

# SolarFertigation: A Unified Cloud Platform for Smart Fertigation and Agrivoltaic System Integration

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**Abstract.** SolarFertigation is an intelligent fertigation system powered by solar energy. It enables precise, adaptive management of fertigation processes based on real-time environmental, agronomic, and operational data [1,2]. Developed to support sustainable and innovative agriculture, the system is also designed for effective integration within agrivoltaic contexts. Flexibility is ensured by the platform's capacity to seamlessly incorporate smart farming sensors and machines, both physically (hardware) and digitally, through a modular and scalable software architecture. The new cloud-based architecture introduces advanced automation models that adjust fertigation schedules dynamically according to crop phenology, weather conditions, soil characteristics, topography, and machine status [3]. The system tracks detailed metrics such as nutrient composition and dosage (g), distributed water volumes (L), crop stages, and field operations across multiple levels (field, zone, crop). These data not only improve fertigation efficiency but also support compliance with the Italian Guidelines for Agrivoltaic Systems (MASE), including metrics such as LAOR – Land Area Occupation Ratio, limited to 40% photovoltaic coverage [4]. These national directives could serve as a foundation for international standards, aligning with the recommendations of the International Energy Agency (IEA PVPS Task 13) [5]. In this framework, SolarFertigation acts as a strategic enabling technology, making these principles operational and scalable. Additionally, the cloud architecture supports future integration of photovoltaic production monitoring, including energy yield, inverter health, and solar panel orientation [6]. Field validation of the system demonstrated its effectiveness in terms of LoRaWAN signal coverage and data transmission reliability, even in the presence of structural obstacles. Moreover, experimental field campaigns revealed a significant reduction in solar radiation and light intensity indices beneath the agrivoltaic modules, with implications on crop performance that will be discussed in the following sections, including a general reduction in yield under photovoltaic panels, which in some cases exceeded 80% compared to open-field conditions. This paper presents the

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system's architecture and outlines future scenarios for intelligent and scalable farm management aligned with ecological transition objectives.

## 1 Introduction

In recent years, there has been a growing convergence between technological innovation, precision agriculture, and renewable energy. This trend is driven by the urgent need to adopt sustainable agricultural practices and to implement an energy transition that aligns with environmental protection. Within this framework, agrivoltaic systems have emerged as a promising solution for the synergistic valorization of agricultural land and energy production, promoting a multifunctional and resilient use of the territory.

However, the integrated management of agricultural activities and photovoltaic energy generation introduces complex challenges, both agronomic and technical. To ensure that these systems deliver real benefits, it is essential to guarantee the continuity of cultivation, maintain optimal environmental conditions for crops, and promote the efficient use of water and fertilizers [7], while also monitoring and mitigating the impact of solar panels on microclimate and productivity. It is therefore crucial to have technological tools capable of integrated monitoring, control, and optimization of operations.

A concrete response to these challenges is provided by SolarFertigation, a smart fertigation system powered by solar energy. It is designed to integrate agricultural equipment, sensor networks, and a centralized, scalable software platform. SolarFertigation enables the automated planning and monitoring of irrigation and nutrient delivery, dynamically adapting to environmental and agronomic conditions [1].

This contribution presents the system architecture, with a focus on its data collection capabilities, intelligent automation, and interoperability with regulatory requirements specific to advanced agrivoltaic systems. The potential of the cloud-based platform will also be explored, along with its configurable automation models and adaptability to various regulatory scenarios, with particular attention to the Italian Guidelines and the broader goal of establishing an international standard.

