# An Ontology Based Approach for Plant Pests and Diseases Diagnosing and Control

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**Abstract:** ***In recent years, ontologies have gained popularity in the domain of agriculture as techniques for semantic knowledge management and modeling. Their ability to allow data integration and enable semantic interoperability across heterogeneous sources is a major advantage in smart agriculture. However, existing ontologies' computational power over semantic expressivity and inference of hidden knowledge has gaps that need to be bridged. Specifically, for these ontologies to be useful in supporting agriculture decisions, all related factors should be considered; moreover, they should be more computationally rigorous to detect the complex relationships hiding between these factors. To address these issues, we present a Plant Diseases and Pests Ontology (PDP-O). This ontology captures all related concepts, terms, and semantic relations about plant diseases and pests, and defines a schema to describe these elements on the basis of formal semantics. To enhance PDP-O's reasoning capabilities we adopted three strategies: (1) describing PDP-O classes using logical description; (2) modeling to enrich the meaning of PDP-O relationships; and (3) adding SWRL rules to represent complex relationships that cannot be defined through OWL DL. As proof of concept, we provide a brief use case to identify a disease affecting date palm crops. To demonstrate PDP-O's efficacy and validity, automatic consistency checking was performed, and the results obtained show that PDP-O is both coherent and consistent. This ontology can benefit both domain stakeholders and systems developers. First, it contains information on various factors relating to plant diseases and pests (such as symptoms, most susceptible varieties, outbreak time, preferable environmental factors, and treatment or control measures), empowering agricultural stakeholders to improve farm management and enhance their adherence to best practice. Second, it provides an in-depth computationally enriched schema, based on which developers can develop more intelligent decision-support systems and simplify their integration of data from heterogeneous sources.***

**Keywords:** Ontology, RDF/OWL, Machine reasoning, Agriculture, Pest recognition, Pest control

## 1. Introduction

On a global scale, agriculture plays a key role in the economy of any country. However, considerable value is lost to plant pests and diseases. The estimated loss from invasive species and pathogens in crop and forest production is about $40 billion annually in the United States alone [1]. Plant pathology, also referred as phytopathology, is the study of plant disease caused by living entities and environmental factors, as well as the mechanisms by which these factors produce plant diseases, the interactions between them (causal agents) and plants, and methods of prevention and control [2]. Entomology is the scientific study that, among other things, deals with insect pests [3]. Pests, such as insects, mites, or other organisms that affect plant health by consuming plant tissues, are not categorized as pathogens [4]. Plant pathology is a multidisciplinary field that covers knowledge from microbiology, botany, crop science, ecology, soil science, genetics, molecular biology, biochemistry, and physiology [5]. Consequently, the effective management of plant pests and diseases requires stakeholders to gain knowledge in various fields to make informed decisions. The sheer volume of information available on these factors is overwhelming and is usually scattered among several heterogeneous data sources [6]. There is a need to harmonize this knowledge (in this case, phytopathology and entomology) and make it accessible in a clear and intuitive way for agricultural professionals such as farmers, researchers, and agricultural organizations, to help them to make informed decisions.

Semantic Web Technologies (SWT) has emerged as an outstanding approach to knowledge representation in a machine-understandable format, allowing data processing and integration from heterogeneous sources. Ontologies are the pillars of SWT. They provide an explicit specification of the concepts of a given domain [7], meaning that they describe real-world objects or the concepts within their context as symbols in a semantic schema. The logical formalisms behind the ontological models give machines a human-like commonsense in problem-solving and allow inference of new knowledge from existing knowledge. Ontology has a proven ability to represent knowledge across various domains for different purposes: to handle heterogeneous data in healthcare [8]; to automate higher education activities [9]; to improve recommendations for online retail markets [10], to enhance recommender system in tourism [11]; and to support intelligent decisions in agriculture [12], among others.

