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An interoperable ontology for CPS-enabled Polyhouse Solar Dryer: A case study of the AgroESP project

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ABSTRACT

Polyhouse is a commonly used conventional method for solar drying of food products. These Polyhouse Solar Driers (PSDs) are characterized by their enclosed structure and translucent covering, providing a controlled environment conducive to efficient food drying. Smart polyhouses, equipped with a Cyber-Physical System (CPS), further enhance this process by optimizing environmental conditions and enabling real-time monitoring. In smart PSDs, the data are obtained from diverse sources with different specifications in accuracy, resolution, and range. This multifaceted nature of the information obtained from various sources significantly compounds the complexity of the system. This complexity of data from diverse sources within smart polyhouses necessitates a standardized knowledge representation. Ontologies serve this purpose by establishing a common vocabulary and structure for data integration, promoting semantic interoperability and effective communication among diverse systems. This paper proposes a novel unified ontology designed to model complex polyhouse CPSs, aiming to address semantic interoperability issues and streamline data integration across various domains. The proposed polyhouse ontology attempts to reuse the concepts defined in existing ontologies rather defining new concepts for efficient knowledge sharing and enhanced understanding of polyhouse operations. The practical applicability of the polyhouse ontology has been verified with competency questions and through field deployment in a CPS enabled smart Polyhouse Solar Dryer.

1. Overview

Food preservation and food safety are one of the most important UN Sustainability Development Goals (SDG 2). Food preservation greatly reduces food waste during excess produce, food processing, and post-harvest, thus increasing the shelf-life of the food items. The most common food preservation methods can be categorized into conventional and modern preservation techniques. The modern preservation techniques involve overheads like investment in purchasing equipment, operational cost, and may not be suitable for all types of food items. Because of these reasons most of the developing and underdeveloped countries prefer conventional food drying methods such as open-air *sun drying, smoking,* and *canning* which involves minimal or no setup and operational costs. The conventional sun drying method is one of the most adopted traditional food preservation methods that rely on sunlight and natural airflow. This preservation process removes moisture from food items, preventing the growth of microorganisms and preserving the food for future consumption. Although it is a low-cost and energy-efficient method, there are several issues associated with this technique, such as lack of hygiene and contamination, weather dependency, and seasonal limitations. Polyhouse-based food drying, a modernization of open-air sun drying, is one of the effective methods for food preservation that addresses above mentioned challenges by providing a controlled environment.

A Polyhouse Solar Dryer (PSD), also known as a hoop house, has a frame covered by a translucent polyethylene plastic sheet as shown in Fig. 1. The temperature inside polyhouse will be significantly higher than the outside ambient temperature as it traps the long wave infrared radiation and reduce heat loss through convection and conduction [1]. This results in faster and more efficient drying of the food, reducing the time required for the process. Incorporating a polyhouse in food drying offers several advantages over conventional open-air sun drying, such as faster drying, less weather dependency, and provide extended drying seasons [2]. In addition, the food products can be left in the PSD

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overnight since dryers are waterproof, prevent fuel dependency, reduces the environmental impact and is more efficient and inexpensive [3]. By virtue of these, PSDs become a natural choice for food processing in rural settings, closer to where the harvest is produced, eliminating the need for expensive transportation or storage of fresh produce [4]. Consequently, PSDs are widely used for drying several food products including copra, medicinal plants, vegetables like tomato, capsicum, carrot, greens, fruits, groundnuts, roots, grains, millets, fish, spices-chillies, cloves, and cardamom [5].

Despite PSDs' advantages, there are few critical challenges that need to be addressed for their mass adoption. As PSDs are predominantly manually operated, monitoring and control to achieve efficient drying of food products is by no means an easy task. This leads to inconsistencies in the drying of food items such as over-drying, or under-drying causing food materials to get spoilt. Automating the monitoring and control of PSDs overcomes the mentioned limitations and has huge potential in making PSDs a go-to choice for both farmers and small-scale industries.

A smart polyhouse is an evolved form of a traditional polyhouse, incorporating technologies such as sensors, actuators, and use data analysis techniques to create an optimal and highly controlled environment for food drying. The smart polyhouses are preferred over conventional polyhouses for various reasons, particularly because the temperature inside the polyhouse is noticeably higher, potentially impacting human operations within. Moreover, the smart polyhouse offers precise control of environmental factors, including temperature, humidity, and light intensity. The intelligent algorithms employed within the polyhouse control system utilize these environmental parameters to deliver improved monitoring, provide real-time conditions of the food items being dried, estimate drying time, and offer other insights.

1.1. The polyhouse CPS

Cyber-physical systems (CPS) are intelligent systems that include engineered networks with the ability to interact with physical and computational components (based on algorithms). These systems are highly interconnected and integrated, providing new functions to improve and enhance the quality of life and leading to technological advances in critical areas such as smart manufacturing, produce and consume energy [6,7].

Conventional polyhouses, also known as passive solar polyhouses, offer no control over the drying of the food products as they are entirely driven by the dynamic environmental conditions. The primary objective of deploying CPS in polyhouse is to control and maintain the conditions within a PSD using appropriate sensors and actuators to ensure effective drying of food products.

- Due to high temperatures inside PSDs, it is not recommended for frequent manual inspection. In addition, frequent manual inspection also causes contamination of food products. CPS facilitates remote monitoring of polyhouse environmental conditions, current state of food products, and helps users to take informed decisions on what products are to be dried.
- The monitoring mechanisms in CPS provide real-time alerts to users by analyzing the current drying status of food products. More importantly, the feedback mechanism of CPS helps control the conditions inside polyhouse using actuators to preserve the quality of the products being dried. By introducing man-in-the-loop mechanism of CPS the users can also manually control the conditions inside the polyhouse from remote locations.

Because of the aforesaid reasons the Cyber-Physical System (CPS) stands out as one of the optimal methods for integrating polyhouse components to achieve the desired objectives.

A typical polyhouse CPS integrates the physical system of the polyhouse with computation units and a complex network. The physical system comprises sensors for monitoring environmental parameters such as temperature, humidity, moisture, and airflow as shown in Fig. 2. The edge and end nodes deployed inside the polyhouse serve as computational units. Additionally, it includes actuators that control airflow within the polyhouse to optimize drying conditions. The microcontrollers at the edge and end nodes of the polyhouse represent sensor units, observing environmental conditions and aiding in detecting/enhancing the drying rate of food products. These nodes mostly share similar hardware designs but differ in communication interfaces. The network component of the polyhouse CPS facilitates communication among these edge/end nodes deployed within the polyhouse for distributed, intelligent sensing, and actuation. Furthermore, it enables interaction between nodes in the polyhouse and an external server, specifically to coordinate operations and support federated leaning. These edge/end nodes and the external server of the polyhouse CPS are primarily involved in the data acquisition, aggregation, and processing operations.

1.2. Need for polyhouse ontology

In a smart polyhouse, data from multiple sources and different types of devices need to be integrated and processed together. The data is collected from various sources, such as sensors, communicating devices, computing devices, topological information of polyhouse, and properties of food items. Each of these sources generates different types of data such as time-series, geospatial, and multimedia data, contributing to the overall heterogeneity of the collected information. It is crucial to have a standardized and organized knowledge representation to maximize the potential benefits of polyhouses, such as automatic device registration, federated querying across diverse data sources, effective data aggregation, and a sophisticated querying system.

This demands formal representation of the data that enables the data

Fig. 1. Polyhouse solar dryer.

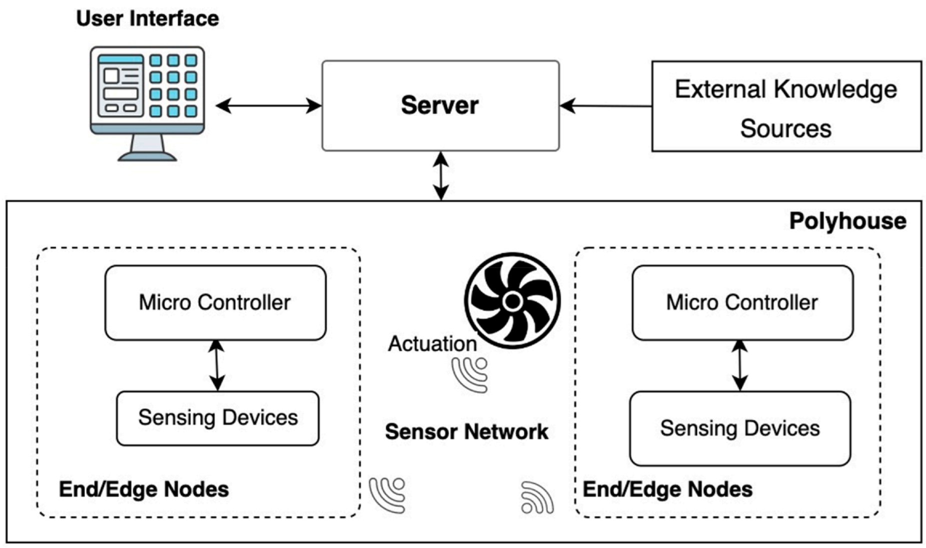

Fig. 2. Smart polyhouse.

to be easily shared, transmitted, and displayed across heterogeneous applications. The main advantage of using formal representation of data is that it provides an unambiguous means of expressing complex concepts. Without the formal representation the data observed from polyhouse, user data, and weather information will be stored in isolated silos with no semantic connections. This is crucial for managing the smart polyhouse, as well as for understanding the trends and patterns in the data.

In the context of modeling complex systems, ontologies play a crucial role in representing domain knowledge. Ontologies enable semantic interoperability between these sources by establishing a standardized vocabulary and structure for data representation. Furthermore, ontologies effectively align data from various sources, including sensor details, control systems, and agricultural practices, facilitating data integration and reducing inconsistencies and redundancies. The importance of ontology becomes more pronounced as the system complexity increases, particularly when multiple CPSs in a polyhouse collaborate to achieve effective drying of food items, such as the coordination between the airflow system and the psychrometric system.

