]” (E19).

E17 mentioned that, in digital agriculture, areas of knowledge that may seem unrelated need to work together, such as biology, geostatistics, and georeferencing.

“[...] In the world of digital agriculture, everything is connected, everything is highly interconnected [...] It involves biology, it involves geostatistics [...] In digital agriculture, data must be georeferenced and properly structured; otherwise, they have no value at all [...]” (E17).

Communication, Teamwork, Empathy, Negotiation, and Entrepreneurship

Communication, Teamwork, Empathy, and Negotiation received eight citations, representing 6% of the total mentions. Communication competencies were cited by E18, GF1, and GF2. E18 also highlighted the importance of teamwork, collaboration with professionals from other fields, and proactivity. GF1 emphasized the need to put oneself in another person's position. GF2 highlighted that farmers are entrepreneurs and need to improve their negotiation skills.

“Teamwork [...] I think people need communication skills; they need to interact with multiple areas [...] proactivity and a communicative spirit are fundamental in digital agriculture [...]” (E18).

“[...] Today, companies' biggest problem is behavioral. [...] Professionals do not know how to approach people [...] Before talking to a farmer, the first thing I need to understand is: Who is this farmer? What is their educational background? What are they like? Are they engaged with technology? [...]” (GF1).

“Farmers are entrepreneurs in the agricultural business, right? They need strong communication skills [...] They need to negotiate with bank managers [...] negotiate with companies to hire technical assistance, negotiate with equipment suppliers, brands, inputs [...] and with customers [...]” (GF2).

Creativity and Problem Solving, Systems Thinking, and Analytical Thinking

Nineteen citations were associated with Creativity and Problem Solving, Systems Thinking, and Analytical Thinking, corresponding to 15% of the competencies identified. Combining different fields of knowledge, referred to as multidisciplinarity or multidisciplinary teams, was mentioned by E16, E18, and E19.

“Well, professionals need to know agriculture [...] data and data analytics [...] They need at least some understanding of the business itself [...]” (E16).

“I think the main skill is multidisciplinarity [...] I cannot understand only agronomy; I need to understand a little about IT, a little about data [...] and those working in IT need to understand what a soybean plant is and what a corn plant is [...] this heterogeneity of knowledge [...] digital agriculture has brought this particularity [...]” (E18).

“[...] We need to build teams with competencies from different areas [...] We will never master all the skills necessary to work in digital agriculture [...] We will have to build multidisciplinary teams [...]” (E19).

The need for Systems Thinking was highlighted by E20, who emphasized that technological innovations require validation before being implemented in agriculture.

“[...] I realize there is still a lack of technical knowledge. For example, if we talk about agronomy and soil sampling, there is a correct procedure and established methodology [...] Sometimes a technological solution appears [...] but it is still superficial [...] It still needs a stronger technical foundation before it can actually be implemented [...]” (E20).

The demand for Analytical Thinking was emphasized by GF1, who pointed out that data analysis generated by agricultural equipment is still mostly carried out by professionals working with large agricultural producers.

“[...] It is already difficult to use the equipment installed on agricultural implements [...] analyzing data is an even greater challenge [...] This behavior is still mostly observed among large producers [...]” (GF1).

Curiosity, Lifelong Learning, Proactivity, and Resilience

Attitudes related to Curiosity, Lifelong Learning, and Resilience received 15 citations, corresponding to 11% of the competencies considered necessary for digital agriculture. E17 and E18 mentioned curiosity and lifelong learning using different expressions. E18 also highlighted proactivity.

“[...] The first and most important thing, in my view, is this desire to keep learning all the time, this curiosity, this willingness to always discover more [...] because this knowledge is not yet systematized [...] The second aspect is being self-taught [...]” (E17).

“[...] Continuous learning [...] this need to keep learning and constantly updating oneself [...] Proactivity is also extremely important [...] being restless and proactive [...]” (E18).

E20 explained that work in digital agriculture requires resilience because making mistakes is an inherent part of technological development.

“[...] Sometimes we make mistakes, sometimes we succeed; that is normal [...] We cannot be afraid of making mistakes [...] This will always happen [...] We cannot be afraid to test things and make mistakes [...]” (E20).