The identification and control of plant pests and diseases is a complex decision- and knowledge-handling topic. Where multiple factors affect the decisions, ranging from environmental conditions to biological causes, the various casual agents may produce overlapping symptoms, and not all the necessary knowledge is readily accessible. Consequently, there is a need for technology-based solutions to facilitate the complex decisions by making agricultural scientific knowledge and expertise more accessible to non-experts (e.g., farmers), thus enhancing their decision-making.

In this article we describe PDP-O, an ontology for the domain of plant pests and diseases. This ontology has been constructed as a knowledge base to develop an intelligent agricultural decision-support system to assist in the identification and control of plant pests and diseases. It is currently a work in progress. To achieve its purpose, the PDP-O models the domain of plant pathology and entomology by formally describing the related key concepts and semantic relationships among them, such as environmental conditions, living agents, symptoms, plant diseases, and pests. To populate it, we are carrying out a process to transform unstructured and non-ontological knowledge resources into a semantically enriched format. As a use case, this is applied to convert the knowledge about disease and pests affecting date palm crops into instances according to the PDP-O model. This is because such knowledge has rarely been addressed in the literature and has not been made semantically available to the public. PDP-O is easily extensible to further crops when needed.

The rest of this article is organized as follows. Section 2 discusses some recognized agricultural controlled vocabularies and ontologies, emphasizing those developed specifically for plant pests and diseases. Section 3 provides a detailed description of the PDP-O, including its classes, properties, and individuals. In section 4 we describe our approach to enhancing the PDP-O's reasoning capabilities. Section 5 shows a usage scenario and a preliminary validation of PDP-O, and in section 6 we present conclusions and directions for future work.

## 2. Literature Review

Reviewing the literature reveals that ontology applications in the agricultural domain have attracted the research community's attention. The main application of ontology is in agriculture: improvements to data integration and access [13] for timely and location-based answers to questions [14]; improvements to the performance of information retrieval systems [15]; (iv) facilitation of knowledge management [16]; semantic interoperability between heterogeneous sources; and to support decision-making [17]. According to one study [18], a frequent application of semantic technologies in agriculture is decision-support. This interest is because agricultural decisions are complex and depend mainly on knowledge that is spread across multiple domains and includes various factors and parameters. Ontology is considered an effective solution in supporting agricultural stakeholders to exploit existing knowledge to improve decision-making [12].

Several well-known ontologies and controlled vocabularies have been developed for the agricultural sector to represent agriculture knowledge. In addition, ontology repositories such as AgroPortal [19] have been developed as a reference resource to serve the agronomy community with vocabularies and ontologies. AGROVOC [20] is the most comprehensive semantic resource in the domain and was developed by the Food and Agriculture Organization (FAO). Similarly, the National Agricultural Library Thesaurus (NALT) [21] was originally released in 2002 by National Agricultural Library to satisfy the needs of the United States Department of Agriculture (USDA) and is primarily used to improve the indexing and retrieval of agricultural information. Plant Ontology [22] is a controlled vocabulary that has become the most popular reference to describe plants' anatomical structures (such as roots, fruits, stems, leaves, and seeds) and their growth and development stages from germination to ripening. The NCBI taxonomy [23] is a classification repository of living species, and it includes organisms' names and taxonomic lineages for the source organisms in the International Nucleotide Sequence Database Collaboration (INSDC). Regarding crop treatments, PubChem [24] provides information on chemical structures, biomedical annotations, and biological activities. This model provides information on chemical substances (i.e., pesticides) and the environmental effects that they may cause. Similarly, the ChEBI is an ontology [25] that provides an ontological classification of chemical substances. It contains molecular entities, both natural or synthetic, that can affect living organisms. Despite the huge size of these ontologies they describe plant pests and diseases in broad view only, with limited details, and their descriptions are informal, using text-based definitions.

