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# UAV, PHOTOGRAMMETRY, GIS, AND DIGITAL TWIN IN AGRICULTURE – A THEORETICAL APPROACH

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**Abstract**

*The rapid advancement of remote sensing and spatial analysis technologies has led to a profound transformation of agricultural practices, fostering the transition toward precision, sustainable, and resource-efficient agriculture. In this context, unmanned aerial vehicles (UAVs) have become essential tools for acquiring high-resolution data, which, through advanced photogrammetric processes, can be converted into complex geospatial products—orthophotos, digital terrain models (DTMs), and detailed three-dimensional models. The integration of these products into geographic information systems (GIS) facilitates spatial and temporal analyses of agricultural crops, providing decision support for integrated farm management. Furthermore, the evolution toward the concept of the agricultural Digital Twin enables the creation of dynamic digital replicas of fields and crops, updated in real time with data collected from UAVs, IoT sensors, and satellite sources. These models allow the simulation of agronomic scenarios, optimization of irrigation, fertilization, and crop protection processes, as well as the prediction of yield performance. This paper presents an integrated analysis of how UAVs, photogrammetry, GIS, and Digital Twin technologies can be combined into a coherent workflow for data acquisition, processing, and interpretation, with a particular focus on their applicability in agriculture. The discussion addresses technical advantages, implementation challenges, and future research directions concerning the standardization and interoperability of these technologies. The conclusions highlight the significant potential of these tools to enhance efficiency, reduce costs, and promote a sustainable, data-driven agricultural paradigm.*

***Key words: UAV, Photogrammetry, GIS, Digital Twin, Precision Agriculture***

## INTRODUCTION

Contemporary agriculture is undergoing an extensive process of transformation and digitalization, driven by the need to ensure global food security (Godfray et al., 2010), enhance the efficiency of natural resource use, and reduce environmental impact. Over the past two decades, the rapid development of information and remote sensing technologies has enabled the emergence of the concept of precision agriculture, in which decisions related to fertilization, irrigation, seeding, and crop protection are based on quantifiable, spatially and temporally localized information (Pop et al., 2024).

One of the key pillars of this technological revolution is the use of unmanned aerial vehicles (UAVs), which have established themselves as versatile tools for acquiring high-resolution geospatial data (Fraser et al., 2022). UAVs allow for frequent and flexible monitoring of agricultural fields, regardless of weather conditions or crop phenology, complementing and, in some cases, replacing traditional satellite-based remote sensing sources (Călina A. et al., 2019). Multispectral and thermal imagery collected by drones provides detailed information regarding vegetation condition, soil moisture levels, crop biotic and abiotic stress, and canopy coverage (Călina J. et al., 2019; Mandal et al., 2024).

The data obtained from UAV flights are processed photogrammetrically to generate orthophotos, digital terrain models (DTMs), digital surface models (DSMs), and three-dimensional point clouds. These products constitute a robust foundation for advanced geospatial analyses, particularly when integrated into geographic information systems (GIS) (Călina J. et al., 2021-A). GIS platforms facilitate the storage, management, and analysis of such data, enabling their correlation with other sources (satellite imagery, in-situ measurements, meteorological data) and supporting the identification of spatial and temporal variations in agricultural parameters (Călina J. et al., 2021-B; Khanal et al., 2020).

In recent years, the integration of these technologies has evolved toward the emerging concept of the agricultural Digital Twin—a dynamic digital representation of a real system (field, farm, irrigation network) that is continuously updated with data from multiple sources: UAVs, IoT sensors, satellite imagery, and predictive models (Călina J. et al., 2022). The Digital Twin enables the simulation and prediction of crop behavior under different management scenarios, thereby reducing decision-making uncertainties and optimizing real-time interventions (Uztürk et al., 2024).

Thus, the convergence of UAV, photogrammetry, GIS, and Digital Twin technologies delineates a new analytical and control framework in agriculture, oriented toward efficiency, sustainability, and climate resilience (Călina J. et al., 2025-A). However, the integration of these technologies raises several challenges related to data accuracy, platform interoperability, workflow standardization, and the analysis of large data volumes (big data) (Bwambale et al., 2025; Călina J. et al., 2025-B).

