

IEEE Recommended Practice for Data Expression, Exchange, and Processing in Smart Agriculture

IEEE Industrial Electronics Society

Developed by the
Industrial Electronics Society Standards Committee

IEEE Std 2992™-2025

IEEE Recommended Practice for Data Expression, Exchange, and Processing in Smart Agriculture

Developed by the

Industrial Electronics Society Standards Committee
of the
IEEE Industrial Electronics Society

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IEEE SA Standards Board

Abstract: Recommended practices for data design in smart agriculture are established in this document. It emphasizes standardized methods for data formats, tags, naming conventions, and transfer protocols to enable interoperability, scalability, and efficient data exchange between heterogeneous systems. These practices are pivotal for integrating advanced technologies such as IoT, AI, and robotics into agricultural operations. This recommended practice provides for coexistence and interoperability through common data structures and transfers between heterogeneous systems; various systems from different manufacturers work together to efficiently and effectively meet farmers' requirements, as in a smart agriculture system.

Keywords: data encapsulation, data interoperability, hierarchical data structures, IEEE 2992™, smart agriculture, tagging conventions

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Introduction

This introduction is not part of IEEE Std 2992-2025, IEEE Recommended Practice for Data Expression, Exchange, and Processing in Smart Agriculture.

This document provides a recommended practice for data expression, exchange, and processing in the domain of smart agriculture. The goal is to address the challenges of data integration, interoperability, and standardization in a sector increasingly reliant on advanced technologies such as IoT, robotics, and AI.

Smart agriculture systems often consist of heterogeneous components from various manufacturers, creating barriers to seamless data exchange and management. This standard introduces a unified framework for handling agricultural data, including hierarchical tagging systems, standardized naming conventions, and flexible protocols for data transmission. These elements help ensure that systems can coexist and interoperate effectively while maintaining scalability and reliability.

The document also emphasizes practical application scenarios, detailing how JSON-based data representation and hierarchical structures can improve data handling efficiency and reduce complexity. By fostering compatibility between proprietary systems and standardized practices, IEEE Std 2992 aims to enable robust data-driven decision-making, enhanced sustainability, and increased agricultural productivity.

The standard is a cornerstone for the digital transformation (DX) of agriculture, providing the foundation for future advancements in precision farming, market-responsive crop management, and environmentally optimized cultivation practices.

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IEEE Recommended Practice for Data Expression, Exchange, and Processing in Smart Agriculture

1. Overview

1.1 Scope

This standard defines recommended practices for designing smart agriculture data, focusing on data formats, tags, naming rules, and data transfers to demonstrate unified practices for data expression, exchange, and processing. This is indispensable for smart agriculture systems, including data acquisition, data management, data service provisioning, data processing, data security, and privacy, from the perspectives of agricultural machinery control, greenhouse management, crop and harvesting management, supply chain management, and farming management. This recommended practice provides for coexistence and interoperability through common data structures and transfers between heterogeneous systems; various systems from different manufacturers work together to efficiently and effectively meet farmers' requirements, as in a smart agriculture system.

1.2 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Normative references

This recommended practice does not contain normative references. For information on sources referred to in this document, see the bibliography in Annex A.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

This document does not contain any definitions. The *IEEE Standards Dictionary Online* should be consulted for necessary terms.⁸

3.2 Acronyms and abbreviations

AI	artificial intelligence
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
CoAP	Constrained Application Protocol
CRC	Cyclic Redundancy Check
C-OP	Comma-Separated Values Operation
CPS	cyber-physical systems
CSV	comma-separated values
D0	Dot 0 (IEEE Std 1451.0 [B1]) ⁹
DBSCAN	density-based spatial clustering of applications with noise
DDS	Data Distribution Service
DID	decentralized identifier
DBMS	database management systems
DTLS	Datagram TLS
DX	digital transformation
ECMA	European Computer Manufacturers Association
EPC	Electronic Product Code
FTP	file transfer protocol
FQDN	Fully Qualified Domain Name
GH	greenhouse
GID	Group Identifier
gzip	GNU zip
HLS	HTTP Live Streaming

⁸*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

⁹Numbers in brackets correspond to the bibliographical references in Annex A.

HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
ID	identification
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
JSON	JavaScript Object Notation
KVS	key-value store
LSB	least significant bit
MAC	Media Access Control
MD5	Message-Digest Algorithm 5
MIME	Multipurpose Internet Mail Extensions
MQTT	Message Queuing Telemetry Transport
MSB	most significant bit
MSG	message
NFS	Network File System
NCAP	Network-capable Application Processor
NIC	Network Interface Controller
NoSQL	No SQL/Not Only SQL
OBJ	Object
OGC	Open Geospatial Consortium
OSI	Open Systems Interconnection
PLY	Polygon File Format
RANSAC	Random Sample Consensus
RDF	Resource Description Framework
REST	Representational State Transfer
RFC	Request for Comments
SCP	secure copy
SCTP	Stream Control Transmission Protocol
SFTP	Secure File Transfer Protocol
SGTIN	Serialized Global Trade Item Number
SN	serial number
SMB	Server Message Block
TEDS	Transducer Electronic Data Sheet
TLS	Transport Layer Security

UID	Unique Identifier/User Identifier
URI	Uniform Resource Identifier
UTF	Unicode Transformation Format
UUID	Universally Unique Identifier
XML	eXtensible Markup Language
XPath	XML Path Language
XQuery	XML Query Language
XSD	XML Schema Definition
YAML	YAML Ain't a Markup Language

4. Framework design

4.1 Background

Smart agriculture has become popular and is indispensable for the current energy and cost-efficient farming industry. Around the world, there is a notable acceleration in the trend toward agricultural efficiency and the modernization needed to achieve it. This movement is driven by the urgent need to increase productivity, enhance sustainability, and help establish global food security.

Smart agriculture has been recognized as a pivotal technology in addressing these pressing challenges within the agricultural sector. It encompasses the application of cutting-edge technologies, including robotics, artificial intelligence (AI), and the Internet of Things (IoT), to enhance farming practices. A variety of innovative systems and services have been introduced, including remote monitoring systems and disease detection systems, both of which leverage IoT and AI to enhance functionality. These technological advancements are poised to mitigate labor shortages while simultaneously ensuring consistent quality across agricultural products.

However, the integration of agricultural machinery and the harmonization of various data types across different manufacturers remain underdeveloped, thus inhibiting the full potential of smart agriculture. In response, the agricultural industry is endeavoring to standardize data exchange interfaces to facilitate seamless interoperability.

In considering the future of smart agriculture, its importance will expand further. Information infrastructure and the data services it handles are shifting from centralized processing to a distributed system across multiple layers, including cloud, fog, edge, and IoT. As illustrated in Figure 1, the network hierarchy features clear differences in data size, processing latency, communication delays, the amount of computational and storage resources, and the level of data anonymity required. Leveraging these differences enables the provisioning of data services optimally suited to each specific context.

Target Area	Narrow	Building <100m	Town <10km	City <100km	Worldwide	Wide
Allowable Processing Delay	Short	Power System Stabilization Auto drive Collision Avoidance <10ms		Facility Control <1s Dynamic Pricing <30min		Long
Calculation Cost Computing Platform	Small	Embedded Microcontroller		Server	Cluster Datacenter	Big
Anonymity	Weak	Plain	Weak Anonymization Strong Anonymization			Strong
Amount of Data	Small	<KB	<MB	>GB		Big