At a closer range various other ontologies have been developed to model knowledge in the domain of plant pests and diseases. CropPestO [26] is an ontology to model the domain of plant pests. It was created by extensively reusing AGROVOC terms and relations; examples of such terms and relations are Plant Products, Plantae, Symptoms, Pests, and Control methods, isProducedBy, and hasPest. The symptoms caused by pests are presented in Spanish only. Plant Disease Ontology (PDO) [27] provides disease descriptions on the basis of the interaction between host plant and causal agents, mainly biotic, such as bacterial, fungal, and viral diseases; however, it does not consider other biotic factors such as insect pests or noxious weeds, or abiotic factors such as nutrient deficiency or environmental stress. RiceDO and TreatO [28] were created to model the plant disease domain, focusing on rice diseases in Thailand. RiceDO extended PDO, the previously mentioned ontology, and contains nine top-level classes and 13 object properties to meet the ontology's requirement for disease representation. By contrast, TreatO was developed to model rice disease control methods, with a focus on two methods: biological and chemical control. However, the modeling approach of these ontologies is limited to class description, which makes the observation data about plant disease exclusive to the system using this ontology.

The Plant-Pathogen Interactions Ontology (PPIO) [29, 30] was created to model the interaction between a host plant and pathogens, with a focus on bacteria. The design principle for this ontology is the disease triangle. This states that disease occurs when a pathogen interacts with a susceptible host in preferable environmental conditions. The ontology was created to model knowledge relating to the domain of plant pathology [31, 32], focusing on short-cycle diseases and perennial crops. For the identification of plant disease, this ontology relies on a set of SWRL rules to describe diseases based on their associated symptoms. These rules specify the disease to be inferred when the symptoms provided match the set of symptoms that describe that disease. Similarly, in another study [3] the authors propose an ontology to help farmers to identify insect pests affecting crops including sugar cane, soya, rice, and cacao, offering recommendations for disease treatment and controls. However, this modeling approach relies solely on the SWRL rules to define the insect pest damage (symptoms), making it necessary to present all symptoms linked to a given insect pest so that the system can determine the corresponding pest damage. A further study [33] presents an ontology developed to facilitate plant pests' identification and recommend suitable treatments. This ontology adapts the idea of the disease triangle described in PPIO and extends it to non-pathogen pests such as insects and weeds, yet most elements have only an informal description.

The above works present ontologies and semantic models that successfully capture and represent knowledge in the agricultural domain, specifically concerning pest and disease identification and control. However, most present less-formal representation models (lightweight ontologies), limiting their computational power and causing difficulties in inference, resulting in inadequate knowledge models for intelligent decision-support systems.

To address these limitations, this study provides an ontology to empower any system using this ontology to become more intelligent. In contrast to other ontologies, this ontology uses OWL expressivity and SWRL rules to describe its entities to maximize the reasoner engine's computational power. Furthermore, this ontology is enriched with in-depth computational data to provide a relevant and sufficient level of knowledge to support complex agricultural decisions.

## 3. PDP-O: Plant Diseases and Pests Ontology

To diagnose a plant pest or disease correctly and to provide trusted recommendations, knowledge concerning plant pests and diseases (in this case, plant pathology and entomology) needs to be modeled and represented in a semantically enriched format. The design of the PDP-O ontology involved collaboration with plant pathology and entomology experts from the Agricultural Department of King Abdulaziz University (KAU), Saudi Arabia. These experts are highly experienced in plant pests and diseases, specifically of date palm crops.