In this context, the present paper aims to:

- present the main UAV technologies used in agriculture and the principles of photogrammetric data processing;
- highlight the role of GIS systems in the analysis and integration of spatial agricultural information;
- explore the applicability of the *Digital Twin concept* in precision agricultural management;
- discuss the benefits, limitations, and research perspectives regarding the integration of these technologies.

By addressing these objectives, this study contributes to the consolidation of the theoretical and methodological framework necessary for the development of smart farming, in which decisions are based on updated, accurate, and interoperable spatial information.

## MATERIALS AND METHODS

The approach proposed in this study is based on the integration of UAV technologies, digital photogrammetry, GIS, and Digital Twin into a coherent workflow for the acquisition, processing, analysis, and modelling of geospatial data applied to agriculture (Figure 1). The methodology aims to generate high-precision

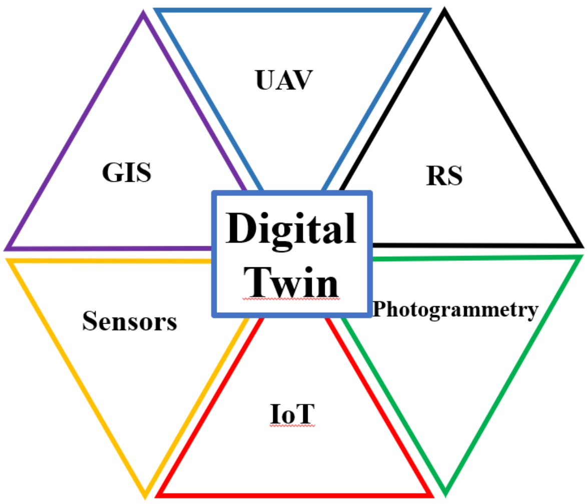


Figure 1. *Support technologies for Digital Twin in agriculture*

cartographic products capable of describing and anticipating the dynamics of agricultural processes—from vegetation status to the management of water and nutrient resources.

**UAV Technologies Used in Agriculture**

UAV platforms employed in agriculture can be classified according to their flight architecture (multirotor, fixed-wing, or hybrid) and the type of integrated sensors. Multirotor drones are preferred for high-precision mapping missions over small areas (experimental plots, horticultural crops), offering stability and control at low altitudes (30–120 m). Fixed-wing platforms, on the other hand, are better suited for covering large agricultural areas (over 100 ha), benefiting from greater flight autonomy and higher speeds.

Sensors Used (Vangu et al., 2022):

- *RGB sensors* (e.g., Sony Alpha 6000, DJI Phantom 4 RTK) — for generating high-resolution orthophotos (1–3 cm/pixel) and 3D terrain models.
- *Multispectral sensors* (MicaSense RedEdge-MX, Parrot Sequoia, Altum PT) — for acquiring data across multiple spectral bands (blue, green, red, red-edge, NIR), useful in calculating vegetation indices such as NDVI, GNDVI, NDRE, or SAVI.
- *Thermal sensors* (FLIR Vue Pro R, Workswell WIRIS) — for identifying water stress and assessing the efficiency of irrigation systems.

For precise georeferencing, integrated GNSS/RTK systems are used, providing horizontal and vertical accuracies at the centimeter level. Flight mission planning is carried out using dedicated applications (*DJI GS Pro*, *Pix4D Capture*, *DroneDeploy*), which allow for the automatic definition of flight trajectories, image overlap (70–80%), and optimal flight altitude.

**Photogrammetric Processing of UAV Data**

The images collected during UAV missions are processed using modern photogrammetric methods based on *Structure from Motion* (SfM) and *Multi-View Stereo* (MVS) algorithms, which enable the three-dimensional reconstruction of terrain surfaces from overlapping image sequences (Ochiai et al., 2024).

The processing workflow includes the following main stages:

- *Image import and calibration* – correction of optical distortions, determination of the camera's internal parameters, and verification of GPS metadata.
- *Detection of tie points* – automatic identification of common points between images using feature-matching algorithms (SIFT, SURF).
- *Image alignment and camera position estimation* – generation of a sparse point cloud.
- *Point cloud densification* – application of MVS methods to obtain a complete three-dimensional model.
- *Generation of the Digital Terrain Model (DTM) and Digital Surface Model (DSM)* – extraction of terrain morphology and surface objects (vegetation, constructions, etc.).
- *Orthophoto generation* – geometric and radiometric rectification of images and projection into a GIS coordinate system (e.g., WGS84/UTM).