Moreover, this formal representation assists in maintaining the semantic integrity of intrinsic design aspects of the smart polyhouse, such as topological concepts, user-friendly 3D models, sensor node locations, and internal component details. Ultimately, ontology-based representation fosters effective communication and comprehension of domain knowledge among both humans and machines, thereby supporting efficient knowledge sharing.

Based on our understanding, there currently exists no ontology capable of capturing the full complexity and nuances of the various domains involved in polyhouse operations. This underscores the necessity of developing a sophisticated ontology that can accurately represent polyhouse knowledge. The following are the primary contributions of this work.

- This paper proposes a unified ontology that is necessary and sufficient to model the polyhouse CPSs.
- The proposed ontology attempts to reuse the concepts defined in existing ontologies rather defining new concepts.
- Addresses semantic interoperability issues while integrating numerous domain knowledge and sensor observations.

An overview of related work is provided in Section 2. Section 3 details the process constructing polyhouse ontology. The ontology requirement specification and definition of competency questions are detailed in Section 4. Identification of lightweight ontologies from the related domains and ontology design patterns are highlighted in Section 5. Section 6 provides an overview of designing interoperable ontology from the identified LWO and ODPs. Section 7 outlines the real-time implementation of the polyhouse ontology in the AgroESP project. The quality assessment of the polyhouse ontology is highlighted in Section 8. Finally, the discussions and conclusion of the work is presented in Sections 9 and 10 respectively.

2. Related work

Polyhouse Solar Dryers (PSDs) are enclosed structures that facilitate efficient and natural sun drying of food items. However, PSDs are predominantly human operated and hence lack effective monitoring and control mechanisms. Such effective mechanisms can be realized through a Cyber Physical System (CPS) enabled smart PSD that has the potential to provide a controlled environment. PSDs with CPS brings in multiple entities into the system such as food materials, sensing devices, and actuators. Seamless communication and data exchange between these entities, constituting heterogeneous devices, is crucial for effective functioning of a smart PSD. In addition, as each entity generates valuable information, integrating and correlating such information is very essential to leverage the power of CPS. Otherwise, the different entities will remain in isolated silos depriving insightful information about the dynamic environment within PSD. Consequently, introducing new technology or devices into the polyhouse increases the complexity of managing the entire PSD system. This complexity multiplies when the system shares knowledge across multiple polyhouses.

The issues in the effective management and operation of a smart PSD stem from the lack of a formal representation of the polyhouse knowledge. An ontology can be used to formally represent various structural and functional aspects of the PSDs. Significant efforts and resources are required to manually integrate and align various entities in a smart PSD, which could otherwise be automated through a well-defined ontology. Although ontologies proposed in the related domains have been highlighted in the literature, unifying such ontologies and making them interoperable to realize a coherent functional system is a challenge. The primary contribution of this paper is to unify existing ontologies relevant to various aspects of a smart PSD into a coherent, interoperable unified ontology that can address various issues of a smart PSD. As the proposed work employs Smart PSDs and their ontologies as the materials and methods respectively, this section presents the prior art in the literature on both these aspects.

2.1. Smart polyhouse systems

There have not been much research attempts in the literature towards the design and development of *smart* PSDs. The existing approaches primarily focus on the monitoring of different environmental parameters of PSD. Those approaches either employ IoT based solutions or CPS for effective monitoring.

Dagar et al. [8] and Javvaji et al. [9] proposed systems that monitor and control temperature and humidity inside a polyhouse designed for plant growth. CPS-based systems have also been proposed which monitor parameters like soil moisture, rain detection, and carbon dioxide monitoring [10]. The observed parameters are transferred to a remote server for storage, to perform analytics and for end-user monitoring. However, the transferred data is unstructured, lacking the semantic and relational context which is necessary for complex inferencing and interoperability [11,12]. This results in inconsistencies, misinterpretations, and significant integration challenges when combining data from heterogeneous sources. Towards this, standard knowledge representation mechanisms like ontologies are essential to address the mentioned limitations for such IoT and CPS based systems.

2.2. CPS ontologies

Petnga et al. [13] proposed an ontological framework to construct a domain-specific determinant semantic model for CPS. This framework uses a set of semantic models and tools to ensure the developed CPS model is conclusive, provable, and executable. The framework consists of a set of components, each providing a wide range of functionalities, including automatic data acquisition from physical entities, generating knowledge representation of data, and constructing a semantic model. Additionally, the framework provides a method to interface external solvers and lookup tables with the system's rule engine. However, they did not cover any concrete methods to address the issues raised during the reuse of existing ontologies and the handling of conceptual interoperability issues.

Serrano et al. [14] and Agarwal et al. [15] proposed the IoT interoperable ontologies as part of Fiesta-IoT project, which serves as a valuable resource for achieving semantic interoperability among various Internet of Things (IoT) ontologies. This ontology is primarily developed by integrating fundamental concepts from several established ontologies and taxonomies, including DUL, M3-lite, WGS84, Time, IoT-lite, and SSN. By leveraging these existing ontologies, Fiesta-IoT ensures compatibility and semantic alignment with a wide range of IoT-related concepts and entities. The adoption of Fiesta-IoT allows for seamless integration and communication between different IoT systems and applications, providing a common semantic framework for representing and interpreting IoT data and interactions.

Bajaj et al. [16] proposed a method to identify the fundamental requirements needed for an IoT ontology by formulating a set of competency questions. These competency questions were derived by addressing 4W (What, Where, When, Who) and 1H (How) aspects associated with IoT applications. Based on these questions, the authors initially identified state-of-the-art generic ontologies in the IoT domain. Subsequently, each of these ontologies underwent evaluation for accuracy, completeness, and efficiency using the chosen competency questions. The authors concluded by presenting the capabilities and limitations of each ontology. Additionally, they highlighted the necessity for extensible and interoperable features in existing core ontologies, specifically when applied in developing application dependent IoT systems.

Kovalenko et al. [17] have developed a semantic representation of the AutomationML (AML) standard, supporting the integration of heterogeneous data during the design of industrial systems. The AML ontology is crafted to merge and refine concepts, relationships, and data property structures from the ontologies developed by Biffi et al. [18] and Grangel et al. [19]. The AMLO incorporates design decisions, including limited predefined restrictions, developed class hierarchies to capture hierarchical relationships between elements of libraries in AutomationML, the use of sub-property relations to model complex and generic properties applicable across different AML libraries, and alignment of class and property names with terminologies defined in the AML standard. This semantic model was developed with the aim of addressing a key challenge of CPPS systems: facilitating effective collaboration among stakeholders from various engineering disciplines to deliver high-quality end products.

Hildebrandt et al. [20] proposed an ontology construction method for designing highly flexible CPS systems in a modular fashion using the concept of Methodological Building Blocks (MBBs). The method suggests the use of three MBBs, namely Requirements Gathering, Lightweight Ontology Construction (LOW), and Heavyweight Ontology Construction (HWO), which reflect the different phases of the ontology construction stages. As part of this work, the authors have also developed a set of reusable ontology Design Patterns for the industrial environment, specifically in the manufacturing domain.

Lefrancois Maxime [21] proposed a generic ontology pattern SAREF4SYST which primarily defines topology of features of interest. The concepts defined in this ontology facilitates annotation of CPS domain applications. The ontology proposed three major concepts to represent System and subsystems, ConnectionPoint, and Connection. These three concepts respectively model the behaviors of an independent entity and its interaction with environment, connection points uniquely associated with a system or subsystem, and connection between one system with another system through its connection point. As SAREF4SYST is also part of SAREF family of ontology patterns, extending its knowledge representation to domains supported by SAREF such as smart building, smart city, and agrifood will be straightforward with minimal efforts.

Ciolofan et al. [22] developed an ontology based smart farming system designed to predict nitrogen losses in water bodies. The primary objective of this system is to help farmers to adopt innovative and sustainable farm practices based on estimated changes in the nitrogen cycles. In this system the current state of nitrogen is observed from various hydrology, meteorology, and farm management sources. The sensors deployed in these sources generate enormous amount of observed data in a diverse format. Consolidating these data and taking intelligent decision is a cumbersome process. To address this issue the authors have proposed an ontology-based solution that help formally representing of the data observed from various sources. This ontology-based solution facilitates the generation of unified and cleaned data which is further used by the intelligent system to estimate the nitrogen losses. The ontology proposed in this work is constructed primarily by reusing popular ontologies defined in the sensors, measurements, and agricultural domains.

Ovsiannikova et al. [23] proposed a generic Instrumentation and Control (I&C) architecture for designing safety critical CPS systems. These systems are modeled using ontology by defining their physical and functional layers with varying complex requirements. These requirements are further realized in the form of Functional Block Diagrams (FDBs) which define the design principles and non-functional requirements of the system. Further, the components of the system are verified by appropriate domain specialists, who play specific and specialized roles in the system and possess appropriate privileges. The authors have demonstrated their proposed method by designing end-to-end nuclear I&C system using ontologies where the complex requirements are verified using special functional blocks SPARQL FB.

Nilsson at al. [24] carried out a systematic study on the use of ontologies in solving dynamic interoperability issues prevailing across heterogeneous System of Systems (SoS) such as CPS. The study highlighted that solution to interoperability issues get complicated when the human-defined symbols and uncertain variables are used while exchanging messages between System of CPSs (SoCPSs). The solutions often include definition of knowledge graphs for each CPS system that can interpret communication from external CPSs through its metadata using appropriate reasoning mechanisms. The study also highlighted the role of automatic alignment of ontologies to handle the heterogeneity issues as well as explores its usefulness in the Artificial Intelligence (AI) and Machine Learning (ML) based applications. The study concluded that handling interoperability issues in complex SoS is still open problem and opens many new avenues for research.