Customer Experience

Skills related to customer relationship management represent 4% of the competencies and were mentioned by GF2, who referred to the direct interaction between family farmers and consumers.

“[...] When we show our faces, whether through delivery services or at farmers' markets, consumers know exactly who we are [...] If anything happens, they know where to find us [...]” (GF2).

Management

The Management domain gathered eight citations, corresponding to 6% of the total competencies. GF2 emphasized the need for family farmers to have a detailed understanding of their activities and the context in which they operate.

“[...] Developing marketing, packaging, certification, legal compliance, and labeling [...] It is our responsibility to offer a quality product [...] Historically, farmers focused only on what happened inside their properties [...] but today it is important to understand what is happening outside [...] It is no longer enough to manage only what is inside the farm boundaries; they need to look beyond them [...]” (GF2).

Specialized Machinery and Equipment

A total of sixteen knowledge areas and/or skills were mentioned under Specialized Machinery and Equipment, corresponding to 12% of the competencies cited. According to GF1, many farmers who purchase agricultural machinery do not know or use all the functionalities available in the equipment.

“[...] Even today, they buy the machines and turn some functions off because otherwise the machines keep beeping [...] They do not use all the available tools [...] Perhaps only 1% use all the available functionalities [...] The equipment is certainly underutilized [...]” (GF1).

E19 mentioned the need for agronomists to know about remote sensing and satellite imagery. GF1 mentioned the use of artificial intelligence in drones, equipment, and robots.

“Another area that is already a reality and will become increasingly important is remote sensing [...] the use of satellite imagery and drones, which are also part of remote sensing [...]” (E19).

“[...] Artificial intelligence is already being used in digital agriculture [...] in drones, equipment, and robots that harvest fruit with extremely high efficiency while reducing human labor [...]” (GF1).

Technology

Technology was the domain that gathered the largest number of competencies, with 32 citations, corresponding to 24% of the total. E16 associated this domain with data, data analytics, computing, IT architecture, and information and communication technologies. E20 stated that agronomists need knowledge of data and image processing.

“[...] Data, data intelligence, data analytics [...] there is also a basic computing component [...] we have been working on IT architecture as well [...]” (E16).

“[...] Agronomists need to know how to retrieve data, download data, process information and images, and begin to pay more attention to this area [...]” (E20).

E16 and E20 also emphasized programming knowledge. According to GF1, professionals who do not master programming languages should at least know how to use spreadsheets and Power BI.

“[...] If someone works in development, they need to know programming, such as Python [...] In my team, many people have basic programming knowledge because they need it for everyday tasks [...]” (E16).

“[...] They do not need to be software development specialists [...] but they may be required to create customized solutions, and if they do not understand programming languages [...] they need to know Excel and Power BI [...]” (GF1).

GF1 also explained that professionals need knowledge of databases, data extraction, and data transmission.

“[...] They need to understand databases, data transmission and transfer [...] they need to know the software being used [...] and understand not only agribusiness but also embedded technologies in order to extract data from them [...]” (GF1).

Conclusion

The comparative analysis between the data obtained from the literature review and the field research revealed consensus competency domains, including Agriculture, Natural Sciences, Entrepreneurship, Management, Technology, Creativity and Problem Solving, Teamwork, and Proactivity. In contrast, divergent competency domains were identified, that is, domains mentioned in only one of the data sources: Communication (oral and written), Empathy and Negotiation, Systems Thinking and Analytical Thinking, Curiosity, Lifelong Learning and Resilience, Customer Experience, Specialized Machinery and Equipment, Ethics, Leadership, Motivation, Reliability, and Sustainability.

The evaluation of the competencies mentioned within the same domains or themes in the literature review and the field research revealed that these specific competencies often differ from one another. It was also observed that the competencies present different levels of granularity across the data sources. Competencies identified in the literature review were, in most cases, broader or more generic than those obtained from participants' accounts collected during the field research.

The findings indicate that, although technical and digital competencies remain essential for precision agriculture systems, stakeholders emphasize multidisciplinary collaboration, analytical reasoning, adaptability, teamwork, and continuous learning as crucial factors for effective technology adoption and systems integration.

Future investigations involving additional documentary data sources may reveal complementary competencies, as may the conduction of new interviews and focus group sessions with different digital agriculture stakeholders.

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