Commonly used software applications include *Agisoft Metashape*, *Pix4Dmapper*, *DroneDeploy*, *RealityCapture*, and *OpenDroneMap*. During processing, *Ground Control Points* (GCPs) measured with GNSS/RTK equipment may be employed to ensure absolute accuracies better than 3 cm.

The final output of photogrammetric processing consists of interoperable geospatial datasets: orthophotos, DTM/DSM models, point clouds, and textured 3D models. These products serve as fundamental inputs for GIS-based analysis and for the construction of the agricultural Digital Twin model.

**Integration of Photogrammetric Data into GIS**

Geographic Information Systems (GIS) provide the integrative framework necessary for managing, analyzing, and visualizing data obtained through UAV photogrammetry. In this context, the methodological workflow involves the following steps:

- *Import of geospatial data* (orthophotos, DTM, DSM, NDVI maps) in compatible formats (GeoTIFF, LAS, shapefile, GeoPackage).
- *Creation of a geodatabase* that includes thematic information (plots, crop types, cadastral boundaries, agricultural infrastructure).
- *Spatial and temporal analyses:*
  - calculation of vegetation indices and delineation of homogeneous zones;
  - identification of areas affected by drought, erosion, or disease;
  - terrain analysis (slope, aspect, drainage) for agricultural planning;
  - assessment of seasonal crop variations based on UAV orthophoto time series.

Applications such as *ArcGIS Pro*, *QGIS*, *ERDAS Imagine*, and Python extensions (*GDAL*, *rasterio*, *geopandas*) are commonly used for these analyses. Integration within GIS allows the correlation of UAV-derived data with other sources (e.g., *Sentinel-2* satellite imagery, IoT sensor measurements, meteorological data), providing a holistic understanding of the agricultural ecosystem (Yao et al., 2019).

**Construction and Use of the Agricultural Digital Twin**

The agricultural Digital Twin is a dynamic digital representation of a farm, reflecting in real time the physical state of the land and crops, continuously updated with data from multiple sources. Building such a model involves several stages:

- *Initial static modeling*: using UAV photogrammetric data (DTM, DSM, orthophotos) to generate a basic three-dimensional model of the agricultural area.
- *Integration of dynamic data*: incorporating data streams from IoT sensors (temperature, humidity, salinity), weather stations, irrigation systems, and satellite imagery.
- *Model updating and calibration*: periodic synchronization of data to accurately reflect real field conditions.
- *Process analysis and simulation*: running predictive scenarios on water consumption, crop response to fertilization, or yield evolution based on climatic parameters.

Implementing an agricultural Digital Twin requires the use of data integration platforms (e.g., *Microsoft Azure Digital Twins*, *Siemens MindSphere*, *Dassault Systèmes 3DEXPERIENCE*) and artificial intelligence algorithms for predictive analysis. The primary benefit lies in the ability to proactively monitor and control agricultural processes, optimizing resource use and reducing losses (Ameslek et al., 2024).

Thus, the proposed methodology establishes a direct link between UAV data acquisition, photogrammetric processing, GIS-based spatial analysis, and Digital Twin modeling, providing a comprehensive framework for the digital evaluation and management of modern agricultural holdings.

## RESULTS AND DISCUSSIONS

The practical implementation of the proposed methodology, based on the integration of UAV, photogrammetric, GIS, and Digital Twin data, can demonstrate and validate the potential of these technologies in optimizing agricultural processes and supporting data-driven decision-making. Within the research, several scenarios of crop monitoring were simulated using products derived from multispectral UAV flights and high-precision photogrammetric processing.

**Results of UAV Photogrammetric Processing**

Flights conducted at altitudes ranging from 60 to 100 m above ground level, with 80% forward overlap and 70% side overlap, generated image sets with spatial resolutions of 2–3 cm/pixel. Processing these images resulted in high-precision orthophotos, Digital Terrain Models (DTM), and Digital Surface Models (DSM) with mean vertical errors below 3 cm, validated using GNSS control points.

Comparative analysis across different flight periods (early vegetation, peak growth, and maturity stages) revealed significant changes in spectral and topographic parameters. The resulting NDVI maps enabled the identification of areas with uniform vegetation as well as zones affected by water stress or nutrient deficiencies. Problematic areas showed NDVI values below 0.45, while healthy regions exhibited values between 0.65 and 0.85.