The characteristics of the proposed unified and interoperable polyhouse ontology has been compared against CPS ontologies proposed by notable related works in terms of eight different categories consisting of around twenty ontology features as shown in Table 1. Each of the eight categories represents the ability of the compared ontologies in annotating the domain knowledge of a CPS in a formal and interoperable manner. Apart from the binary description of ontology characteristics in the table, the textual description highlights the minimal and constrained attempt by the respective ontology to realize the mentioned characteristics. As shown in the Table 1, most ontologies can annotate basic knowledge of a CPS system including its spatial information, components, temporal dynamics, control and communication. However, those ontologies are not effective in terms of handling internal and external conditions of the system, entities inside the system (like food samples in case of PSDs), user information, spatial relationships of components, their 3D models, and the intelligence and analytics. Needless to say, the above-mentioned characteristics form essential aspects of a typical CPS system. In fact, the proposed ontology has been designed to annotate all the above characteristics of smart CPS enabled polyhouse. In addition, it has been observed that most of the CPS based ontologies (including the compared ones in Table 1) annotate the measurement details related to CPS in numerical format alone and lacks support for measurements in non-numerical formats such as images which are crucial for designing a real-time CPS system like PSD. The proposed ontology also supports representing knowledge of measurements in both numeric and non-numerical formats.

The current state-of-affairs in terms of ontology characteristics clearly highlights that there is a need for coherent, unified and interoperable ontology for annotating various domains of a complex CPS. The proposed polyhouse ontology addresses the above discussed shortcomings of the existing CPS-based knowledge representation systems, specifically focusing on polyhouse solar dryer CPS.

3. Polyhouse ontology construction

Fig. 3 provides an overview of the polyhouse CPS ontology construction process, specifically focusing on the reuse of popular ontologies and proposing new Ontology Design Patterns (ODP). As a preliminary step, the domain details related to Polyhouse Solar Dryers (PSDs), including their structural, functional, and physical properties, are gathered. Based on the collected information, a requirement specification document will be developed, which outlines the primary objectives of the proposed ontology and formulates competency questions. Competency questions are expressed in natural language primarily to elicit requirements for the ontology's content and structure. These questions serve as a means of clarifying the information the polyhouse ontology should possess and the types of queries it should be able to answer. Furthermore, ontologies meeting our requirements are identified from related domains, ensuring that they are capable of capturing our needs and facilitate answering competency questions. Finally, these domain ontologies are integrated to create a coherent and comprehensive ontology that models the knowledge of PSDs and preserves semantics present in the original ontologies.

The polyhouse ontology has been constructed by following the guidelines provided by the Semantic Web Best Practices and Deployment Working Group (SWBP) [25]. In addition, we have used guidelines provided by the Ontology Engineering and Patterns Task Force (OEP) in developing reusable ontology patterns. We also have adopted and extended the high-level ontology construction process for CPS systems proposed in Hildebrandt et al.'s [20] . However, Hildebrandt et al. work do not specify the methods of reusing or including the structural and spatial components, environmental conditions and communication process of the systems into the ontology. These limitations are highlighted in Table 1 of the manuscript. Adhering to the above-mentioned standards ensure that the ontologies constructed are interoperable, reuseable, and semantically coherent specifically in CPS domain.

4. Ontology requirements specification

The scope of the polyhouse ontology is to enable the integration of various components of PSD and CPS. Primarily, this ontology provides a comprehensive view of the smart polyhouse environment, facilitating the representation of physical, cyber, and spatiotemporal aspects of the polyhouse. Within this scope, the ontology aims to delineate the structural components and operational aspects of PSDs, such as columns, walls, slabs, foundations, roof trusses, covering materials, and ventilation units of the polyhouse. The ontology integrates knowledge related to CPS-enabled control systems along with temperature, humidity, and ventilation levels within the polyhouse environment, to maintain optimal drying conditions. Additionally, the ontology represents knowledge about food products for solar drying, drying schedules, and monitoring criteria tailored to CPS-enabled operations. Based on these requirements, a set of Competence Questions (CQs) has been defined.

4.1. *Definition of competency questions*

The semantic representation of polyhouses enables the automatic retrieval of any combination of aspects such as food, sensors, communication, control, and structural elements of the polyhouse. The Competency Questions (CQs) outlined in this section are proposed based on interactions with domain experts and an extensive literature review. These CQs will help us determine the scope of the polyhouse ontology and evaluate whether the ontology can retrieve the required details.

CQ1. What are the tangible components of a polyhouse solar dryer system?

CQ2. Which materials and properties are essential for constructing a polyhouse solar dryer?

CQ3. What do the 3D models of polyhouse grid or element structures look like?

CQ4. What food items can be dried using a polyhouse solar dryer?

CQ5. What is the nutrient content of food products dried in a polyhouse solar dryer?

CQ6. What food items, sensor devices, microcontrollers, actuators, and communication devices are associated with a polyhouse?

CQ7. Where the edge or end nodes and their sub-components are present in a polyhouse?

CQ8. What sensors and monitoring devices are integrated into a smart polyhouse to collect data on environmental conditions, such as temperature, humidity, and solar radiation?

CQ9. How can various components, sensors, and devices within a smart polyhouse be connected and integrated using wired or wireless communication technologies?

CQ10. What is the schematic of wired and Wi-Fi networks for inter- and intra-polyhouse communication?

Table 1
Summary of related CPS ontologies in comparison with our work.

Author	Component Characteristics				Environmental and Internal Conditions		Process and Temporal Dynamics		Communication and Control		Quality and Measurement		User and Access Control		Spatial Information and Relationships				Sample Characteristics	Machine Learning and Smart Analytics
	Physical Components	Structural Components	Component Descriptions	Component Interfaces	Environmental Conditions	Internal Conditions	State of Sample	Temporal Dynamics	Control Systems	Communication Protocols	Quality Metrics	Measurement Details	User Information	Access Control	Spatial Information of Components	Spatial Information of Observations	Spatial Relationships of Components	3D Geometry Model		
Petnga et al. (2016)	Yes	No	Yes	Yes	No	No	No	Yes	Yes	Yes	No	No	No	No	Yes	No	No	No	No	No Developed Rule based system not. Supported to annotation of runs and HP of ML
Serrano et al. (2018)	Yes	No	Yes	Yes	No	No	No	Yes	Yes	In the context of data Exchange Mechanism.	Yes	Yes	No	No	Supports geolocation but does not provide precise spatial details, observations, or relationships inside multi-level structures			No	No	No
Bajaj et al. (2018)	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	No	No	No	No	No	Yes	No
Kovalenko et al. (2018)	Yes	No	Yes	Yes	No	No	No	Yes	Yes	No	No	Yes	User roles are provided, but user-specific information is not annotated.	Yes	No	No	No	No	No	No (Authors mentioned use of COLLADA in the future work)
Hildebrandt et al. (2020)	Yes	No	Yes	Yes	No	No	No	Yes	Yes	Yes	No	Yes	No	No	No	No	No	No	Yes	No
Lefrancois Maxime (2023)	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	No	Supported through SAREF family ontologies	No	No	Supported through s4bldg, SAREF family of ontology			No	No	No
Ciolofan et al. (2023)	Yes	No	Yes	Yes	Yes Only nitrogen loss	No	No	Ontology level support not provided	No	No	Yes	Yes	No	No	Not modeled using ontology			No	Yes	Not supported through ontology annotations; uses cloud services
Ovsiannikova et al. (2024)	Yes	No	Yes	Yes	No	No	No	No	Yes (Core part of this work)	Yes (In the context of data interface)	Yes (Focus on non-function requirements)	No	No	No	Yes	No	Yes (based on DiD principle)	No	No	No
Work	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

CQ11. What machine learning models are deployed on the Edge/End Nodes?

CQ12. What algorithms, hyperparameters, data and feature characteristics are used in the ML model?

5. Lightweight ontology construction

Based on the requirements the proposed work adopts standard ontologies for representing a smart polyhouse. The proposed polyhouse ontology is designed to represent various interconnected components that influence the food drying process and the operational aspects of the

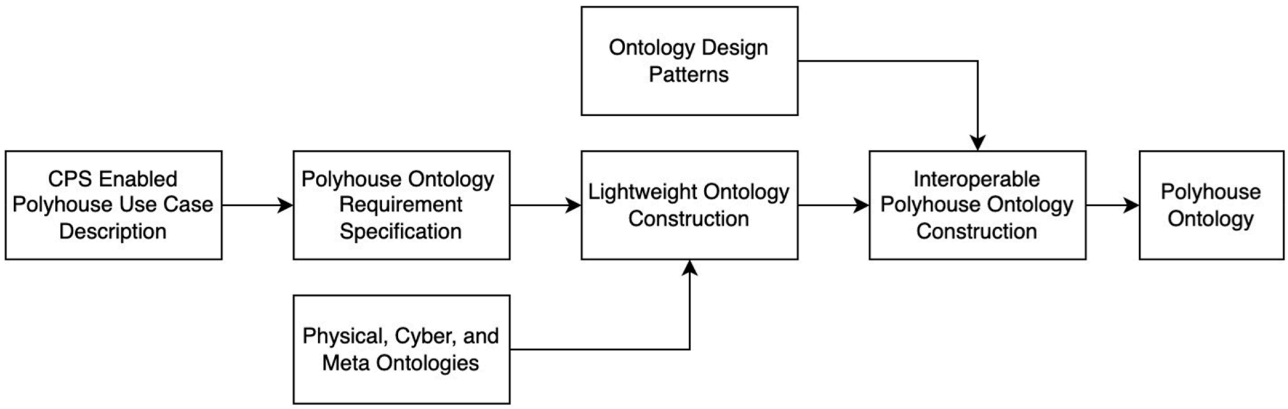

Fig. 3. Polyhouse ontology construction process.

polyhouse. This ontology can describe the concepts, relationships, and constraints inherent in a polyhouse environment. Key elements represented in a polyhouse ontology are broadly categorized into structural components, environmental conditions, food characteristics, control system, sensor data, temporal aspects, and other external factors. We construct a unified lightweight polyhouse ontology by leveraging concepts from various popular ontologies.