## 2 System Architecture of SolarFertigation

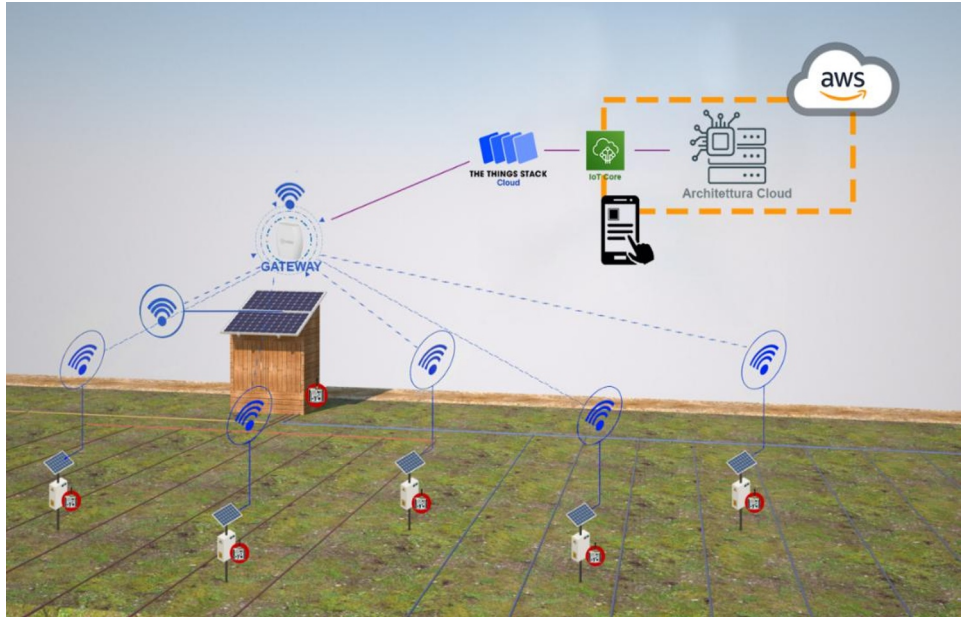
SolarFertigation is designed as a modular and scalable system, capable of integrating distributed field devices with a centralized Amazon Web Services [8] cloud-based management platform. The SolarFertigation system employs LoRaWAN communication [9] between distributed sensor nodes and the central unit, which is responsible for the automated management of fertigation. Both devices are based on microcontrollers with integrated sub-GHz LoRa transceivers. The sensor nodes are deployed in open-field conditions, while the central unit and the gateway are housed inside a wooden shelter, as illustrated in the system's architectural diagram (Figure 1). Two gateway configurations were tested for the LoRaWAN connection:

- a low-power indoor unit with integrated antenna, suitable for cost-effective scenarios.
- a high-performance unit with external antenna and enhanced receiver sensitivity, intended for large-scale deployments.

Based on standard LoRaWAN parameters (868 MHz frequency, 14 dBm transmission power, spreading factor SF7–SF12), field tests demonstrated reliable coverage ranging from 600 to 1500 meters, depending on environmental conditions and gateway configuration.

Under optimal line-of-sight conditions, the system achieved a 98% transmission success rate over distances exceeding 1 km.

The results were obtained through dedicated field measurement campaigns, by analyzing the packets received by the gateway and monitoring the radio link quality between the sensor nodes and the central unit in various operational scenarios.



**Fig. 1.** SolarFertigation general hardware and cloud architecture.

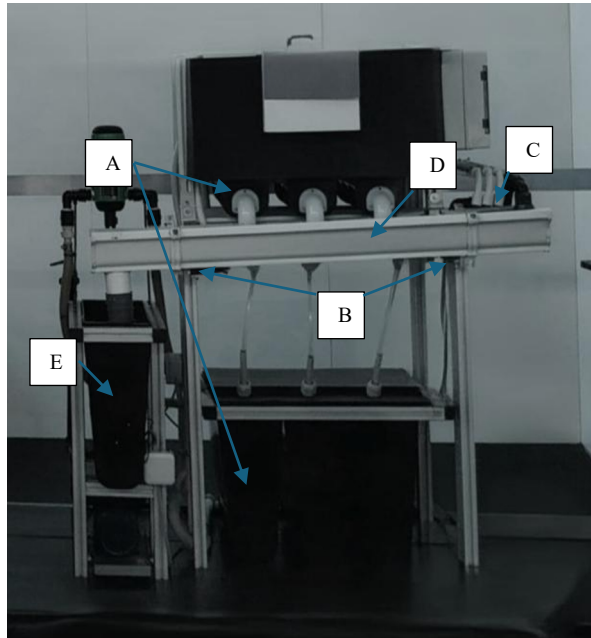
## 2.1 Sensor Nodes: Distributed and Unified Network

The sensor nodes monitor agro-environmental conditions in real time. Installed in various zones of the field, they form a mesh network adaptable to the farm layout or application type. Each node [1] can be equipped with sensors for:

- soil moisture and temperature,
- air temperature and humidity,
- electrical conductivity (EC),
- pH,
- solar radiation,
- wind,
- precipitation,
- nutrient levels in soil and solution.

Each node uses the same microcontroller as the central units, ensuring maintenance simplicity, expandability, and uniformity across the network. The data transmission interval is customizable via web app. The data are sent to the gateway, which routes them to the cloud platform for storage, visualization, and analysis.

## 2.2 Control Unit: Dosing, Mixing, and Monitoring



**Fig. 2.** Front view of the SolarFertigation dosing system unit in a modular configuration, with an aluminum profile structure. Top: drawers for solid (granular or powdered) fertilizers; bottom: liquid fertilizer modules with electronic control. Left: suction module, mixing tank, and mixing pump. The modularity allows management of up to 6 different fertilizers per event, ensuring flexibility and precision in nutrient delivery.

