
# MAPPING OF DIGITAL TECHNOLOGIES, CLOUD PLATFORMS AND ARTIFICIAL INTELLIGENCE IN PRECISION AGRICULTURE: A SOFTWARE BASELINE FOR A LIVING LAB IN CITRUS AND SUGARCANE

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***Abstract.*** *The digital transformation of Precision Agriculture (PA) has been driven by the growing supply of Farm Management Information Systems (FMIS), cloud platforms and Artificial Intelligence (AI) solutions. This work, linked to the Smart B100 Science Centre for Development (CCD-SB100) — funded by FAPESP and led by the Agronomic Institute of Campinas (IAC) in partnership with FATEC Shunji Nishimura (Pompéia) — aimed to build a multicriteria matrix (technological inventory) of digital PA solutions and their supplier companies applicable to citrus and sugarcane production. The methodology was based on a technical-scientific literature review, on the analysis of institutional materials and on the technical documentation of the platforms (product datasheets, API documentation and data policies). The solutions identified and their respective developers, ranging from emerging agricultural technology (AgTech) startups to consolidated technology corporations, were categorized by functionality — including agricultural Enterprise Resource Planning (ERP) systems, FMIS platforms, telemetry and Internet of Things (IoT) dashboards, predictive agronomic models and field mobile applications — and were assessed under criteria such as target crop, producer size, dependence on field connectivity, Technology Readiness Level (TRL) of the embedded algorithms, integration capability through open Application Programming Interfaces (APIs) and the type of intelligence offered (descriptive, predictive or prescriptive). The study showed that the sugar-energy sector, driven by the operational scale of the mills and by integrated industrial management, presents greater maturity in the adoption of corporate ERPs and logistics-routing systems, whereas citrus production still depends heavily on fragmented tools, such as spreadsheets and isolated mobile applications. In addition, the consolidated results allowed the construction of a 40-criteria matrix for the analysis and classification of 20 digital solutions. Of these, 10% correspond to FMIS-IoT, 10% to ERPs and 10% to informal technologies, while the remainder is distributed among various types of technology, with a prevalence of assorted FMIS. It is therefore concluded that the data gathered*

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*confirmed the effectiveness of the method and ensured the definitive construction of the criteria matrix with the different digital solutions.*

***Keywords.*** *Precision Agriculture; Farm Management Information Systems; Digital Transformation; Sugarcane; Citrus Farming.*

## 1. INTRODUCTION

Precision Agriculture (PA) has established itself as a paradigm for managing the spatial and temporal variability of crops and, more recently, has shifted its axis from machinery toward software and data, relying on data-driven approaches to optimize the management of crops, soil and resources (Getahun et al. 2024). This digital transformation is increasingly driven by three technological pillars: Farm Management Information Systems (FMIS), which centralize the recording and planning of operations; cloud computing, which provides scale, remote access and reduced infrastructure costs; and Artificial Intelligence (AI), which converts large volumes of data into actionable recommendations. Within this movement, machine-learning-based yield prediction (Saha et al. 2025) and the convergence of the Internet of Things (IoT), cloud and AI (Padhiary et al. 2025) are among the most active fronts, alongside emerging trends such as digital twins (Wang 2024).

The counterpart of this advance, however, is the accelerated proliferation of agricultural technology (AgTech) solutions. An abundant and poorly articulated supply tends to produce a fragmented digital ecosystem, in which tools from different vendors compete in overlapping functions, rarely integrate with one another and lock information into isolated compartments, the so-called data silos. This scenario helps to explain why the availability of technology does not always translate into effective use in the field: a report by the Government Accountability Office (GAO) notes that PA technologies can be complex and have high initial costs, in addition to encountering producers' distrust regarding data collection and sharing, and records that only 27% of United States farms employed precision agriculture practices in 2022–2023 (GAO 2024). When it occurs, adoption is uneven: it is concentrated in large mechanized properties, while features such as variable-rate application do not reach half of the cultivated area and use on non-mechanized properties is almost nonexistent (McFadden et al. 2024). Although bibliometric studies record the significant growth of scientific output in PA, especially since 2019 (Xu et al. 2024), fragmentation and low adoption remain relevant practical obstacles.