The knowledge related to polyhouse structural information is precisely represented using the Building Topology Ontology (BOT). The information related to food items being dried inside the polyhouse is represented using the FoodOn ontology, which primarily annotates details of food products, ingredients, drying processes, and the biological origins of food items. The smart polyhouse generates a substantial amount of IoT data from sensors integrated into the edge/end nodes, and actuators. This data can be effectively utilized for monitoring food products and controlling the polyhouse environment. This IoT system and data generated as part of this are represented using the Federated Interoperable Semantic Internet of Things (FIESTA-IOT) ontology. It is used to describe IoT Devices, Observations and Measurements, Spatial and Temporal Context of IoT data, and Service Descriptions of the IoT systems. The IoT system deployed in the polyhouse involves a complex communication network, including communication between edge nodes, end nodes, actuators, and external servers are modeled using the Topology and Communication ontology (ToCo). The hybrid communication infrastructure, channel details, services, and Users and Roles are effectively modeled using the ToCo ontology. The ML Schema ontology facilitates annotating the details of machine learning experiments deployed in the embedded devices and their associated tasks. The knowledge related to users are annotated using user access part of the ontology. The relationship between users, resources, and associated

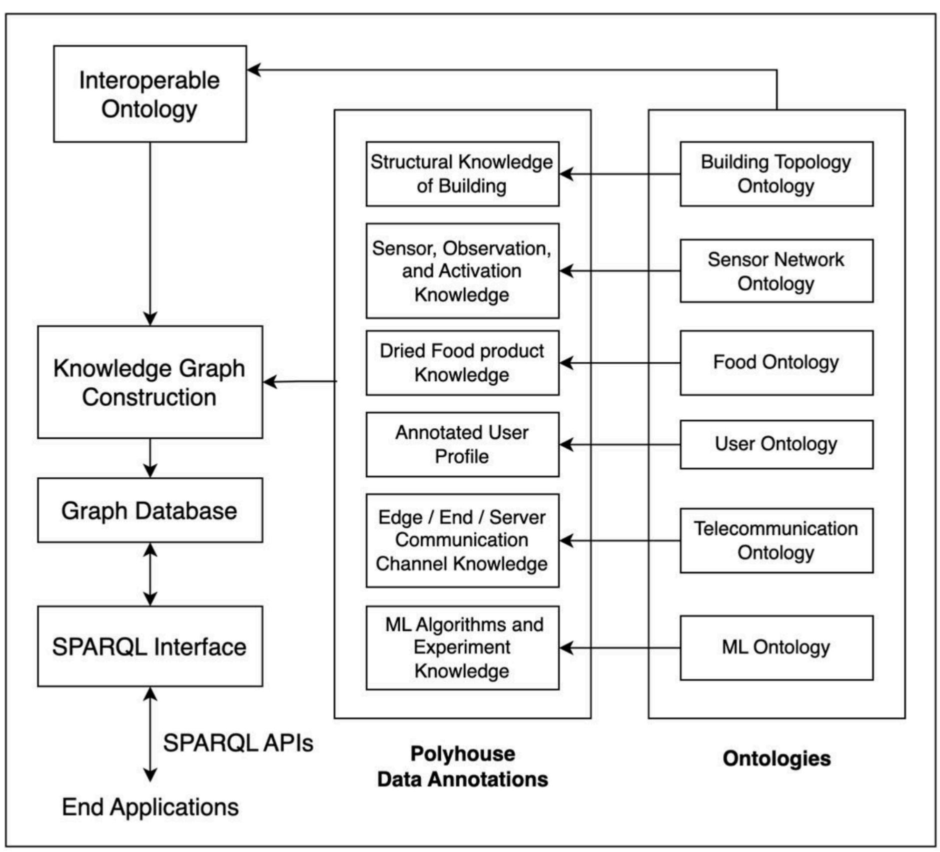

Fig. 4. Polyhouse knowledge graph generation.

privileges is modeled with the aim of enabling better management of the resources. The proposed work integrates all the mentioned ontologies by addressing semantic interoperability challenges and conceptual differences, providing a unified polyhouse ontology. Fig. 4 shows a set of ontologies involved in designing a unified polyhouse ontology, along with data annotation and the knowledge graph generation process, in a coherent way.

5.1. Ontologies for representing topology of polyhouse

The topological information of a polyhouse is represented through Linked Data and Semantic Web techniques to meet the requirements of Building Information Model (BIM) Maturity Level 3 [26]. This necessitates an ontology capable of not only representing the structural components of the building but also annotating elements such as sensors, microcontrollers, and logical grids associated with the polyhouse. This knowledge facilitates easy exchange of structural information of polyhouse among stakeholders. Additionally, helps to regeneration of 3D views of the polyhouse at varying levels of detail based on specific needs.

The W3C Linked Building Data Community Group (W3C LBD CG) has proposed a lightweight Building Topology Ontology (BOT) [26], for providing high-level descriptions of buildings. BOT was proposed as a central Architecture, Engineering and Construction (AEC) ontology that provides generic terms for specifying any feature of interest in the context of components of building. In addition to BOT ontology the Building Element Ontology (BEO) and Distribution Element Ontology (DEO) are used to represent finer structural details of the buildings. The major building elements used in polyhouse construction, such as doors, ramps, and roofs, are precisely represented using the concepts defined in the BEO. Additionally, this ontology helps define the minor elements used to connect polyhouse elements, such as reinforcement details [27]. The elements involved in the process of conveying or distributing services inside the polyhouse, such as electrical, heat, ventilation, and air flow are represented using the DEO. This ontology provides additional information to bot:element by describing the characteristics of the distribution elements. A new Object property *bot:has3DModel* has been included into the BOT ontology to add appropriate geometric details of the entities. Furthermore, the ontology facilitates establishing relationships with other objects it is part of, belongs to, or connected to the polyhouse [28].

The various building elements and associated properties described in the BOT, BEO, and DEO ontologies help us cover CQs 1, 2, and 3. These CQs specifically focus on modeling and retrieving structural information of the polyhouse.

5.2. Ontologies for representing sensor, observation, and activation

Fiesta-IoT is a unified ontology designed for the Internet of Things (IoT), aimed at enabling interoperability and federation of testbeds. This ontology is primarily utilized for annotating concepts related to IoT devices, sensors, observations, and services. In addition, it facilitates annotating security, privacy, and trust aspects of IoT operations. This ontology is developed based on existing popular ontologies and standards, such as the W3C Semantic Sensor Network Ontology (SSN), OneM2M common data model, IoT-lite, WGS84, DUL and Time ontologies.

In this ontology, a class *Polyhouse* is added as a subclass of '*Feature of Interest*' which is part of SOSA ontology. The *Feature of Interest* (FoI) class denotes a thing whose properties are being estimated during observation, in our case it's the Polyhouse. The class *Zone* from the BOT ontology is mapped as a subclass of *Physical Object* from DUL ontology. This is because the *Physical Object* denotes an object which has a proper space region, and the *Zone* denotes a location in the world which has three-dimensional spatial region. Similarly, the class *Site* from the BOT ontology is included as a subclass of *Physical Place*. The entity *Site* denotes a part of a *Zone*, and *Physical Place* denotes the place in which the physical object is located. The class *Sample* from SOSA ontology denotes a feature that acts as a representative of FoI.

The polyhouse ontology facilitates annotating concepts related to images observed through camera sensors. The class *Image* from *Pantheon* ontology [29] is used to represent image data, also the same image is represented as an instance of *Input* and *Observation* class of SSN ontology. The information related to type of images obtained, translation and image processing techniques applied are annotates using the *ImageClassDefinitionElement* and *GoalFormulationPart* classes respectively.

Most of the times, the smart polyhouse operations use the data observed from conventional sensors along with image data to take intelligent decisions. The concepts covered and various abstractions provides by these ontologies covers the CQs 6,7, and 8.

5.3. Ontologies for representing food knowledge

Polyhouse solar dryers are primarily used for sun-drying food products which necessitate representation of food properties, drying processes, and effects. The proposed ontology employs FoodOn, a global farm-to-fork food ontology, for food-related information. FoodOn encompasses fourteen facets such as product type, cultural origin, preservation process, and source [30]. Among these, our focus is the "food preservation process" concept defined under the "food transformation process" hierarchy. Since polyhouse uses tunnel dryers, a new subclass, "solar drying", is added under the class "natural heat drying", and the concept "solar tunnel drying" is defined under "solar drying" in the "food preservation process" hierarchy.

The "Food product" hierarchy defines information related to food items or produce. For example, sun-dried tomatoes are represented as "tomato (tunnel-dried)" under the class hierarchy "tomato (solar-dried)" ⊑ "tomato dried" ⊑ "tomato food product" ⊑ "solanaceous fruit food product". Additionally, suitable restrictions are applied when defining dried food item classes, such as "tomato (tunnel-dried)".

$$\begin{aligned} tomato(tunnel-dried) \equiv\ & tomato(dried) \\ & \sqcap (\exists\, '\textit{formed as a result of}' . '\textit{solar tunnel drying}') \end{aligned}$$

The nutrient values for each food item are included as annotation properties. For example, tomato's major nutrients, Carotenoid, Lycopene, and Vitamin C, are included as annotation properties. Likewise, for other vegetables such as copra, moringa, and peanut, essential classes, restrictions, and annotations are defined in the ontology. The core and extended concept defined in the FoodOn ontology covers competency questions related to food items being dried in the polyhouse, specifically the CQs 4, and 5.

5.4. ***Modeling polyhouse network***

The Topology and Communication (ToCo) ontology plays a significant role in representing the communication and networking aspects within the polyhouse environment [31]. This ontology focuses on modeling the interaction and data flow between the nodes present in the polyhouse. Specifically, it depicts the communication between the following entities: edge nodes, end nodes, edge node and actuator, edge node and host, and microcontroller and sensor devices. The edge/end nodes facilitate data collection, processing, and transmission of information within and across the polyhouse. The ToCo ontology models the network infrastructure through three central concepts: *Device, Link*, and *Interface*, along with the relationships between them. Additionally, the ToCo ontology incorporates classes to represent both quantitative and qualitative measurements. The *Observation and Measurements* class captures the observations made within the polyhouse, while the units associated with these measurements are represented under the *Units* class. This inclusion allows for specific measurement values and units in the ontology, enabling precise and standardized representation of the observed data. By integrating the ToCo ontology with the FiestaIOT ontology, a comprehensive representation of the communication and networking aspects within the polyhouse environment can be achieved. This integration empowers us to analyze and study the communication patterns, data flow, and networking infrastructure in smart polyhouse systems. This in turn addresses the competency questions related to sensor network, and device integration inside and across the polyhouses, specifically CQs 9, and 10.