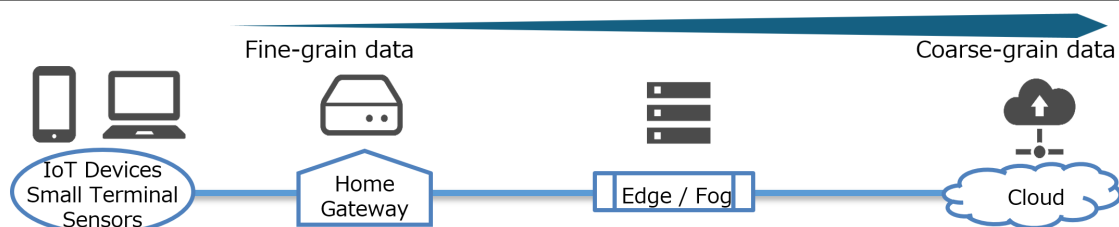


Figure 1—Characteristics of data services in each layer of the Internet hierarchy

In smart agriculture, as shown in Figure 2, various data services are envisioned. Based on this hierarchical structure, the appropriate locations for service delivery are determined. Under such circumstances, streamlining data transfer between layers becomes crucial. While diverse data representations are essential to meet the unique needs of each service, the importance of sharing these representations uniformly across layers, and even among different services, will grow further in the future. A standardized method for data representation and a mechanism capable of packaging and encapsulating data in any format will become increasingly necessary.

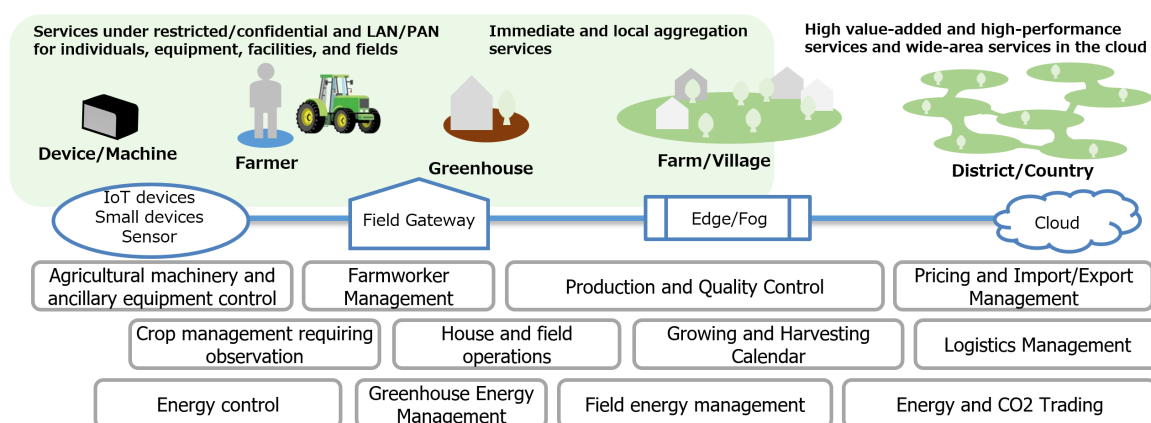


Figure 2—Deployment of smart agriculture data services focusing on the Internet hierarchy

The standard will provide recommendations for the design of smart agricultural data. It emphasizes data formats, tags, naming conventions, and data transfer protocols, aiming to facilitate coexistence and interoperability by employing a unified data structure and transfer methodology across diverse systems.

This standard not only provides best practices for designing the common data infrastructure for smart agriculture to provide the coexistence of multiple agricultural data system domains, but also provides recommendations for the design of smart agricultural data.

4.2 Requirements and corresponding measures for Smart Agriculture framework

In developing a Smart Agriculture framework, the requirements from an information systems perspective encourage unified data expression, exchange, and processing practices. This includes specifying standard data formats, tagging conventions, naming rules, and data transfer protocols. These requirements are critical for the interoperability, scalability, and integration of various systems and devices in smart agriculture. Below is an overview of these requirements. By adhering to these requirements, the framework ensures seamless integration, interoperability, and scalability of smart agriculture solutions, fostering data-driven decision-making and enhancing agricultural productivity. The requirements and their corresponding measures in this standard are described.