The control unit is the operational core of the system [1], responsible for preparing and distributing fertigation solutions. Each unit is equipped with a dosing and mixing system as illustrated in Figure 1, including:

- drawers for solid (granular/powdered) and liquid fertilizers [Fig.2 A],
- independent motors and peristaltic pumps for dosing,
- load cells ( $\pm 50\text{g}$  precision) for direct weight measurement [Fig.2 B],
- controlled release vessel for liquid fertilizers (2L capacity) [Fig.2 C],
- collection gutter [Fig.2 D],
- washing and mixing system [Fig.2 E].

The dosing process unfolds in two stages:

1. Controlled dosage of fertilizer, measured via load cells;
2. Transfer to the mixing tank using dedicated water jets, ensuring complete gutter flushing and homogeneous mixing.

This setup enables not only accurate monitoring of the applied quantities but also automatic diagnosis of errors (e.g., empty containers or failed release), through integrated alarm logic.

Traditional fertigation systems rely primarily on low-cost volumetric dosing, often using Venturi injectors or manual control, as outlined in FAO guidelines for small-scale farmers [10]. Most automated fertigation systems rely on volumetric dosing using Venturi injectors or proportional pumps, with preset configurations and limited monitoring [11,12]. In contrast,

SolarFertigation introduces a weight-based dosing system driven by cloud logic, overcoming the limitations of manual or semi-automated setups.

### **2.3 Cloud-Based Automatic Nutrient Optimization**

A distinctive feature of the SolarFertigation system is the ability for users to configure fertigation events directly through a web app by defining the target nutritional composition (e.g., N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O, CaO, MgO), independently of the type or brand of fertilizers loaded into the control unit drawers.

The generation of the optimal mixture is performed by a mixed-integer linear programming (MILP) algorithm running in the cloud, which calculates the quantities of each available fertilizer based on:

- the declared chemical composition of each product,
- the remaining availability in each drawer,
- solubility and chemical compatibility,
- and the maximum dosage allowed per fertigation event.

Users can replace the fertilizers in the drawers without needing to recalculate doses: the system automatically recalculates the new optimal combination while maintaining the desired nutritional profile. This approach standardizes nutrient management logic independently of commercial products, simplifying operations and improving interoperability.

An additional advantage is the system's ability to store the actual distribution data in terms of active nutrients (e.g., grams of N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O per zone and event). This allows for direct correlation with agronomic and environmental variables such as crop type, phenological stage, location, and season building a structured data foundation that supports historical analysis and agronomic calibration, reporting and traceability and the development of predictive, data-driven models.

From a system perspective, this abstraction process feeds into an agricultural data lake, aggregating environmental, operational, and decision-making data. This enables the use of data analytics and machine learning techniques to optimize fertigation plans over time and generate increasingly accurate and context-aware automated events.

In existing systems, fertigation strategies are often limited to threshold-based adjustments of EC or pH [13], without dynamic optimization logic. SolarFertigation stands out for its ability to enable cognitive automation [14] through the native integration of hardware, data, and intelligent algorithms.

## 2.4 Hydraulic and Energy Configurations of the Central Units



**Fig. 3.** Front view of the central unit in standalone configuration with integrated pump. Top: logic panel with microcontroller, power supply, and relay system. Bottom: hydraulic manifold with zone solenoid valves, pressure gauges, and impulse water meter.

The SolarFertigation central unit is engineered to adapt to different operational configurations based on field size, water availability, and energy supply strategy. Structurally, each central unit can be customized with:

- up to 10 fertilizer drawers (solid or liquid),
- up to 10 irrigation zones managed through independent solenoid valves.

A real-world implementation of the logic and hydraulic section of a central unit with an integrated pump and a 4-zone manifold is shown in Figure 3.

Two main hydraulic-energy architectures are currently supported, enabling scalable deployment of the platform across agricultural A and B scenarios.

### 2.4.1 A. Standalone Configuration with Integrated Pump

In this configuration, the central unit includes an internal distribution pump powered directly by its own photovoltaic system. The locally stored solar energy can support:

- 4–5 hours of daily autonomous operation,
- coverage of plots up to approximately 2000 m<sup>2</sup>,
- fully off-grid use, ideal for remote locations or fields without pre-existing infrastructure.

This setup maximizes the system’s “smart & solar” concept, offering an autonomous and ecologically sustainable fertigation model, particularly suited for small to medium-sized farms.