Additionally, DSM models provided supplementary information on microtopographic variations, which are valuable for water runoff analysis and irrigation system planning. In some cases, elevation differences of only 20–30 cm influenced soil moisture distribution and crop yield (Canicattì et al., 2024).

**GIS Spatial Analysis**

The integration of photogrammetric data within a GIS environment enabled the execution of complex analyses, correlating vegetation indices with soil and climatic factors. By overlaying data layers (orthophotos, NDVI, DTM, soil and irrigation maps), significant relationships were identified between vegetation variability and terrain parameters.

For example, spatial analysis revealed that areas with slopes exceeding 5° exhibited an average NDVI reduction of 12–15%, associated with rapid water runoff and soil erosion. Conversely, low-lying and flat areas showed higher NDVI values, indicating better moisture retention. Thus, GIS proved to be an effective tool for mapping critical zones and prioritizing interventions (Almalki et al., 2022).

Another notable outcome was the automatic identification of parcel boundaries and drought-affected areas using unsupervised classification methods (k-means, ISODATA), achieving an overall accuracy of 88%. These results validate the potential of combining UAV-derived data with GIS analyses to support informed agricultural management decisions.

**Modeling and Interpretation of Data Using an Agricultural Digital Twin**

The agricultural Digital Twin model was developed by integrating UAV and GIS data with information from IoT sensors (soil moisture, air temperature, nitrogen content). This model was used to simulate the impact of different irrigation and fertilization scenarios on vegetation indices and crop productivity.

Simulations conducted over a three-month period demonstrated that implementing a variable-rate irrigation regime, guided by the Digital Twin data, resulted in an approximate 18% reduction in water consumption and an estimated 7–10% increase in crop yield compared to a uniform irrigation scenario.

Furthermore, the integration of climatic data (precipitation, evapotranspiration) enabled the anticipation of water stress events and dynamic adjustment of the irrigation schedule.

These results highlight that the Digital Twin functions not merely as a visualization tool but as a complex analytical system capable of providing real-time decision support and contributing to resource optimization.

**Discussion on the Benefits and Limitations of the Approach**

The results obtained confirm the methodological effectiveness of integrating UAVs, photogrammetry, GIS, and Digital Twin technologies in agriculture. The main benefits identified include:

- Rapid and precise acquisition of geospatial data;
- Continuous crop monitoring at high spatial and temporal resolutions;
- The ability to anticipate yield losses through predictive modeling;
- Reduction of operational costs by optimizing irrigation and fertilization;
- Data-driven decision support based on objective and up-to-date information.

However, practical implementation of these technologies is subject to several limitations:

- High initial costs of UAV platforms and multispectral sensors;
- Complexity of photogrammetric processing and the requirement for advanced technical training;

- Lack of standardized interoperability between platforms;
- Regulatory constraints on UAV flights in certain areas;
- Challenges in managing and storing large volumes of geospatial data.

These considerations suggest that sustainable large-scale implementation requires an integrated approach combining technological support with innovative agricultural policies, digital education, and open data infrastructures.

Overall, the research demonstrates that the integration of UAV, photogrammetry, GIS, and Digital Twin technologies constitutes a unified framework for intelligent agricultural management. The results obtained validate the usefulness of this digital ecosystem both for real-time monitoring and for the modelling and simulation of agricultural processes. Consequently, this confirms the transition from empirically based agriculture to data-driven agriculture, in which every decision is scientifically grounded and quantifiable.

## CONCLUSIONS

The integration of UAV, photogrammetry, GIS, and Digital Twin technologies marks a critical step in the evolution of modern agriculture toward a digital model based on high-resolution geospatial information and scientifically informed decision-making. The results obtained in this study demonstrate that these technologies, applied within a unified workflow, can transform the way agricultural processes are observed, analyzed, and managed.

By using UAV platforms, data can be collected quickly, flexibly, and with high spatial accuracy, providing a detailed view of the actual state of crops and environmental conditions. The photogrammetric processing of these data, performed through Structure from Motion and Multi-View Stereo techniques, generates complex digital products—orthophotos, 3D models, DTM, and DSM—that serve as the foundation for subsequent GIS analyses.