4.2.1 Data format

A standardized data format is crucial to help ensure seamless data integration and exchange across various systems and devices used in smart agriculture. The data format should include the following requirements.

4.2.1.1 Interoperable data formats

Requirements: It should use widely accepted, interoperable formats such as JavaScript Object Notation (JSON), XML eXtensible Markup Language (XML), or comma-separated values (CSV) to represent different types of agricultural data (e.g., soil moisture, temperature, crop health). YAML Ain't a Markup Language (YAML) and other widely-used formats are also considerable, which might not have specific Schemers.¹⁰

Measures: Sensor data should be managed using hierarchical identifiers (e.g., Location/Endpoint) for efficient search and access.

4.2.1.2 Schema definition

Requirements: Data formats may come with schema definitions to provide a clear structure for data representation. This ensures that data from different sources can be consistently validated and interpreted.

Measures: Schema is strongly connected to the service design. Since this standard is meant to be used in any kind of service, it does not provide schema but defines recommended tag names. This feature enables broadening the applicable services.

4.2.1.3 Data compression and encoding

Requirements: It should support data compression (e.g., gzip) and efficient encoding (e.g., Base64 for binary data) to optimize storage and transmission, particularly in bandwidth-constrained environments.

Measures: This standard provides a data compression method using the alias function. Moreover, additional encoding is applicable and will not interfere with this standard.

¹⁰ This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.

4.2.1.4 Hierarchical structuring

Requirements: Hierarchical structure allows structuring to capture complex relationships between different data elements (e.g., farm → field → crop → sensor data as a location hierarchy).

Measures: In addition to the hierarchical structure of the original coding, the IEEE 2992-based tag name also provides a clear hierarchy according to the framework design (Figure 3).

4.2.2 Tagging conventions

Tagging provides metadata that facilitates the organizing, searching, and processing of agricultural data. Effective tagging conventions are essential for the smart agriculture framework, and the following points should be considered.

4.2.2.1 Semantic tags

Requirements: To describe agricultural entities, processes, and data, standardized semantic tags based on well-known ontologies, such as AgroVoc or the Open Geospatial Consortium (OGC) standards, should be used.

Measures: This standard does not define any agricultural entities, processes, or data. Any kind of data format and ontology expressions can be applied to this standard. Hence, this standard defines the communication among heterogeneous systems. Therefore, this standard can be used either to precisely determine the structure of data or as a framework to encapsulate existing data. In both cases, the tag names are used to describe what is embedded.

4.2.2.2 Tag granularity

Requirements: Tags should be sufficiently granular to capture specific details (e.g., “soil_moisture_sensor” vs. “sensor”) but not overly specific to avoid redundancy and excessive complexity. The granularity depends on the applications.

Measures: The granularity can be designed by users. However, the top hierarchy of the domain was defined in this standard, as shown in Figure 3. As for the example, soil_moisture_sensor as an end-device name is permissive; however, it is recommended that elements like soil be declared as a “Location” and described as a temperature sensor as the end device. In this standard, the domain is specified at the top-level hierarchy, which helps ensure that information related to field environment sensing can be identified at a minimum. The domains follow the classification of representative applications and are designed such that the necessary domain can be identified for service construction and the information within that domain is sufficient.

4.2.2.3 Consistency and reusability

Requirements: Establish a set of predefined tags that are consistently used across different datasets and applications to encourage reusability and interoperability.

Measures: To enhance reusability, this standard prescribes unified methods for representing tags and structures. On the other hand, considering interoperability, flexibility is needed due to the existence of various representation methods. In this standard, the top-level domain, such as F1, is defined, and as long as uniqueness is ensured in the lower hierarchy, relatively flexible specifications can be set. Therefore, even if different predefined tags exist, they can be encapsulated to generate new tags that comply with this standard.

4.2.2.4 Contextual information

Requirements: Include contextual tags that describe the environment (e.g., weather conditions, geographic Location) and operational parameters (e.g., sensor type, data acquisition time) for better data interpretation and analysis.