It is in this context that the Smart B100 Science Centre for Development (CCD-SB100) is situated — funded by the São Paulo Research Foundation (FAPESP) and led by the Agronomic Institute of Campinas (IAC) in partnership with institutions such as FATEC Shunji Nishimura (Pompéia) — within which the development of a digital Living Lab is proposed; that is, an open-innovation environment, user-oriented and operated under real production conditions, focused on citrus and sugarcane crops in the state of São Paulo. The choice of the two crops is not incidental: in addition to their economic weight for the state, they represent contrasting production logics. Sugarcane, semi-perennial and heavily mechanized, has a consolidated history of phytosanitary monitoring through remote sensing, as in the detection of foliar diseases from hyperspectral imagery (Apan et al. 2004). Citrus, in turn, a perennial and sanitarily sensitive crop, demands frequent monitoring and plant-level diagnosis, an area in which hyperspectral imaging and digital phenotyping have proven promising (Song et al. 2025). One of the central objectives of SB100 is to deploy generative AI, in the form of Large Language Models (LLM), to optimize the agronomic recommendations offered to producers.

For this On-Farm Experimentation (OFE) environment to be successful, it is essential to understand, first of all, the current digital maturity of producers: a new AI layer will hardly integrate into a technological routine that has not been previously mapped. The present scientific-initiation project is thus justified, aiming to systematically map and critically assess the software, digital platforms and AI applications currently used by farmers in the two chains. While parallel fronts of SB100 are dedicated to soil analysis and to physical hardware, this research isolates the digital infrastructure, establishing what is termed, in this work, the software baseline: the portrait of the technological repertoire already in use, on which the future AI platform must rely.

To this end, the construction of a multicriteria technological-inventory matrix is adopted as an instrument, in which solutions are categorized by functionality — among them Enterprise Resource Planning (ERP) systems, FMIS, IoT dashboards, predictive agronomic models and mobile applications — and cross-referenced with variables such as crop type, producer size, dependence on connectivity and User Experience (UX) barriers. The matrix also assesses the Technology Readiness Level (TRL) of the algorithms and their interoperability, understood as the capacity for integration through Application Programming Interfaces (API). The detailing of the criteria and of the assessment procedures is presented in the materials and methods section.

In light of the above, the general objective of this work is to map and critically assess the digital software infrastructure employed by citrus and sugarcane producers in the state of São Paulo, establishing the software baseline for the SB100 Living Lab. As specific objectives, it seeks to: (i) catalog and categorize by functionality the digital solutions in use and their supplier companies; (ii) cross-reference them with variables of crop, producer size and connectivity; (iii) assess the technology readiness level (TRL) and the degree of interoperability (API) of each solution; and (iv) distinguish the solutions that effectively solve problems in the field from those that represent merely market expectation (hype). Preliminary observations suggest a contrast in digital maturity between the two chains, to be characterized in the results section. By consolidating this baseline, the aim is to ensure that the future AI platform of Smart B100 integrates seamlessly into the existing technological routine, promoting a user-centered, highly adoptable and data-driven agricultural Living Lab.

## 2. METHODOLOGY

This work was developed under a qualitative approach, of an analytical and exploratory nature, combining primary and secondary research. The study was articulated in systematic stages, which can be summarized into two major operational axes: the review and collection of data and the definition of the assessment and categorization criteria. While parallel studies mapped the physical hardware layer, this research focused exclusively on the technological survey of the software layer.

### 2.1. Data Review and Collection

The review of the technical-scientific literature was based on the search for and analysis of articles and works drawn from indexed databases such as arXiv, Google Scholar, Web of Science and SciELO. From this theoretical foundation, the fundamental concepts for assessing the mapped solutions were established, using standardized metrics such as the Technology Readiness Level (TRL).

For the construction of the technological inventory applicable to citrus and sugarcane crops, the methodology relied on the rigorous analysis of institutional materials and on the technical documentation of the mapped platforms. This primary data-collection process included the scrutiny of product datasheets, API documentation and the mapping of the data-ownership and data-management policies adopted by the developer companies.