5.5. Machine intelligence in polyhouse

Most of the intelligent applications today deploy Machine Learning models at the Edge/End nodes to make critical decisions and forecast future values in real time. This requires substantial effort and time in designing an ML pipeline specifically for resource-constrained devices. The process includes experimentation, from selecting appropriate data curation method to testing and deploying the model. The entire process involves conducting and repeating a wide variety of ML experiments to determine an appropriate ML pipeline. Similarly, the reproducibility of research involving ML experiments is highly challenging due to the lack of available details. ML ontologies bridge the gap by providing a systematic way of recording metadata related to ML experiments. In the polyhouse environment, the need for such an ontology is crucial because conventional ML algorithms may not be suitable for embedded devices or may not perform optimally. Therefore, it is essential to keep track of the nuances of each ML experiment.

This section highlights the utilization of the top-level and lightweight ontology, ML Schema (MLS) [32], within the framework of the proposed Polyhouse ontology. The ML Schema defines a comprehensive set of classes, properties, and constraints aimed at annotating machine learning algorithms and their associated tasks. This ontology encompasses a diverse array of classes that elucidate various aspects of machine learning pipeline, including dataset representations, detailed algorithmic representations and their implementations, relevant hyperparameters, and associated software components. Ultimately, MLS serves as a versatile tool for illustrating machine learning experiments across varying levels of detail, spanning from intricate representations of algorithmic executions to more comprehensive overviews of research studies.

On the other hand, the ontology covers only a specific part of the ML pipeline and did not focus on modeling the details of the dataset specifically features that are part it. Also, did not provision the set of features that are used as part of final ML experiments, and its association with data values. All these aspects MLS ontology is carefully observed, and necessary design patterns has been developed and integrated as part of Polyhouse ontology to address the mentioned limitations.

5.5.1. ML schema extensions

The extension of the *’Dataset’* and *’Feature’* classes defined in the MLS ontology and alignment with the *’polyhouse’* ontology are highlighted in Fig. 5. Specifically, the extension primarily focuses on detailing datasets, including their properties, annotations, and corresponding datatypes. Additionally, the extension annotates the features and feature vectors involved in specific runs of ML experiments. For instance, the class *’Data’* is described as individuals that possess a *’Feature’* type and have a value.

$$\mathrm{Data} \equiv (\exists \mathrm{hasType.mls} : \mathrm{Feature}) \sqcap (\exists \mathrm{mls} : \mathrm{hasValue.}(\mathrm{xsd} : \mathrm{double} \sqcup \mathrm{xsd} : \mathrm{integer}))$$

The ML models are usually deployed on the microcontrollers installed in the polyhouse. Therefore, it is imperative to establish a semantic connection between the terminologies defined in the Sensor and MLS ontologies. The class *’device’* defined as part of the SSN ontology is connected to the ML deployment through the ’hasDeployment’ property, which is connected to a specific run of the MLS through the ’hasRun’ property. This semantic representation of ML ontology covers the competency research questions Q11, and Q12.

6. Interoperable polyhouse ontology

Fig. 6 illustrates the overview of the polyhouse ontology, depicting the integration among various ontologies as detailed in Section 3. The detailed concept level alignment between ontologies are highlighted in the Table 2.

7. Real-time implementation of the polyhouse ontology: a use case in AgroESP project

The Polyhouse Ontology plays a vital role as an integral component of the AgroESP project, which is funded by Sensing Solution University Collaboration Program (SSUP) of Sony Group Corporation. AgroESP aims to enhance the effectiveness and efficiency of polyhouse solar drying through the integration of sensors and actuators, enabling intelligent monitoring of environmental parameters within the unit. This cost-effective and energy-efficient approach enables the intelligent system to ensure optimal quality parameters during food processing while providing real-time alerts, predictive analytics, and control mechanisms to enhance the overall quality of the food processing procedures.

This section offers a comprehensive overview of the methodologies utilized to depict the polyhouse in a semantic format, covering both its structural features and operational processes. Furthermore, it explores

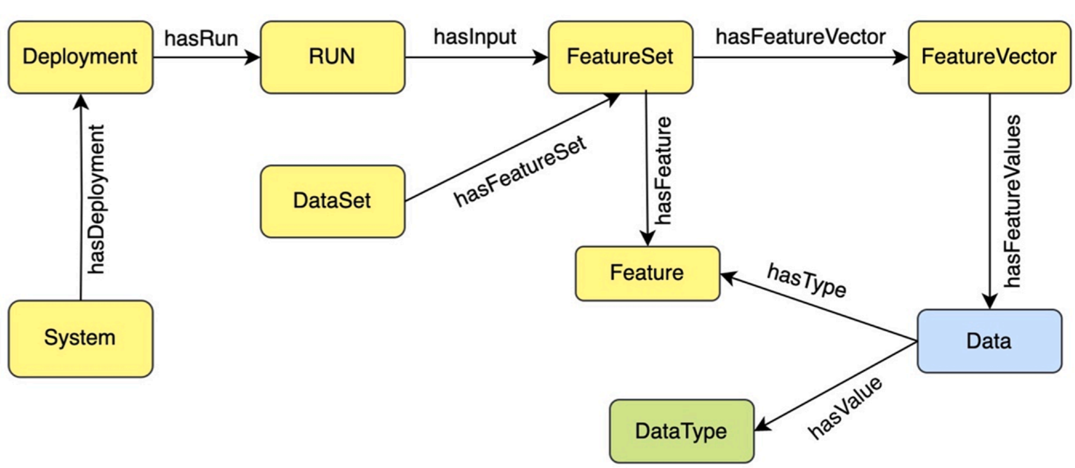

Fig. 5. ODP of FeatureSet representation.

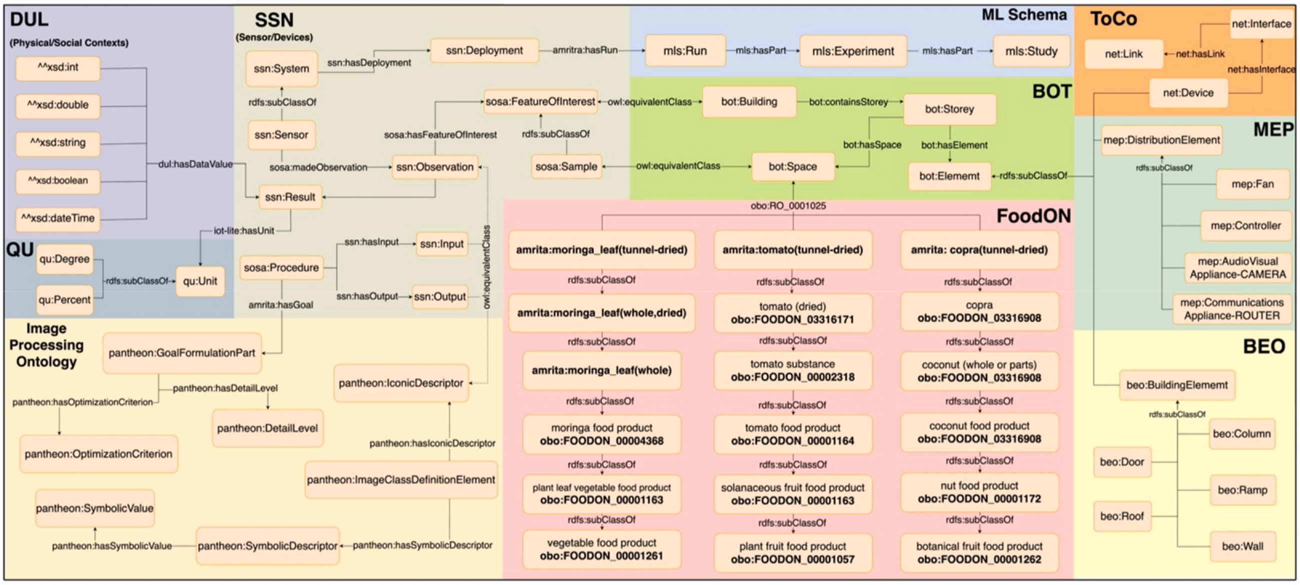

Fig. 6. Interoperable polyhouse ontology.

Table 2
Ontology alignment.

Ontologies	Concept alignment (In Triples)	Description
BOT – SSN	bot:Building owl: equivalentClass sosa: FeatureOfInterest bot:Space owl: equivalentClass sosa:Sample	The polyhouse is the feature of interest and the target of our observation. Bot: Space represents a portion of a polyhouse (a logical grid), while sosa: Sample is segment of Feature of Interest.
BOT - FoodOn	FOODON:00001015 obo: RO_000125 bot:Space	obo:RO_000125 precisely determines the location of the food product within the polyhouse.
BOT - ToCo	net:Device rdfs:subClassOf bot:Element	The device specializes in networking functionality and is an integral component of the polyhouse.
BOT – MEP	mep:DistributionElement rdfs:subClassOf bot:Element	The devices specialize in the distribution operations and is an integral component of the polyhouse. (eg., Actuator controlling environmental conditions of polyhouse)
BOT - BEO	beo:BuildingElement rdfs: subClassOf bot:Element	Building elements are integral components of the building.
SSN – Pantheon	sosa:Procedure amrita: hasGoal pantheon:Goal	Goal of the application which occurs across observations. Specifically focusing on Image processing.
SSN – MLSchema	ssn:Deployment amrita: hasRun mls:Run	An ML model has been deployed on an edge/end node
SSN - QU	ssn:Result iot-lite:hasUnit qu: unit	Defines the unit of measurement

the real-time annotation process, which involves annotating sensor data, food items, and network specifications using the polyhouse ontology. The proposed polyhouse ontology is integrated with the AgroESP project, and this section provides a "Task-Based" evaluation.