Furthermore, the PDP-O design considered and reused existing ontologies of plant pests and diseases, the most relevant being the Plant Disease Ontology (PDO), Crop-Pest Ontology, AgriDPalmOnto, PCT-O, Plant-Pathogen Interactions Ontology (PPIO), RiceDO and TreatO, and CropPestO. Investigation of these sources allowed us to identify and collect commonly used concepts to represent plant diseases and pests such as plant disorder, plant disease, causal agent, organism, microorganism, bacterium, fungus, virus, pest, pest damage, plant part, pathogens, and growth stage. Concerning the analysis of non-ontological sources (i.e., books, research articles, guidelines, and spreadsheets) we aimed to expand the knowledge base by adding further terms not included in previous ontologies. This activity allowed data collection to populate the ontology (assigning instances to the class to which they belong). For use case purposes, we paid special attention to sources published by the relevant authorities that relate to date palm cultivation, date palm morphological description, and the integrated management of date palm pests and diseases. Their textual content was parsed to extract related elements and then transformed into instances according to the PDP-O model and was also used to fill in the various properties that describe the ontology's instances.

PDP-O was implemented using Web Ontology Language (OWL) [41]. It is based on description logic (DL) and the most common knowledge representation language in the field of the Semantic Web. OWL increases RDF/RDFS description capabilities by describing complex relations between classes using logical rules, constraints, and detailed properties characterization. By building OWL ontology we could construct an intelligent ontology-based system with powerful reasoning ability. As a suitable ontology development environment, we chose Java-based Protégé [42]. Protégé is an open-source ontology editor that entirely supports the latest OWL 2.0 specification and provides a set of plugins for ontology visualization, integration, and reasoning, among others, to facilitate the creation of OWL ontologies. Ontology development is an iterative engineering process that includes several fundamental phases to ensure the correct achievement of deliverables, so to create PDP-O we merged various steps recommended by popular methodologies such as Methontology methodology [43], Grüninger and Fox methodology [44], and Noy and McGuiness methodology [45].

As a result, PDP-O contains 152 classes, 80 object properties, 32 data properties, 33 annotation properties, and a total of 534 individual instances. In its current version PDP-O contains 146 symptoms, 27 fungi, 18 diseases, and 14 insect pests relating to the date palm, all semantically described. For the purposes of the use case, PDP-O currently focuses on diseases and pests that affect date palm crops and have a major economic impact. However, PDP-O could be easily extended by integrating a wider set of diseases, pests, and symptoms. An excerpt from PDP-O is shown in Figure 1. In the next subsections we describe the PDP-O's main classes, properties, and individuals.

### 3.1 PDP-O Classes

Classes are sets that can contain individuals. A class hierarchy shows the special binary relation referred to as a 'subclass-of', or an 'is-a', or a 'subsumption' relationship, which captures the inheritance between classes. PDP-O was developed by following the middle-out approach introduced