### 2.2. Definition of the Assessment and Categorization Criteria

To organize the technological ecosystem — which ranges from agricultural management platforms (ERPs and FMIS) and IoT telemetry dashboards to predictive agronomic models and mobile applications — a multicriteria matrix was built. The assessment table was based on 40 technical and functional criteria, designed to diagnose the digital maturity and the interoperability of the tools against the reality of rural producers. To enable the analysis, the criteria were categorized into six sequential blocks (from A to F), as detailed in Table 1.

**Table 1** Categorization of the assessment criteria of the multicriteria matrix

| Blocks | Criteria covered | Total criteria |
|---|---|---|
| A | 1–7 | 7 |
| B | 8–13 | 6 |
| C | 14–17 | 4 |
| D | 18–27 | 10 |
| E | 28–34 | 7 |
| F | 35–40 | 6 |

Source: prepared by the authors

Block A, intended for the identification of the digital solution, comprised the criteria of code, functional category, subcategory, commercial name, developer company, country of origin and availability of the technology in Brazil. This stage visually organized the inventory and highlighted the geopolitical distribution of the technologies, revealing the prominence of the national ecosystem relative to external dependence on solutions.

Block B was responsible for the agronomic and functional classification, encompassing the main function, the stage of the production cycle, the primary crop, the suitability for citrus, the suitability for sugarcane and the respective justification. This perspective made it possible to map the coverage of the platforms and the production phases served, identifying contrasts in maturity and gaps in digitalization between the crops investigated.

Block C contributed to structuring the user profile and the business model, covering the criteria of target-producer size, cost to the user, revenue model and access platform. These variables were used to assess the economic barriers to entry and served as critical indicators of digital inclusiveness and accessibility in the rural environment.

As the technical core and the grouping with the largest number of criteria, Block D identified the digital technical specifications. The interoperability and the analytical depth of the market were investigated through variables such as: type of embedded Artificial Intelligence (descriptive, diagnostic, predictive or prescriptive), level of intelligence, TRL of the algorithm, availability of open APIs, supported data formats, integration and compatibility with precision hardware, dependence on connectivity, storage and data-sovereignty policies.

Block E focused on the relevance of the tools to the Living Lab stakeholders. The impact generated by the adoption of each software was measured through a hierarchical scale from 1 to 5, assessing the practical and institutional value attributed by rural producers, researchers, the machinery industry, AgTech startups, rural extension services, mill/packing-house managers and public-policy makers.

Finally, Block F analyzed the integration with the Living Lab and the feasibility of adopting the solutions as methodological tools. The criteria established encompassed the priority within the project, the capacity to generate data for On-Farm Experimentation (OFE), the current adoption landscape in the state of São Paulo (for both citrus and sugarcane), the main adoption barrier and the integration potential with Smart B100. This block justified the practical application of the study by ranking investments on the basis of a realistic diagnosis of regional digital maturity.

## 3. RESULTS AND DISCUSSION

The application of the technological-inventory matrix to the twenty solutions that make up the software baseline revealed two main results: a marked asymmetry of digital maturity between the two chains studied and a functional concentration of the supply around agricultural management systems. The sectoral contrast between sugarcane and citrus is discussed below and, subsequently, the functional distribution and the intelligence profile of the solutions assessed.

### 3.1. Sectoral Overview: Sugarcane vs. Citrus

The two crops start from very different points of digital maturity, and the root of this difference lies in the production structure of each chain. The sugar-energy sector is organized around large-scale mills, with integrated industrial operation and a high degree of mechanization, conditions that favored the consolidation of corporate platforms. ERP systems illustrate this scenario well: SAP S/4HANA (SW-001) stands as the market standard among the large mills, articulating financial management, transshipment logistics and traceability, while TOTVS Agro (SW-002), a national alternative, maintains good penetration in the same segment. To this core are added platforms born within the sector itself: Solinftec (SW-003), headquartered in Araçatuba (São Paulo), has the largest installed base in mechanized sugarcane operations and delivers precisely the fleet-management and logistics-routing functions that characterize industrial operation; and the embedded-telemetry environments of the machinery manufacturers, such as John Deere Operations Center (SW-004) and CNH AFS Connect (SW-005), are consolidated in the mills that operate fleets of those brands.