### 2.4.2 B. Configuration on Pressurized External Line

In this scenario, the central unit is installed on a pre-pressurized irrigation line maintained by an external system (well, tank, or public network). Locally generated solar energy is then used exclusively for powering solenoid valves and control logic, significantly reducing the unit's energy requirements.

This configuration allows:

- greater energy availability (up to continuous operation),
- parallel deployment of multiple central units along the same mainline,
- effective adaptation to large-scale installations or farms with existing water infrastructure.

Although the pressure system's power supply is not inherently renewable, this limitation can be overcome in agrivoltaic contexts through on-farm photovoltaic integration.

## 3 Automation Models for Fertigation

The **SolarFertigation** system is designed to offer users a wide range of automation strategies, scalable according to the technological level of the farm and the degree of digitalization of the field. All automation logic is managed through the cloud platform and is powered by the data collected from sensor nodes and central units.

### 3.1 Guided Manual Programming

In the basic mode, users can configure fertigation events by specifying:

- the target crop,
- desired nutritional composition (e.g., N-P-K),
- irrigation zone,
- schedule and duration,
- maximum volume or concentration thresholds.

This approach, widely used in **precision irrigation systems** [15], enables gradual digital adoption even in low-tech contexts, while maintaining full user control over the fertigation plan.

### 3.2 Conditional Automation: Environmental Thresholds and Logical Rules

The second level of automation is based on customizable *if-then* rules, which can trigger, modify, or cancel fertigation events based on environmental thresholds or operational conditions. Example rules include:

- "Irrigate only if soil moisture < 20%" (to avoid overwatering),
- "Suspend irrigation if rainfall forecast > 5 mm in the next 12 hours",
- "Block fertigation if EC > 3.5 mS/cm or pH < 5.8",
- "Irrigate only between 07:00 and 11:00 if wind speed < 3 m/s",
- "Cancel pre-irrigation if soil moisture > 15%".

These logic-driven strategies, widely applied in smart farming contexts [14], are executed in real-time via the cloud, using live data from the field.

### 3.3 Agronomic Automation: Phenological Logic and Crop Calendar

A more advanced level of automation leverages **agronomic logic**, enabling fertigation plans based on:

- the phenological stage (e.g., germination, growth, flowering, fruiting),
- the season (e.g., reduced irrigation at the end of the cycle),
- the crop  $\times$  zone combination stored in the cloud.

For instance, a lettuce crop in zone 3 can follow a predefined plan of 7 fertigation events during vegetative growth and reduced dosages during flowering.

### 3.4 Predictive Automation and Artificial Intelligence

Thanks to its modular structure and continuous data collection, SolarFertigation is prepared for the integration of advanced predictive models, including:

- regression models to estimate water and nutrient demand,
- recurrent neural networks (RNNs) to forecast future events based on historical data (e.g., daily zone consumption),
- expert systems combining fuzzy logic and conditional rules to emulate agronomist decision-making.

Recent studies show that AI-based fertigation can increase crop yields and reduce fertilizer use [15]. The platform is designed to leverage such models using its internal data lake, which aggregates structured information by crop, zone, season, and environmental conditions.

This evolution toward a cognitive platform enables a shift from a prescriptive to a predictive approach, where fertigation events are automatically generated and dynamically adapted to real field conditions.

## 4 Integration with Agrivoltaic Systems

The SolarFertigation system is designed for synergistic use with agrivoltaic systems, which combine agricultural production with photovoltaic energy generation on the same cultivated land. The aim is to support the ecological transition through a multifunctional and optimized use of available agricultural surfaces.



**Fig. 4** Rendering of the integrated APV with SolarFertigation system.



**Fig. 5** Experimental campaign in an agrivoltaic field (Province of Taranto, Italy).

Figure 4 presents a 3D rendering of the integration between the agrivoltaic installation and the SolarFertigation system. This integration was validated through an experimental field campaign conducted at a commercial photovoltaic plant adapted to an agrivoltaic configuration in the Province of Taranto (Italy) (Fig.5), where the complete system architecture was implemented, including a central fertigation unit and a network of four sensor nodes.

#### 4.1 Experimental Method and Field Layout

The field trials included two crop cycles—winter (lettuce) and summer-autumn (pepper and chili pepper)—under three cultivation conditions:

1. Open-field cultivation (control);
2. Cultivation in the area directly beneath the photovoltaic panels (proximal zone);
3. Cultivation in the inter-row zone, partially shaded between PV strings (distal zone).