Integrating these data into GIS systems enables spatial and temporal analysis of agricultural lands, identification of risk-prone areas (drought, erosion, disease), and strategic planning of interventions. Furthermore, extending these processes into the concept of an agricultural Digital Twin offers a revolutionary perspective: the ability to create a dynamic, interactive digital replica of the farm, capable of simulating and anticipating future developments of the real system.

The main conclusions of the research can be summarized as follows:

- *Efficiency in monitoring*: Multispectral and thermal UAVs provide a fast and precise tool for monitoring crop health and early detection of vegetation stress.
- *High metric precision*: Digital photogrammetry enables the production of cartographic products with sub-3 cm accuracy, suitable for quantitative analyses.
- *GIS-based decision support*: Integrating data into GIS facilitates complex analysis of agricultural variables and supports both operational and strategic decision-making.
- *Predictive modeling through Digital Twin*: The connection between the real and virtual environment allows for the simulation of irrigation and fertilization scenarios, reducing costs and resource waste.
- *Sustainability and resilience*: The integrated approach contributes to more sustainable agriculture, adaptable to climate change and natural resource constraints.

The results confirm that the integration of these technologies significantly enhances agricultural management and increases farm competitiveness. From a scientific perspective, the study validates the UAV–photogrammetry–GIS–Digital Twin workflow as a coherent methodological framework capable of generating actionable knowledge for precision agriculture.

Moreover, the research emphasizes the need to continue investing in digital agricultural infrastructures, developing interoperable platforms, and training specialists in geospatial analysis. The future of smart agriculture will depend on the ability to integrate these technologies into a unified digital ecosystem focused on sustainability, efficiency, and innovation.

## FUTURE RESEARCH DIRECTIONS

The continuous evolution of digital technologies opens significant opportunities for refining and expanding methodologies based on UAV, photogrammetry, GIS, and Digital Twin in agriculture. The results presented in this study provide a solid starting point; however, the full development of the smart agriculture concept requires a series of complementary research and innovation directions.

### Automation of UAV–GIS Workflows

A key objective for future research is the complete automation of the data acquisition, processing, and analysis workflow. Integrating automated UAV flight planning algorithms, AI-assisted photogrammetric processing, and GIS processes based on scripting (Python, R) will enable the rapid and standardized generation of geospatial products. This automation will reduce the time from data collection to decision-making, facilitating the use of these technologies even on small and medium-sized farms.

### Expansion of the Agricultural Digital Twin Concept

Developing agricultural Digital Twins to a higher level of complexity is a major priority. Future models will need to integrate real-time data from a variety of sources—soil IoT sensors, weather networks, nutrient monitoring stations, and high-frequency satellite imagery.

Such dynamic Digital Twins will become predictive tools capable of simulating not only the current state of crops but also their future developments depending on climatic conditions, technological interventions, or environmental changes. In this context, machine learning and artificial intelligence (AI) algorithms will play a central role in the continuous calibration and updating of the models.

### Data Interoperability and Standardization

Another priority research area is the development of open standards and common interoperability protocols among UAV platforms, photogrammetry software, GIS databases, and Digital Twin infrastructures.

Adopting standards such as ISO 19115 (geospatial metadata), OGC (Open Geospatial Consortium), and the FAIR Data Principles (Findable, Accessible, Interoperable, Reusable) will enable the efficient exchange of information among farmers, researchers, and authorities, supporting the development of collaborative digital agricultural ecosystems.

### Integration of Artificial Intelligence and Big Data Analytics

As geospatial data volumes grow exponentially, applying AI algorithms for automatic anomaly detection, crop classification, and yield prediction becomes increasingly necessary.

Big data platforms can provide the infrastructure needed to store, process, and visualize in real-time data collected from thousands of sensors and UAV flights, offering an integrated view of agricultural conditions at regional or national scales. Simultaneously, the development of AI-based predictive models will support proactive decision-making for agricultural risk management and climate adaptation.

### Educational Dimension and Technology Transfer

Efficient adoption of these technologies requires strengthening digital skills among agricultural specialists. Future training programs should include modules dedicated to UAV operation, photogrammetric processing, GIS analysis, and Digital Twin management. At the same time, partnerships between universities, research institutes, and agricultural companies can accelerate the transfer of knowledge and technologies to the economic sector, contributing to increased competitiveness and modernization of agriculture.

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