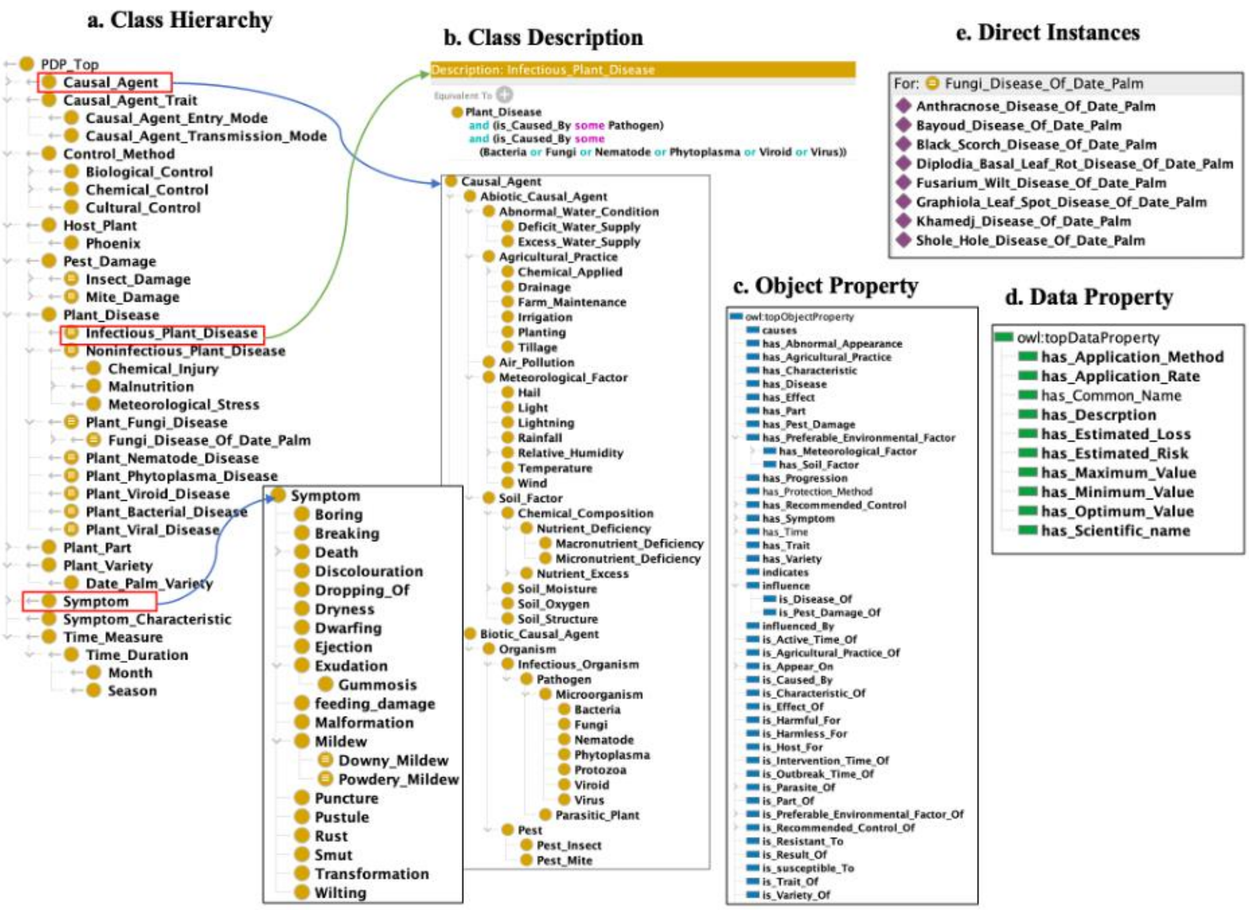


**Figure 1:** Excerpt from PDP-O: (a) class hierarchy; (b) logical description of infection plant disease class; (c) object properties; (d) data properties; and (e) example of instances of fungal disease in date palm class

in an earlier study [34]. The process started with the most notable concepts in the domain, generalizing up and specializing down into other concepts. In the PDP-O, all plant pest- and disease-related concepts are grouped under the *PDP_Top* class, which is a subclass of a predefined class owl:Thing. The *PDP_Top* class is specialized into 11 top-level classes: *Plant_Disease; Pest_Damage; Symptom; Causal_Agent; Causal_Agent_Trait; Host_Plant; Plant_Part; Plant_Variety; Symptom_Characteristic; Time*; and *Control_Method*. These classes represent the key concepts in the domain of plant pests and diseases and the root of their own sub-trees. They are necessary to the correct identification of a plant disease and to provide recommendations. To increase the semantic expressivity of our ontology, we paid special attention to classifying each key concept in PDP-O to a fine level of granularity. The following description focuses on only the important classes in PDP-O:

- ***Plant Disease***: this class represents all possible diseases caused by causal agents (biotic or abiotic) that affect plant health, expressed by the symptoms produced. To increase the semantic granularity of our ontology the *Plant_Disease* class was classified first into two types on the basis of the infection process: *Infectious_Plant_Disease* and *Noninfectious_Disease*. *Infectious_Plant_Disease* is a disease caused by infectious organisms (or pathogens) such as bacteria, fungi, nematodes, phytoplasma, viroids, and viruses. By contrast, *Noninfectious_Plant_Disease* is diseases caused by an abiotic agent, mainly chemical injury, malnutrition, and meteorological stress. Furthermore, the class of *Infectious_Plant_Disease* was specialized into six subclasses to represent each type of disease caused by an infectious organism. In addition, each type of disease was divided on the basis of the host plant. For example, the *Fungi_Disease_Of_Date_Palm* class represents a plant disease caused by a fungus that affects the date palm.
- ***Causal Agent***: this class represents the factor (or combination of factors) that causes plant disease. The Causal_Agent class was classified into broad categories that semantically describe the biotic and abiotic agents' taxonomy, mainly *Biotic_Causal_Agent* and *Abiotic_Causal_Agent*. The *Biotic_Causal_Agent* class, in turn, has an extended taxonomy to represent the various organisms that affect plant health. Examples of these organisms are bacteria, fungi, viruses, phytoplasma, viroids, protozoa, nematodes, parasitic plants, insects, and mites. *Abiotic_Causal_Agent* refers to non-living factors that cause plant disease or affect plant growth, such as humidity, light intensity, rainfall, soil type, and temperature.
- ***Symptom***: this class was created to represent visible external abnormal change in plant, for example clear changes to the normal color, form, or structure that appear on a plant part (such as spots on leaves). The Symptom class has an extended taxonomy or subclasses on the basis of common symptoms associated with plant disease. Examples of these subclasses include *Die_Back*, *Mildew*, *Blight*, *Rotting*, *Scorch*, *Rust*, *Wilting*, *Spotting*, *Dwarfing*, *Discolouration*, *Streaking*, *Spores*, and *Shot_Hole*. These symptoms are critical to diagnose a disease precisely and

to identify the cause of the disease or pathogen.

- ***Symptom_Characteristic***: this is an atomic class and has no subclass. We created it because the symptoms exhibited by a host plant or its parts may overlap, making it difficult to diagnose a disease accurately. Representing the distinct characteristics of each symptom enables the differentiation of symptoms, thus a more accurate diagnosis of disease or pest.
- ***Plant_Part***: this class represents the various plant parts and establishes an 'is_Part_Of' relationship to Host_Plant. We need this class because some pests and diseases tend to affect a specific part of a plant. Thus, to identify a disease accurately it is essential to determine which part is showing the symptom.
- ***Control_Method***: this class was created to model the procedures that can be recommended to control a specific kind of plant disease or pest damage. It was classified into three main types: *Biological_Control; Cultural_Control*; and *Chemical_Control*. *Biological_Control* uses natural enemies or biological agents (e.g., insects and fungi) to control plant diseases or pest damage; *Cultural_Control* describes manual measures such as burning or removing infected parts; *Chemical_Control* makes use of various chemical substances.

### 3.2 PDP-O Properties

Building the class hierarchy is not enough to create an in-depth computational ontology because, itself, the hierarchical structure cannot fully describe any class. Complete description is accomplished by assigning properties. PDP-O defines the set of object properties necessary to identify a given disease or pest correctly and to generate recommendations on the appropriate control methods to counteract that pest or disease. Disease identification is a complex process, involving the complex relationships between entities. Therefore, we paid special attention to capturing and representing as far as possible the inherent relations between concepts. Table 1 describes the most important PDP-O object properties.