7.1. Semantic representation of polyhouse

This section details the process of translating the structural components of a polyhouse into a machine-readable, interoperable semantic form. The semantic representation of the polyhouse will be generated as shown in Fig. 7. The primary requirement of this stage is to generate a 3D model of the polyhouse. To accomplish this, we have used a 3D modeling tool that supports the development and rendering of 3D models into BIM format as shown in Fig. 8. Along with the structural details of the polyhouse, the 3D model also captures the logical grids associated with polyhouse where the food items are being dried. In AgroESP the entire polyhouse drying area was divided into three different logical grid units. In addition, the model also captures the sensors and microcontroller units mounted on the logical grids of the polyhouse.

The 3D model created for the polyhouse considers the entire structure as a single entity. However, the polyhouse comprises various distinct objects, each made of different materials. This necessitates manual grouping of these entities for subsequent processing and querying. Such logical grouping allows us to differentiate between the entities within the polyhouse, enabling us to uniquely identify and extract essential information from each entity. The 3D model of the polyhouse is exported into the open Industry Foundation Classes (IFC) format. IFC is a global standard designed for sharing and exchanging information across construction and management sectors. The BIM-IFC version of the polyhouse is then converted into a BOT-OWL format to semantically represent the building components. The object property "bot:has3DModel" is used to add the relevant geometric details of the

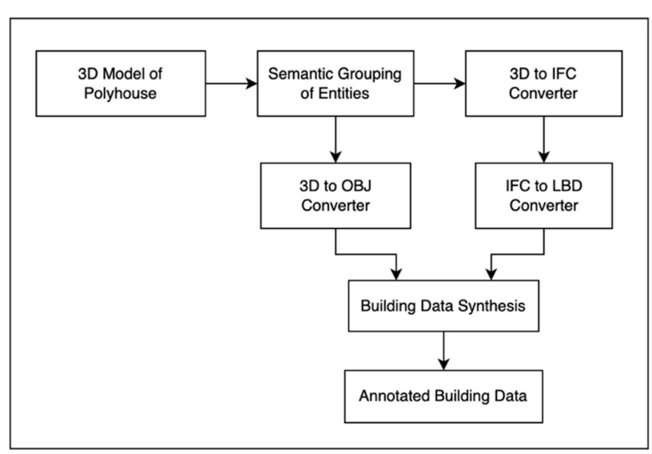

Fig. 7. Semantic representation of polyhouse.

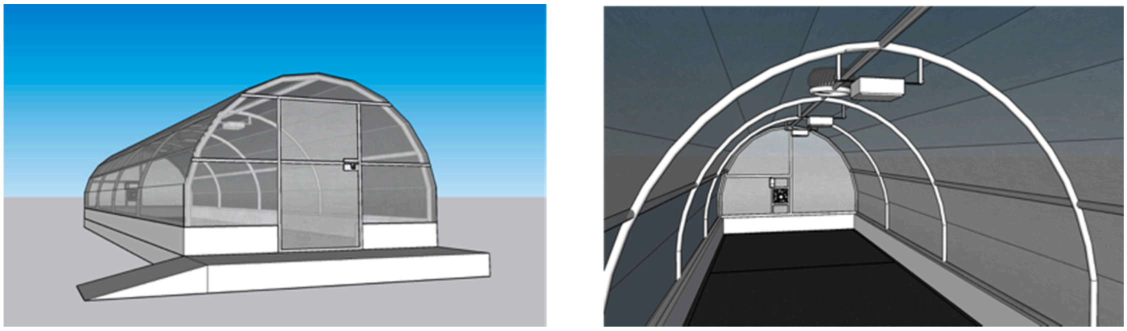

Fig. 8. Outer and inner 3D views of the polyhouse.

building entities to the ontology. In this context, the wavefront OBJ format represents the geometric details of the entities. Given the large file sizes of the OBJ representations, they cannot be added directly to the ontology. To address this issue, the OBJ representations are uploaded to a GitHub repository as OBJ files. These files are then linked to the corresponding polyhouse entities in the ontology using appropriate individuals. The queries shown in Figs. 9 and 10 demonstrate retrieving various implicit and explicit details of the polyhouse entities.

7.2. Semantic annotation of sensing and activation of polyhouse

In AgroESP, three end nodes and an edge node are mounted at independent logical grid positions within the polyhouse. These nodes are responsible for sensing, processing, and executing activation operations in the polyhouse. The end nodes primarily monitor the physical conditions of the designated grid positions using temperature and humidity sensors mounted on them. Additionally, the end nodes analyze the current state of the food items drying in the polyhouse using image data captured through camera units, alongside the other physical parameters observed. The edge node coordinates all the operations among the end nodes and maintains communication with the central server. This node is also responsible for making centralized decisions in the polyhouse and triggering the actuation unit. In AgroESP, the exhaust fan is considered an actuation unit, used to control the physical conditions of the polyhouse as shown in Fig. 11.

Each end/edge node is hosted on the Spresense microcontroller, which is designed and developed by Sony. The Spresense microcontroller features the CXD5602 chip, which runs on six ARM Cortex-M4F cores. In the polyhouse ontology, this microcontroller is represented as an instance of the classes *'Controller', 'Device', 'Element'*, '*IoT Entity*', and *'Platform'*. The polyhouse's temperature and humidity are monitored using the SHT25 sensor. In the polyhouse ontology, an individual bearing the same name is added as an instance of the class *'Air-Thermometer'*, which is a subclass of *'SensingDevice'*. The edge node utilizes the SIM7600, a 4G LTE module, to establish communication with the centralized server. Likewise, the ESP32 is used for Wi-Fi communication between the end and edge nodes. These communication modules are represented as instances of the class *'SystemDevice'*, which is a subclass of *'PhysicalInfrastructure'*. The camera module is depicted as an instance of the class *'AudioVisualAppliance-CAMERA'*, which is also a subclass of *'SystemDevice'*. The entities representing the sensor, communication, and camera modules are interfaced with the microcontroller instance and are connected through the object properties 'hasInterface' and 'hasSubSystem'. To record the sensor observations, we utilized the *'Observation'* and *'observationResult'* classes from the SSN ontology for each sensing device. The queries shown in Figs. 12 and 13 illustrate the devices connected to the end/edge nodes, as well as the observations from the sensor devices, accompanied by timestamp details.

7.3. Food data annotation

The AgroESP project primarily focuses on the valorization of four different food products using a smart polyhouse. These products include Moringa Leaves, Copra, Tomato, and Groundnut. These food items are annotated using the extended FoodOn ontology. For instance, dried tomatoes are represented as an instance of the class *'tomato (tunnel-dried)'*, which is a subclass of *'solanaceous fruit food product'*. Additionally, nutrient values for each dried food item are included as annotation properties. For example, major nutrient contents of tomatoes include carotenoids, lycopene, and vitamin C. The values of these nutrients are annotated as properties of the tomato. Similarly, *'Peanut (solar-dried)'* is defined as a subclass of the existing *'peanut (whole, dried)'* category. Since there was no pre-existing class for *'moringa'* in FoodOn, we constructed an entire hierarchy for moringa in relation to tunnel drying under the class *'plant leaf vegetable food product'*. We also introduced subclasses for *'copra'* based on the drying method. These include *'copra (solar-dried)'* as a subclass of the existing *'copra'* category and *'copra (tunnel-dried)'* as a subclass of *'copra (solar-dried)'*. The Fig. 14 demonstrates the query to retrieve location information of the food deride in

```
PREFIX schema: <http://schema.org/>
PREFIX props: <https://w3id.org/props#>
PREFIX bot: <https://w3id.org/bot#>
PREFIX amrita: <http://amrita.sony.org/terms#>
select * where {
   amrita:Polyhouse_1 bot:hasStorey ?Storey .
   ?Storey props:dimensionsLength ?Length .
   ?Storey props:dimensionsWidth ?Width .
   ?Length schema:value ?length .
   ?Width schema:value ?width .}
```

Fig. 9. Query to retrieve dimensions of polyhouse.

```
PREFIX amrita: <http://amrita.sony.org/terms#>
PREFIX bot: <https://w3id.org/bot#>
select *  where {
   amrita:Polyhouse_1 bot:hasStorey ?storey .
   ?storey bot:hasSpace ?grids.
   ?grids bot:containsElement ?elements.}
```

Fig. 10. List of elements present in a specific logical grid of a polyhouse.

the polyhouse.

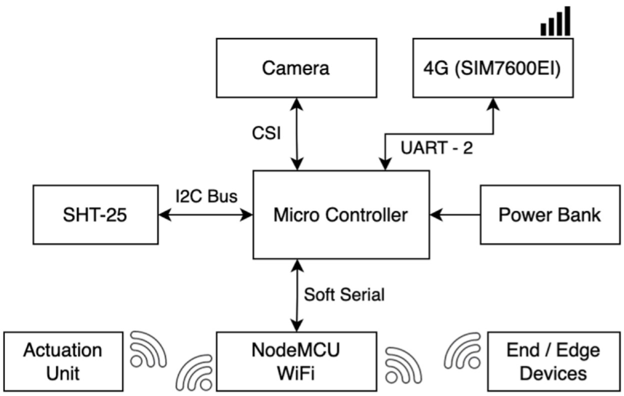

Fig. 11. Architecture of Edge/End node.