Data were collected using the SolarFertigation sensor network and in-field agronomic measurements. The system managed in real time the recording, transmission, and cloud storage of the following parameters:

- solar radiation,
- air temperature and relative humidity,
- wind conditions,
- volume of distributed water (in liters),
- quantity and type of fertilizers applied (in grams),
- fertigation events (geo-referenced per crop and zone).

#### 4.2 Collected Data and Results

During the summer and autumn cycles, the system recorded:

- a 45–50% reduction in solar radiation under the photovoltaic modules compared to the open field (e.g., from 20 to 10 n for pepper);

- over 60 automatic fertigation events monitored and recorded, with adaptive adjustment of water volumes based on real-time temperature and humidity;
- application of simple liquid fertilizers (e.g., calcium nitrate, monopotassium phosphate), dosed precisely through proportional pumps, and managed by the system based on crop calendars and phenology;
- an average distribution of 900 liters of water per fertigation or irrigation cycle, with adaptive variations in response to local microclimate.

Preliminary agronomic results show a general reduction in crop yield in plots cultivated under photovoltaic panels. The extent of reduction varied from 30% to 87% according to the position within the system (proximal or distal zone) and the type of crop.

It is important to note that the field test was not designed to manage different zones independently. Water and fertilizers were applied uniformly across all plots, regardless of local microclimate. This methodological choice allowed for the isolation and quantification of the direct effect of shading from photovoltaic structures on crop yield, without introducing management-related variables.

The environmental and agronomic data collected via SolarFertigation proved essential to identifying critical areas and sensitive environmental parameters (e.g., radiation, humidity, temperature thresholds) most affecting productivity. These insights now form the basis for developing targeted strategies to:

- adapt irrigation and fertilization management by crop zone,
- optimize the interaction between shading and plant development,
- improve overall productivity in agrivoltaic systems.

### 4.3 Compliance and Interoperability

SolarFertigation is compliant by design with the Italian Guidelines for Agrivoltaic Systems issued by the Ministry for the Environment and Energy Security (MASE) [4,10], which require:

- traceability of agricultural operations and water/fertilizer volumes,
- adaptability of systems to coverage constraints (e.g., LAOR  $\leq$  40%),
- and continuous monitoring of agronomic parameters.

Thanks to its modular, cloud-based architecture, SolarFertigation enables:

- detailed recording of activities per crop and zone,
- extraction of standardized reports for regulatory audits,
- direct integration with photovoltaic systems, thanks to off-grid operation capabilities and optimized self-consumption.

Recent developments in agrivoltaic technology focus on dynamic panel orientation systems ("dynamic agrivoltaics"), which adjust the tilt angle of the solar panels based on crop and weather conditions to optimize both agricultural and energy productivity. These solutions, already tested at industrial scale, can: reduce water and thermal stress on crops, increase sunlight use efficiency (Light Productivity Factor) and enhance energy-agriculture balance during critical periods.

SolarFertigation is ready to interface with such dynamic systems, offering: real-time cloud-based access to environmental and agronomic models, synchronization of fertigation events with shading strategies, and potential integration with inverter and solar tracker controllers.

This unified architecture enables synergistic agro-energy management, where agricultural and energy data can be co-optimized within a single digital platform.

## 5 Conclusions

SolarFertigation was not developed as a closed system, but as an open and adaptive platform that integrates agricultural hardware, distributed sensors, cloud architectures, and decision-making logic aimed at sustainability. Throughout its development, the project has followed a clear direction: transforming fertigation from a technical process into a strategic tool—not only to improve the nutritional efficiency of crops, but also to make every cultivated hectare a digital, sensitive, and responsive space.

The adopted approach (from nutrient mix optimization to integrated energy management) demonstrates that it is possible to design systems that are compliance-ready, modular, scalable, and above all agronomically focused. Systems that communicate with the field, with water resources, with the sun, and with data.

Looking ahead, the real challenge is no longer just to monitor, but to anticipate. Not merely to irrigate, but to know when not to. Not only to adapt the system to the field, but to let the field express itself through data. In this context, SolarFertigation positions itself as an enabling technology for agriculture that is not only more precise, but also more intelligent, more ecological, and more autonomous. Not just a system, but a bridge between land and cloud, between energy and cultivation, between knowledge and automation.

## 6 Originality and Contribution Statement

This paper presents the original development and implementation of *SolarFertigation*, a cloud-based platform for intelligent fertigation management in agrivoltaic systems. The work is original, has not been previously published, and proposes a scalable and adaptable approach for integrating regulatory criteria (such as the LAOR metric) into advanced agricultural systems, positioning the platform as a compliant-by-design technology.

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