**Table 1:** Important object properties defined in PDP-O.

| *Object Property* | *Meaning* |
|---|---|
| *has_Symptom* | Describes the relation between a disease or pest X presents abnormal change (Symptom) Y in a host plant |
| *is_Caused_By* | A disease Y occurred because of an agent X (Abiotic or Biotic) |
| *is_Disease_Of* | A plant disease that has influence on host plant |
| *is_Pest_Of* | An organism Y is past of host plant X |
| *has_Active_Time* | Describes the relation of an organism that has active time |
| *has_Effect* | Describes the relation between a causal agent and its effect, which is a symptom |
| *is_Appear_On* | Describes the relation between a symptom and associated plant parts. |
| *has_Agricultural_Practice* | A disease or pest Y occurred because of an agricultural practice X |
| *has_Environmental_Factor* | A disease or pest Y occurred because of environmental factor X such as *Humidity, Rainfall, Temperature and Soil_Factors* |
| *has_Part* | A plant part Y that can be identified as being composed of one or more parts |
| *is_Control_By* | A treatment or action X that might prevent or reduce the effect of a disease or damage Y |
| *has_Variety* | A host plant X has a variety Y |
| *has_Characteristic* | A symptom that has characteristic |
| *is_susceptible_To* | A plant variety that is susceptible to plant disease |

In addition to the properties described in Table 1, PDP-O defines the data properties that establish the relationships between individuals and data values (such as integers and strings). Since it is vital to know both the scientific and common names of each disease or pest, we created the data properties *has_Scientific_Name* and *has_Common_Name* to assign them to each disease or pest. Furthermore, symptom distribution and progression over the affected plant part can be especially important to the identification of the causal agent. For example, suppose the symptoms begin in a specific area of the plant and slowly spread to other areas, with changes to the severity of the disease's symptoms over time. This can be evidence of the presence of a biotic agent, so we defined the *has_Descrption* to provide a textual description of the produced symptoms, such as symptom distribution and progression.

Furthermore, we created and reused some standard annotation properties to add natural language definitions of PDP-O entities. For example, we reused four annotation properties from Gene Ontology [35] – *hasExactSynonym, hasBroadSynonym, hasNarrowSynonym,* and *hasRelatedSynonym* – to express similarity among concepts. These properties play a key role in managing the living species information covered by PDP-O (e.g., bacteria, fungi, viruses, insects, and mites), because of the use of alternative names for semantically equivalent concepts when presenting living species information in agricultural texts. Figure 2 shows an ontological view of using these properties to represent the relationships between PDP-O classes. For example, properties of the class *Plant_Disease* include *has_Symptom, has_Causal_Agent, influence, and has_Recommended_Control*. The binary relation 'is-a' links the classes between each other considered as object properties. It is worth mentioning here that the 'is-a' relation has two uses. For example, when we say that 'Pathogen is-a *Causal_Agent*, we relate two types to one another; however, when we say '*Copper_Oxychloride* is-a *Chemical_Control'*, here we are relating an individual to its class; in other words, we are specifying the type information of a particular individual.

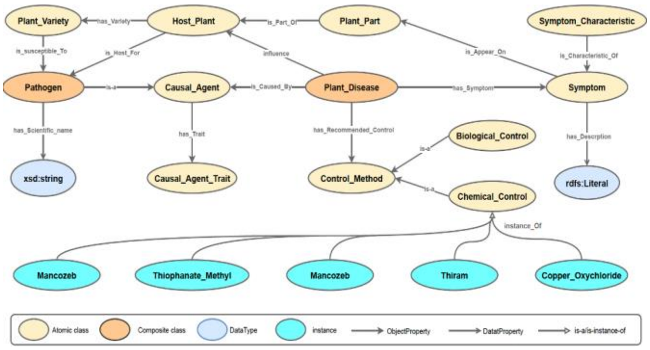


**Figure 2:** Ontological view of relations included in PDP-O and their role in representing relationships between classes

### 3.3 PDP-O Individuals

To instantiate our ontology and build the knowledge base, we extracted data from unstructured specialized documents and put them into the ontology with the extracted triples. Currently PDP-O contains 534 individuals (instances) added to the main classes in PDP-O that are featured in most competency questions. We emphasized *Plant_Fungi_Disease*, *Insect_Damage*, *Organism*, *Plant_Part*, *Control_Method* and *Symptom*, as those classes play an essential role in disease or pest identification and control. In addition, we focused on describing 18 fungal diseases that affect the date palm crop. The ontology covers 14 insect pests that have significant economic impact.