7.4. Implementation of polyhouse network

The ToCo ontology is utilized to model the communication network between edge/end nodes within the polyhouse and with an external server. The entities that constitute the communication network in the polyhouse are primarily represented as instances of the *'Device'* class. Within the AgroESP project, the edge node in the polyhouse communicates with the central server via 4G LTE using the SIM7600 module. This module is configured with a bandwidth of 10 Mbps for downlink and 5 Mbps for uplink. Through this connection, data obtained from sensor nodes, ML inferences, and controllers are communicated back and forth with the central server. The edge, end, and actuator nodes communicate with each other via a Wi-Fi connection, utilizing the NodeMCU's Wi-Fi module which offers a maximum bandwidth of 3 Mbps. Both the SIM7600 and NodeMCU Wi-Fi modules are defined as instances of the *'SystemDevice'* class, which is a subclass of the communication *'Device'*. Additionally, the ontology stores meta information about these modules, such as channel, bandwidth, IP, and MAC address using datatype properties like 'channel', 'hasBandwidth', 'hasIP', and 'hasMAC'. Furthermore, the polyhouse ontology provides annotations regarding the wired interface connections between sensor nodes and the Spresense microcontroller. For example, the camera, NodeMCU, SIM7600, and STH25 are linked to Spresense using CSI, soft-serial, UART2, and I2C interfaces, respectively. These details are denoted with the object property 'hasWiredLink', a subproperty of 'hasLink', and it is disjoint from the property 'hasWirelessAssociation'. The SPARQL queries shown

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX ssn: <http://purl.oclc.org/NET/ssnx/ssn#>
PREFIX amrita: <http://amrita.sony.org/terms#>
select ?Node ?Controller ?SubSystem where {
   ?Node rdf:type ssn:System.
   ?Node rdf:type ?nt
   FILTER (?nt = amrita:EndNode || ?nt = amrita:EdgeNode)
   ?Node ssn:hasSubSystem ?Controller .
   ?Controller ssn:hasSubSystem ?SubSystem .}
```

Fig. 12. Query to retrieve list of End/Edge nodes and associated devices.

```
PREFIX om: <http://www.ontology-of-units-of-measure.org/resource/om-2/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
select ?Sensor  ?Value ?Unit ?Time where {
   ?Sensor a sosa:Sensor .
   ?Sensor sosa:madeObservation ?Observation.
   ?Observation sosa:hasResult ?Result.
   ?Result om:hasNumericalValue ?Value.
   ?Result om:hasUnit ?Unit.
   ?Result sosa:resultTime ?Time.   }
```

Fig. 13. Query to retrieve sensor observations along with timestamp.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX amrita: <http://amrita.sony.org/terms#>
PREFIX bot: <https://w3id.org/bot#>
PREFIX obo: <http://purl.obolibrary.org/obo/>
PREFIX amr-food: <http://amrita_food.org/terms#>
select ?space ?foodsproduct ?vitamin ?value where {
        ?p rdf:type amrita:Polyhouse .
        ?p bot:hasStorey ?storey.
        ?storey bot:hasSpace ?space.
        ?foodsproduct obo:RO_0001025 ?space.
        ?foodsproduct amr-food:contains ?vitamin .
        ?vitamin amr-food:has_value ?value .  }
```

Fig. 14. Query to retrieve current location and properties of the tomato.

in Figs. 15, 16, and 17 retrieves both wired and wireless configurations present in the polyhouse, along with observations of the links.

7.5. Semantic annotations of machine learning

The details of the machine learning algorithms deployed in Spresense™ edge computing platform developed by Sony and experiments conducted are annotated using the Polyhouse Ontology. These ML experiment details encompass the algorithms used, implementation specifics, hyperparameter settings, evaluation metrics employed, and dataset particulars.

For instance, in one of the ML experiments, we utilized a 'Deep Neural Network,' which is a type of neural network architecture, and 'Eager Execution,' a mode of operation. Both of these pieces of information are represented as instances of the *'Model'* and *'ModelEvaluation'* classes, respectively. The proposed DL model is configured as a feed-forward neural network with one input layer, two hidden layers, and one output layer. These characteristics are represented as instances of the class *'ModelCharacteristic'*.

The model is trained using a dataset consisting of forty-seven features. These features include RGB, HSV, and LAB (nine channels) features derived from images obtained from Spresense's camera module, as well as five statistical features (mean, standard deviation, minimum, maximum, and variance) for each channel. Additionally, humidity and temperature measurements of the polyhouse are included in the dataset. These details are represented as instances of the *'Dataset'* and *'Feature'* classes. Similarly, food items are classified based on their dryness levels in the polyhouse, including fresh, semi-dried, and dried categories, which are annotated using *'Task'* class. During the experiments, the model's performance is evaluated using the commonly used accuracy metric, represented as an instance of *'EvaluationMeasure'*. The entire model is implemented using the 'tf.keras' software package, which is represented as an instance of the *'Implementation'* class. The characteristics of these implementation details are annotated using the class *'ImplementationCharacteristic'*.

The details mentioned above pertain to a specific experiment conducted in a polyhouse. Similarly, we have conducted numerous experiments to identify suitable machine learning (ML) and deep learning (DL) models for polyhouse-based food processing applications. All of this information is annotated using the polyhouse ontology. This has been instrumental in preventing the repetition of similar experiments and in deducing nuances from prior experiments, including specific hyperparameter details. The SPARQL queries shown in Figs. 18 and 19 highlight the implementation details of a specific machine learning run and models deployed on a specific node, along with their evaluation results.

7.6. Impact of polyhouse ontology in AgroESP operations

The proposed polyhouse ontology impacts the operations of AgroESP at various levels including Automatic Device registration, Federated querying, Data Aggregation, and Sophisticated querying system.

Automatic Device registration: The conventional system does not support dynamic adaptation of architectural changes in the CPS system. For instance, integrating new sensors or updating existing ones brings various configuration challenges and overheads in managing the related information. Addressing these challenges requires heavy custom integration efforts in the applications which increase the complexity and cost of maintenance. The use of polyhouse ontology as part of this system addresses the mentioned issues.

Federated querying: The polyhouse ontology helps to integrate the AgroESP data with different data sources on the fly. The traditional systems require configuration of data sources and schema integration within the code to combine data dynamically. But in ontology-based applications the configuration of external data sources is not required, and connections can happen dynamically across multiple linked data sources even with data sources not known in prior. For instance, integrating AgroESP data with Open Street Maps to explore nearby potential market details of the dried food item.

Data Aggregation: Polyhouse ontology helps in aggregating data from diverse source and automatically handles incompatibilities across these data variants. For instance, the AgroESP project comprises three different polyhouses, the first polyhouse located inside the university campus where in a sensor node it uses SHT25 for measuring relative humidity. On the other, two polyhouses located 3 km and 25 km (about 15.53 mi) away from the university campus where nodes use DHT11 for

```
PREFIX toco: <http://purl.org/toco/>
select ?from ?Link ?to where {
 ?Link toco:from ?from .
          ?Link toco:to ?to .  }
```

Fig. 15. Query to retrieve wireless associations in the polyhouse.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX amrita: <http://amrita.sony.org/terms#>
PREFIX toco: <http://purl.org/toco/>
select distinct ?interface ?Link ?result ?device where {
   amrita:Spresense_1_P1 toco:hasInterface ?interface .
   ?interface toco:hasWiredLink ?Link .
   ?result toco:hasWiredLink ?Link .
   ?device toco:hasInterface ?result .
   FILTER(?device !=  amrita:Spresense_2_P1)}
```

Fig. 16. List of wired associations of the microcontroller.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX toco: <http://purl.org/toco/>
PREFIX om: <http://purl.oclc.org/net/unis/ontology/sensordata.owl/>
select ?association ?linkprops ?observation where {
   ?association rdf:type toco:Link .
   ?association ?linkprops ?observation .
   ?observation rdf:type om:ObervationAndMeasurement.}
```

Fig. 17. Retrieve observations of the links.

```
PREFIX mls: <http://www.w3.org/ns/mls#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX dcterms: <http://purl.org/dc/terms/issued/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
select ?software ?implementation ?algorithm ?description where {
   ?run_instance rdf:type  mls:Run.
   ?run_instance mls:executes ?implementation.
   ?software mls:hasPart ?implementation.
   ?implementation mls:implements ?algorithm. }
```

Fig. 18. Retrieves implementation details of the ML algorithms.

measuring relative humidity. In this application two different types of humidity sensors were used – while DHT 11 measures relative humidity in integer values, and SHT25 measures with the floating-point precision. Both, these variations are effectively handled by the polyhouse ontology as the semantics of these observations are explicitly annotated in the form of RDF

Sophisticated querying system: Any combination of polyhouse knowledge can be inferred from the knowledge base with available information effectively by virtue of the proposed polyhouse ontology. The advantage of this querying system is that the schema or vocabulary of the ontology need not be known in advance to write any query. Matching the known terms with WikiData, DBPedia, or any other related sources can help us to mine any required information about the polyhouse.

8. Quality assessment of polyhouse ontology

The logical consistency of the ontology, property constraints such as domain, range, cardinality, and data type restrictions of the polyhouse ontology are verified using the reasoner HermiT [33]. This section focuses on evaluating the quality of the polyhouse ontology in terms of its adherence to both functional and non-functional requirements.

8.1. Assessing structural properties of polyhouse ontology

The ontology-based metrics provide insights into the size of the ontology, including the number of axioms, classes, and properties [34]. These metrics consider only the elements explicitly defined within the ontology, without accounting for elements imported from external ontologies. The base metric values of the polyhouse ontology clearly demonstrate the rich set of axioms used to represent polyhouse knowledge.