The reflection of this arrangement in the matrix is direct: of the twenty solutions assessed, eight (40%) are already consolidated in São Paulo sugarcane. At the forefront is the core of corporate management and telemetry, formed by the two ERPs (SW-001 and SW-002) and by the three platforms with embedded telemetry (SW-003, SW-004 and SW-005), to which are added image processing (SW-010), electronic spreadsheets (SW-019) and sectoral plant protection (SW-020). The pattern is consistent with what the international literature describes regarding precision-agriculture adoption, whose diffusion is concentrated in large mechanized properties (McFadden et al. 2024); sugarcane, by its scale and degree of mechanization, is an expressive example of this trend.

In citrus, the picture is inverse. The same corporate platforms that thrived in sugarcane appear as incipient among citrus growers: SAP, Solinftec, John Deere and CNH are all classified as having incipient adoption in citrus. The tools that effectively achieve widespread use in this chain are not agricultural-technology solutions, but informal resources: WhatsApp (SW-015), described in the matrix as the main communication channel between citrus grower and technician, and electronic spreadsheets (SW-019), which correspond to what most citrus growers in fact use to manage the property. The only structured solution at a consolidated stage in citrus is institutional in nature: the Fundecitrus/CTC/MAPA arrangement (SW-020), a worldwide reference in the monitoring of greening (Huanglongbing). In numbers, only one of the twenty solutions is consolidated in citrus, and even so in the field of plant protection; more than half remain at an incipient stage. Table 2 summarizes this contrast.

**Table 2** Adoption stage of the twenty digital solutions (SW-001 to SW-020) in the citrus and sugarcane chains in the state of São Paulo

| Adoption stage | Citrus (n) | Sugarcane (n) |
|---|---|---|
| Consolidated[a] | 1 | 8 |
| Emerging[b] | 6 | 5 |
| Incipient[c] | 11 | 5 |
| Universal[d] | 2 | 1 |
| Not applicable | 0 | 1 |
| **Total** | **20** | **20** |

Source: prepared by the authors

Note: [a] Technology widely diffused and in routine use in the crop. [b] Expanding, with growing but partial adoption. [c] Restricted use or in an early implementation phase. [d] Tool in widespread use, regardless of producer size.

The picture that emerges is, therefore, that of a citrus sector operating on a fragmented digital base, with isolated applications and spreadsheets that do not integrate with one another — exactly the data-silos scenario anticipated in the introduction. The barriers of cost, implementation complexity and distrust regarding data sharing, reported in the literature (GAO 2024), tend to fall more heavily on a perennial and intensively managed crop, in which the average producer can hardly absorb the cost and the learning curve of a corporate ERP.

### 3.2. Application of the Matrix and Analysis of the Digital Solutions

Beyond the adoption stage, the matrix characterizes what these twenty tools effectively are in functional terms. The distribution by family, presented in Table 3, shows that the supply is not divided uniformly: Farm Management Information Systems (FMIS) and their variants prevail by a wide margin, gathering six of the twenty solutions (30%). It is the category that functions as the basis of digital management in the field, bringing together everything from pure platforms (Trimble, SW-006; Aegro, SW-008) to variants coupled with machine telemetry, with analytics and imagery, and with decision-support models.

**Table 3** Distribution of the twenty digital solutions by functional family, with the respective codes and the relative share

| Functional family | Solutions (codes) | n | % |
|---|---|---|---|
| FMIS and variants[a] | SW-004, SW-005, SW-006, SW-007, SW-008, SW-016 | 6 | 30 |
| AI-analytics and IoT (non-FMIS) | SW-003, SW-009, SW-012 | 3 | 15 |
| Corporate ERP | SW-001, SW-002 | 2 | 10 |
| Imaging platforms (RPAS/satellite) | SW-010, SW-014 | 2 | 10 |
| Field mobile and diagnosis apps | SW-011, SW-017 | 2 | 10 |
| Informal tools[b] | SW-015, SW-019 | 2 | 10 |
| Free GIS | SW-013 | 1 | 5 |
| Generative AI (LLM) | SW-018 | 1 | 5 |
| Institutional plant protection | SW-020 | 1 | 5 |
| **Total** | — | **20** | **100** |

Source: prepared by the authors

Note: [a] Includes pure FMIS and the FMIS-IoT (integration with machine telemetry), FMIS-AI (analytics and satellite imagery) and FMIS-DSS (phenological and phytosanitary models) variants. [b] General-purpose resources appropriated as a de facto management system: messaging (WhatsApp) and electronic spreadsheets.