Measures: These also allow for inclusion. Furthermore, specifying the domain provides a classification that indicates what type of service it should be used for, as shown in Figure 3.

4.2.3 Naming rules

Consistent naming rules are essential to help prevent confusion and ensure clarity when data is shared across various stakeholders in a smart agriculture ecosystem. The naming rules should include the features described in 4.2.3.1 through 4.2.3.4.

4.2.3.1 Descriptive naming

Requirements: Names should be descriptive and self-explanatory, and use standardized abbreviations when necessary (e.g., “temperature_sensor_A” instead of “tempA”).

Measures: In this standard, users are free to assign tag names. Abbreviations for these names can also be used considering the hierarchy (see 5.3). Furthermore, the original names can be associated with their abbreviations using optionally defined aliases (see 5.4).

4.2.3.2 Hierarchical naming structure

Requirements: Adopt a hierarchical naming convention that reflects the physical or logical arrangement of entities (e.g., “farmA_fieldB_sensorC”).

Measures: This standard has a hierarchical naming convention. Additionally, since the hierarchical structure can be represented directly within the tag names, it does not interfere with schemas defined by separate applications.

4.2.3.3 Avoidance of special characters

Requirements: Use only alphanumeric characters and underscores; avoid spaces and special characters to maintain compatibility across different systems.

Measures: This is provided as a recommendation in this standard, as defined in 5.1.1.

4.2.3.4 Version control

Requirements: Include version identifiers in names when necessary to manage different versions of data schemas or formats (e.g., “crop_yield_v2”).

Measures: This is provided as a recommendation in this standard, as defined in 6.7.1.

4.2.4 Data transfer protocols

Data transfer requirements focus on ensuring reliable, secure, and efficient communication between various components in a smart agriculture framework. The protocols should support the items listed in 4.2.4.1 through 4.2.4.5.

4.2.4.1 Standard communication protocols

Requirements: Use standard communication protocols such as the Message Queuing Telemetry Transport (MQTT) OASIS standard [B15], Constrained Application Protocol (CoAP), Hypertext Transfer Protocol Secure (HTTP/HTTPS), and Advanced Message Queuing Protocol (AMQP) for reliable and lightweight data transmission.

Measures: This standard does not define or restrict a single data exchange protocol. All protocols mentioned here can be used separately to transmit data.

4.2.4.2 Data integrity and security

Requirements: Help ensure data integrity with checksum mechanisms [e.g., Cyclic Redundancy Check (CRC), Message-Digest Algorithm 5 (MD5)] and data security using encryption standards such as IETF RFC 8446 [B11] or Datagram TLS (DTLS).

Measures: This standard does not preclude the use of various data integrity measures, including checksum mechanisms. Similarly, it does not prevent the use of encryption standards in combination.

4.2.4.3 Real-time and batch processing

Requirements: Support both real-time data transfers (e.g., sensor data streaming) and batch processing (e.g., periodic uploads of aggregated data) to accommodate different agricultural use cases.

Measures: This standard can coexist with various protocols and can be used in both real-time data transfer and periodic transmission of aggregated data. Notably, data described in this standard does not need to be transmitted in a complete form and may be sent in segments. This allows for both fine-grained transmission to enhance real-time capabilities and batch transmission. When transmitting in segments, it is recommended to include a timestamp with each tag name to ensure real-time accuracy and to understand the context of the data.

4.2.4.4 Error handling and data acknowledgment

Requirements: Implement robust error-handling mechanisms and acknowledgment protocols to ensure data delivery and reliability, especially in environments with intermittent connectivity.

Measures: This standard does not specify reliability measures, including robust error handling, allowing for the free combination of necessary methods.

4.2.4.5 Data synchronization

Requirements: Help ensure data synchronization across distributed systems and devices through timestamped data entries and conflict resolution mechanisms.