The Schema Metrics of the ontology emphasize the richness of the ontology's design in terms of the depth and breadth of the ontological constructs employed [35,36]. Tables 3 and 4 showcase set of metrics utilized to evaluate the schema of the polyhouse ontology and their respective values. The Inheritance richness metric measures the average number of subclasses per class in the polyhouse ontology, while the Axiom/Class ratio indicates the average number of axioms defined per class. The corresponding scores of 0.8 and 10.5 demonstrate well-distributed information across the ontology, as well as a rich set of axioms defined per class. However, it's important to note that the Schema metric results do not provide insights into either domain coverage or the semantic correctness of the ontology. The Average Population and Class richness metrics are considered as Knowledgebase

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX ssn: <http://www.w3.org/ns/ssn/>
PREFIX amrita: <http://amrita.sony.org/terms#>
PREFIX mls: <http://www.w3.org/ns/mls#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
select (?la As ?Model) (?em As ?measure) ?value (?label As ?EvaluationProcedure)
(?tts As ?EvalProcedure) where {
   ?Deployment rdf:type ssn:Deployment.
   ?Deployment ssn:deployedSystem amrita:Spresense_1_P1 .
   ?Deployment amrita:hasRun ?Run.
   ?Run mls:hasOutput ?model.
   ?Run mls:hasOutput ?m.
   ?m rdf:type mls:Model; rdfs:label ?la.
   ?model rdf:type mls:ModelEvaluation; mls:specifiedBy ?em.
   ?em mls:hasValue ?value.
   ?es mls:hasPart ?em.
   ?es mls:hasPart ?ep.
   ?ep rdf:type mls:EvaluationProcedure; rdfs:label ?label; mls:hasValue ?tts. }
```

Fig. 19. Detail the models deployed in Spresense along with its evaluation results.

Metrics which primarily reflects the distribution of instances. The scores indicate that the knowledge base of AgroESP has utilized 30 percent of classes defined in the polyhouse ontology.

8.2. *Non-functional assessment of polyhouse ontology*

This section highlights evaluation of polyhouse ontology with respect to maintainability, interoperability, and reusability characteristics using the metrics proposed by OQuaRE [37,38]. The results of the metrics are shown in Table 5. These scores range from 1 to 5 where the score 1 indicates minimally acceptable and 5 means highly acceptable characteristics. For instance, the reusability score 3.16 indicates that the terminologies defined in the proposed ontology moderately support reusability in other ontologies. On the other hand, the scores of *Consistent search and query, Knowledge Reuse, controlled Vocabulary and Guidance and Decision Trees* metrics are maximally accepted. These metrics clearly indicates that the polyhouse ontology is equipped with better querying and searching methods, supports high level of semantic interoperability, and designed with high level of modularity.

9. Discussions

The proposed polyhouse ontology is designed to incorporate various structural and functional aspects of every possible entity in the smart PSD. This ontology can be employed as a turnkey framework to capture the knowledge aspects of other types of solar dryers like step-type dryers, cabinet dryers, rack dryers, greenhouse dryers, multi-rack dryers and flat plate air-heater [39]. Non-natural drying units like biomass-fired dryer and electrically operated food drying units employ specialized components and thus require the existing ontologies to be extended to capture the knowledge of those components [40]. As the proposed polyhouse ontology seamlessly unified the existing domain specific ontologies, extending it for such specialized drying units require minimal efforts.

The proposed ontologies have been built and represented for standard Polyhouse with specific technological intervention setup. But

Table 3
Ontology base metric values.

Elements	Count
Axioms	3742
Logical axioms count	1812
Class count	507
Object property count	117
Data property count	28
Properties count	145
Individual count	260
DL expressivity	SRIN(D)

Table 4
Schema metrics.

Metric	Value
Attribute richness	0.055227
Inheritance richness	1.366864
Relationship richness	0.275105
Equivalence ratio	0.009862
Axiom/class ratio	7.380671
Inverse relations ratio	0.097744
Class/relation ratio	0.530335
Average population	1.31222
Class richness	0.433121

Table 5
Model functional adequacy.

Metric	**Score**
Clustering and similarity	3.5
Consistent search and query	4.4
Controlled vocabulary	5
Guidance and decision trees	5
Indexing and linking	4
Inferensing	5
Knowledge acquisition	3.66
Knowledge reuse	4.62
Reference ontology	3.5
Results representation	5
Schema and value reconciliation	4.25
Text analysis	5
Reusability	3.16

Polyhouses with very finetuned configuration requirements are to be modeled as an extension and to be included as part of the proposed ontology. Similarly, any change/addition to the technological intervention setup in polyhouse requires comprehensive modeling of the component. For instance, PSD serves as a perfect physical test bed for designing and implementing a Cyber Physical System. The primary objective of the CPS is to control and maintain the dynamic conditions within a PSD using appropriate actuators to ensure effective drying conditions for food materials. Achieving this robust control of PSD environment necessitates a digital model of the physical environment and a control system design. Modeling a polyhouse environment requires characterization of parameters that impact drying conditions such as, internal and external temperatures, relative humidity, conditions like moisture content of the food materials, and physical parameters affected by the actuators. To be specific, *Psychrometry* is the study of thermodynamics of moist air-vapor mixtures in a closed environment, primarily focusing on inter-relation between temperature, vapor pressure and the relative humidity. Psychrometric analysis helps to identify and quantify ideal conditions to be maintained in an enclosed environment like PSD to achieve optimal drying. These demands establishing a relationship between the maximal drying rate and psychrometric gap. The psychrometric gap refers to the difference between absolute humidity present in the polyhouse and the saturated absolute humidity. In fact, psychrometric gap is one of the key aspects of the PSD to computationally improve the drying time of the food products by integrating information across physical and logical layers of the polyhouse. The proposed ontology possesses limited means of support to model these operations systematically, and thus requires extensive design to include the psychrometric aspect of polyhouse in the ontology. As per our understanding and extensive survey no such analysis has been reported in the polyhouse literature and there is a dire need for ontology towards modeling physical conditions of the polyhouse and hence is a prominent direction for future work.

The flexible and the extensible ontology proposed in this paper is capable of annotating the concepts of a polyhouse. The proposed ontology can be directly used in farming and food related applications that require standardizing data representation in the CPS to have enhanced control over the system. In terms of farming, the proposed ontology enhances applications related to precision agriculture, agricultural monitoring and management systems, IoT for smart farming, agri-business, and urban farming. Deploying polyhouse ontology in these applications leads to improved decision-making, resource efficiency, and overall system performance, and this ontology will be an invaluable tool for any modern polyhouse operations. However, the wide variety of possible applications of polyhouse might require application specific domain representations in the ontology which are difficult to anticipate and hence are not part of our unified polyhouse ontology. Extending the proposed ontology with such enhancements will require minimal effort. For instance, the proposed ontology is capable of annotating knowledge related to various characteristics of the food materials being dried in the PSD like chemical composition, consumer details associated with a food item before and after drying. However, the ontology design has not been focused towards maintaining knowledge related to specific applications such as recipes related to dried food items, specific packaging and transportation details, and food traceability. Applications requiring such specific knowledge can easily extend the polyhouse ontology by aligning with domain specific ontologies such as FoodKG [41], AgriKG [42], RcpKG7 [43], and OFFF [44].

The polyhouse ontology does not focus on representing application specific processes or data flow operations involved in the PSD. Different applications tend to have different design requirements. For instance, the information from the sensor(s) inside PSD is collected by the end node(s) and communicated to the edge node for decision making. Alternatively, end node can in fact host intelligent algorithms for local decision making rather than at the edge node. As another variant, the intelligent decision making can be done at the central server without overloading end/edge nodes due to resource constraints. Such different requirements by specific applications can be captured using domain specific ontologies and can be integrated with the proposed polyhouse ontology.

The traditional polyhouses usually do not require additional infrastructure other than its very physical structure. Consequently, they are often constructed in remote places for harnessing the maximum benefit from sun drying. However, smart PSDs require electricity and network accessibility. Ongoing research attempts to address these requirements, with special emphasis on power management aspects, often by employing battery operated intelligent CPS nodes. So, power management in the end/edge nodes, communication modules as well as in the actuators of PSDs is very critical. In fact, the real-time systems and their components consume lots of energy due to frequent communication requirements thus affecting their battery life. There is a constant need for improving such systems' energy efficiency thereby improving the battery life of the components. Typical solutions include reducing the high-power state of the network devices, automatically activating power-efficient sleep modes of microcontrollers, activating batch mode operations and use of low-power libraries. The proposed polyhouse ontology annotates the knowledge of various communication, processing, and activation units used in PSD. The ontology also annotates knowledge regarding operating power as well as communication protocols used. In fact, the above-mentioned different cases emphasize the fact that such application specific requirements need to be dealt with on a case-to-case basis and necessary focused knowledge management strategies are to be developed.

The quality of the unified ontology depends on its interoperability amongst different existing ontologies; consequently, ontology alignment is a key problem that needs to be addressed. From an optimization perspective, increasingly metaheuristic algorithms are being employed for effective ontology alignment [45]. Several powerful metaheuristic algorithms exist and are being proposed like Gazelle Optimization Algorithm, Dwarf Mongoose Optimization Algorithm, Geyser Inspired Algorithm, Multi-objective Snow Ablation Optimization Algorithm by way of examples. Metaheuristic-based automated polyhouse ontology alignment will form a definite part of our future research [46–49].

10. Conclusion

A coherent, interoperable unified polyhouse ontology has been designed and developed for a CPS-enabled smart Polyhouse Solar Dryer. This ontology enables a standardized knowledge representation of complex information from diverse data sources within a smart PSD. The common vocabulary provided by the proposed polyhouse ontology facilitates data integration, semantic interoperability, and effective communication among components of CPS enabled PSD as well as across PSDs. The physical, cyber and spatio-temporal requirements of PSD have been suitably converted into a set of Competence Questions, based on which existing domain-specific ontologies have been identified. The polyhouse ontology has been constructed by aligning chosen domain ontologies following the guidelines by SWBP and OLP. The integration involved several techniques - adding new classes, properties, extending an existing concept, defining a new concept as well as adding new ontology design patterns to the existing ontologies. The proposed polyhouse ontology evaluated in terms of its logical consistency, adherence to functional and non-functional requirements.

Subsequently, the unified ontology has been field deployed in a real-time PSD through the AgroESP project. A 3D model of the PSD has been created to annotate the elements using the proposed ontology. Subsequently, semantic annotation of sensing, activation, food data, polyhouse network as well as the intelligent algorithms implemented in the edge/end nodes have been realized. The effective sensing and control of polyhouse environment have been successfully demonstrated using proposed polyhouse ontology in AgroESP project. The potential impact of the unified ontology on PSD operations as well as its limitations have been discussed in detail. A suitable subset of the limitations of the proposed polyhouse ontology will form the base of our future research work.

CRediT authorship contribution statement

Gowtham Ramesh: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **P. Dheepan Kanna:** Writing – review & editing, Visualization, Validation, Investigation, Data curation. **C. Shunmuga Velayutham:** Data curation, Formal analysis, Funding acquisition, Writing – review & editing. **Jancirani Ramaswamy:** Data curation, Formal analysis, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr Gowtham Ramesh reports financial support was provided by Sensing Solution University Collaboration Program (SSUP) of Sony Group Corporation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Polyhouse Dataset (Original data) (Github)

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