The distribution confirms the prevalence of FMIS and, at the same time, shows a set of smaller categories, each with a share between 5% and 10%. Within the FMIS family, the subgroup coupled with machine telemetry (John Deere and CNH) accounts for 10% of the total and deserves particular attention: because it is tied to the ecosystem of each manufacturer, it is also the one that most exposes the problem of technological lock-in, with restricted programming interfaces and low interoperability between brands. The corporate ERPs, the imaging platforms and the field applications each account for 10%.

The presence of informal tools among the most relevant categories, also with 10%, is striking: WhatsApp and spreadsheets are not agricultural technology in the strict sense, but general-purpose resources repurposed as a de facto management system. To disregard them would distort the real panorama of digitalization in the field. For the objectives of the project, this finding is strategic, since it indicates that the future artificial-intelligence layer of SB100 will need to coexist with already-rooted informal channels, rather than competing head-on with them.

Finally, the analysis of the level of embedded intelligence puts into perspective the current use of the term artificial intelligence in agriculture. Although most platforms announce some degree of intelligence, the delivery of genuinely prescriptive recommendations is still rare: only four of the twenty solutions (20%) — namely Solinftec (SW-003), Agrosmart (SW-012), Agricolus (SW-016) and the language models themselves (SW-018) — reach this level, whereas most operate at descriptive and diagnostic levels. This low presence of prescriptive solutions delimits the project's scope of action: by proposing the use of generative AI for agronomic recommendation, SB100 operates in a still-underfilled segment, but one that, to be effective, will need to rely on FMIS and dialogue with the informal tools that predominate in the producer's daily routine, especially in citrus.

## 4. CONCLUSION

The construction of the multicriteria matrix proved to be an effective methodological approach for cataloging and systematizing the ecosystem of digital solutions aimed at Precision Agriculture (PA) in the citrus and sugar-energy chains. The data gathered confirmed the effectiveness of the method, ensuring the definitive construction of a 40-criteria matrix applied to the analysis and classification of 20 digital solutions. This standardization fills a critical gap in the literature and provides a realistic diagnosis of regional digital maturity.

As the main analytical contribution, the inventory revealed a marked structural asymmetry between the two crops investigated: driven by the operational scale of the mills and by integrated industrial management, the sugar-energy sector presents greater maturity in the adoption of corporate ERPs and logistics-routing systems. In contrast, citrus demonstrated a persistent dependence on fragmented ecosystems and informal tools, such as spreadsheets and isolated mobile applications. The distribution of the mapped market revealed that 10% of the solutions correspond to FMIS-IoT platforms, 10% to corporate ERPs and 10% to informal technologies, with the remainder distributed among various categories and with a strong prevalence of assorted FMIS systems. Additionally, the application of the technical criteria put into perspective the commercial use of the term "artificial intelligence" in the sector; it was found that only 4 of the 20 mapped solutions offer genuinely prescriptive intelligence, while the remaining 16 operate predominantly at descriptive or diagnostic levels.

The consolidated technological inventory definitively fulfills the role of establishing the digital baseline necessary for planning the Living Lab of CCD-SB100. The validated parameters serve as scientific input for the prioritization and integration of the software platforms that will support On-Farm Experimentation (OFE) and the development of generative Artificial Intelligence aimed at agronomic recommendation. As an unfolding for future work, the need is pointed out to carry out the systematic cross-referencing of this matrix with the parallel mapping of the physical hardware layer, integrating interoperability data to consolidate the architecture of the future Smart B100 platform.

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