Measures: The generated data can include timestamps along with user-defined dedicated tags. This standard does not specify the methods to be used for these synchronization mechanisms, allowing users to freely combine them as needed.

4.3 Smart agriculture framework design

The framework diagram (Figure 3) focuses on data flow within smart agriculture. It is designed to define the structure of data as set by this standard, taking into account the presence of various stakeholders. The

goal is to organize these stakeholders and clarify what each piece of information represents. For instance, when presenting temperature information, even if the Location is specified, ambiguity may arise regarding whether the data refers to the leaf temperature of a plant at that Location, the temperature of the sensor device in contact with the leaf, or the ambient air temperature. To eliminate such ambiguity, this standard organizes the smart agriculture-related fields it covers, allowing stakeholders to instantly discern to which domain a piece of data pertains.

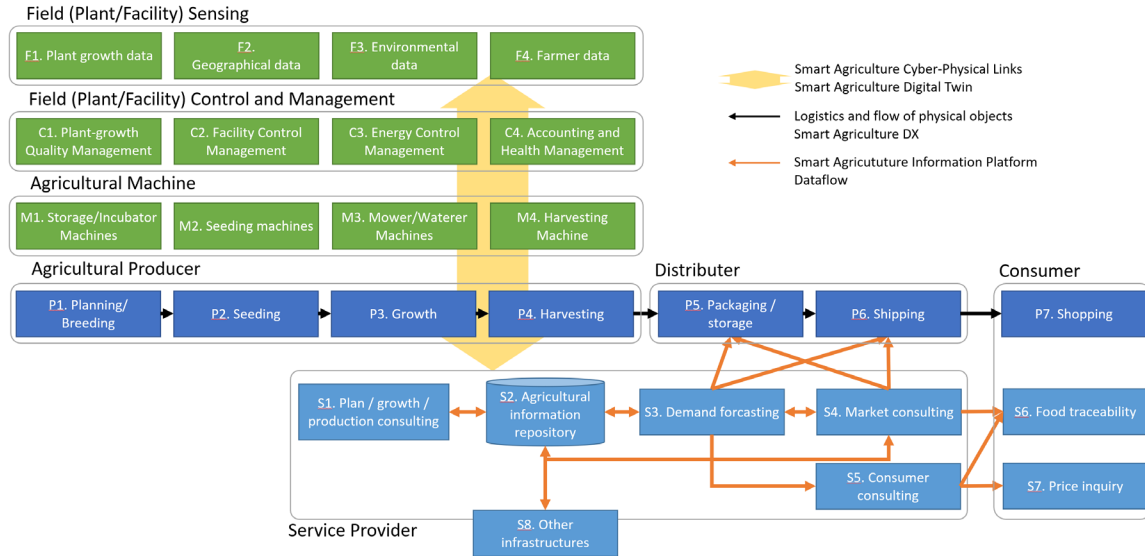


Figure 3—Smart agriculture data framework

The arrows in the diagram indicate data flow and logistics flow, representing the exchange of information. The black arrows represent the “logistics and flow of physical objects (Smart Agriculture DX),” while the orange arrows indicate the “Smart Agriculture Information Platform Dataflow.”

This diagram is designed to provide a comprehensive overview of data flow within the smart agriculture ecosystem by visualizing digital transformation (DX) processes among various stakeholders in smart agriculture and showing the relationship between data flow and physical flow. It categorizes various areas and sub-areas with specific symbols and enables stakeholders to understand the context and significance of the data quickly from the perspective of enhancing clarity, interoperability, and efficiency in agricultural data management. The diagram helps remove ambiguity regarding data meaning and supports data exchange and processing in smart agriculture.

4.3.1 Diagram overview

The diagram is divided into three main areas of *field area*, *product area*, and *service provider area*. Each area is distinguished by different colors for easy identification.

- a) Field area: The field area represents the actual agricultural field and is further divided into the following three sub-areas:
 - 1) Sensing: Focuses on collecting data from various sensors deployed across the field.
 - 2) Control and management: Includes systems that manage and control agricultural operations, such as irrigation, fertilization, and pest control.
 - 3) Agricultural machinery: Refers to equipment such as tractors, drones, and other machinery used for agricultural activities.

- b) Product area: Area representing the flow of agricultural products from production to delivery and to consumers.
- c) Service provider area: Service providers who use the smart agricultural data for providing services to improve instances in field and product area, as well as services in itself.

4.3.2 Key components and use case of the diagram

Figure 3 illustrates the overall flow of smart agriculture. The diagram is also useful for designing cyber-physical systems (CPS) and the digital twin of agricultural fields. The diagram is mainly divided into the following domains and sectors.

Each area and sub-area is marked with different symbols—F, C, M, P, S—to represent finer granularity. Each symbol corresponds to a domain that provides more granular data. For example, F3 (Field Sensing Domain, Environmental Data Sector) domain covers environmental information in the field area, such as the temperature inside a greenhouse.

4.3.3 Details about domains and sectors

- a) Field (Plant/Facility) Sensing: This domain shows the collection of sensing data in fields or facilities. The following types of data are collected here:
 - F1. Plant growth data sector: Information on plant growth (e.g., growth status, health conditions).
 - F2. Geographical data sector: Data related to land and region (e.g., soil type, terrain).
 - F3. Environmental data sector: Environmental information such as weather, temperature, and humidity.
 - F4. Farmer data sector: Information about the activities and management of agricultural workers.
- b) Field (Plant/Facility) Control and Management: This domain involves the management and control of fields or facilities based on the sensing data.
 - C1. Plant-growth Quality Management sector: Systems to monitor and control plant growth and quality.
 - C2. Facility Control Management sector: Operation and management of agricultural facilities (e.g., HVAC).
 - C3. Energy Control Management sector: Management of energy usage.
 - C4. Accounting and Health Management sector: Financial and overall health management of the farm.
- c) Agricultural Machine: This domain covers the use of agricultural machinery, including various automation equipment.
 - M1. Storage/Incubator Machines sector: Machines for storing crops and early-stage cultivation.

- M2. Seeding machines sector: Machines used for sowing seeds.
 - M3. Mower/Waterer Machines sector: Machines for mowing grass and watering plants.
 - M4. Harvesting Machine sector: Machines for harvesting crops.
- d) Agricultural Producer: This domain represents the processes of agricultural producers, with each step reflecting a production stage.
- P1. Planning/Breeding sector: The stage of crop production and breeding. It may include data such as cultivated area and the number of plants.
 - P2. Seeding: The stage of sowing seeds sector. It may include the required number of days and specific dates and times.
 - P3. Growth sector: The stage of crop growth. It may also include the required number of days and specific dates and times.
 - P4. Harvesting sector: The state of crop harvesting. It may include information such as harvesting methods.
- e) Distributor: This domain represents the stages involving distributors, including processes from packaging to shipping crops.
- P5. Packaging/storage sector: The process of packaging and storing crops after harvest. For example, it may include inventory management information.
 - P6. Shipping sector: Shipping crops to consumers or retailers. It may include information such as sales locations and prices.
 - P7. Shopping sector: The stage where consumers purchase the crops. It may include purchase locations and prices.
- f) Service Provider: This domain involves service providers who offer agricultural information and consulting services.
- S1. Plan/growth/production consulting sector: Support for planning and optimizing agricultural production.
 - S2. Agricultural information repository sector: A repository that manages and provides agricultural data.
 - S3. Demand forecasting sector: Forecasting market demand.
 - S4. Market consulting sector: Consulting on market trends.
 - S5. Consumer consulting sector: Providing advice and support to consumers.
 - S6. Food traceability sector: A system to ensure the traceability of food products.
 - S7. Price inquiry sector: Providing information on prices.
 - S8. Other infrastructures sector: Other related infrastructures.