## 4. Modeling for Enhanced Reasoning

As mentioned, we aimed to address the limitations of previous works by developing a domain ontology with sufficient semantic expressivity and far stronger reasoning ability. Since this ontology is anticipated to become a knowledge base to enable the development of an intelligent decision-support system that facilitates plant disease identification and control, three main strategies were adopted: (1) Enhanced reasoning through logical class description; (2) Enhanced reasoning through relationship modeling; and (3) Enhanced reasoning through SWRL rules. The following subsections provide a detailed description of each strategy.

### 4.1 Enhanced reasoning through logical class description

A class can be defined in various ways: (1) informally, by natural language text (textual definition); (2) by logical formulae; (3) by properties; or (4) by the set of individuals, or instances, that belong to the class. Among these ways, reasoning over the textual definition is not employed, so to enhance the reasoning power of ontological models a developer needs to focus on the other three. We paid particular attention to describing the main classes in PDP-O by logical description, for example *Fungi_Disease_Of_Date_Palm* class was defined thus:

$$Fungi\_Disease\_Of\_Date\_Palm \equiv Plant\_Fungi\_Disease \sqcap is\_Disease\_Of.Date\_Palm. \quad (1)$$

**Definition 1** states that fungal disease of date palms is a plant disease caused by fungus and affects the date palm. We defined the *Plant_Fungi_Disease* class using the following logical definition:

$$Plant\_Fungi\_Disease \equiv Infectious\_Plant\_Disease \sqcap \forall\, is\_Caused\_By.Fungi \quad (2)$$

**Definition 2** states that plant fungal disease is an infectious plant disease caused by fungus. We defined the *Infectious_Plant_Disease* class using the following logical definition:

$$Infectious\_Plant\_Disease \equiv Plant\_Disease \sqcap \exists is\_Caused\_By.Pathogen. \quad (3)$$

**Definition 3** states that an infectious plant disease is a plant disease caused by an infectious organism (or pathogen i.e., bacteria, fungi, nematode, phytoplasma, viroid, and virus).

Where ≡ is a symbol in DL to indicate equivalence between classes, ∃ is the existential restriction symbol in DL, which is used to denote that at least one instance of a class has a relation with the classes on the right-hand side of axioms, ∀ is the universal restriction symbol in DL that is used to denote that all values of the specified relation must come from the classes on the right-hand side of axioms, ⊓ is a conjunction symbol in DLs to indicate the intersection between classes, and ⊔ is a disjunction symbol in DL to indicate the union between classes.

Based on these definitions, a reasoner can automatically infer new knowledge or facts when an individual or data item is added to these classes. For example, we added Fusarium_Wilt_Disease as an instance of the class Fungi_Disease_Of_Date_Palm. When this RDF triple has been asserted, the reasoner automatically infers the following additional RDF triples, based on the definition (1-2):

*Fusarium_Wilt_Disease rdf:type Plant_Fungi_Disease.*
*Fusarium_Wilt_Disease rdf:type Infectious_Plant_Disease.*
*Fusarium_Wilt_Disease is_Disease_Of Date_Palm.*

Furthermore, when this RDF triple has been asserted (*Fusarium_Wilt_Disease is_Caused_By Fusarium_Oxysporum_Schlecht*), the reasoner automatically infers the following additional RDF triples based on definitions (2-3):

*Fusarium_Oxysporum_Schlecht rdf:type Fungi.*
*Fusarium_Oxysporum_Schlecht rdf:type Pathogen.*

These inferences, as well as the triples that lead to them, can be seen in Figure 3.

### 4.2 Enhanced reasoning through relationships modeling

OWL 2 allows provides various property characteristics to make explicit the relationship between entities and describe it more precisely. For example, we can specify which property is the inverse of another or disjoint to. Consequently, we can enhance computational reasoning power by enriching the meaning of object properties with properties' characteristics.

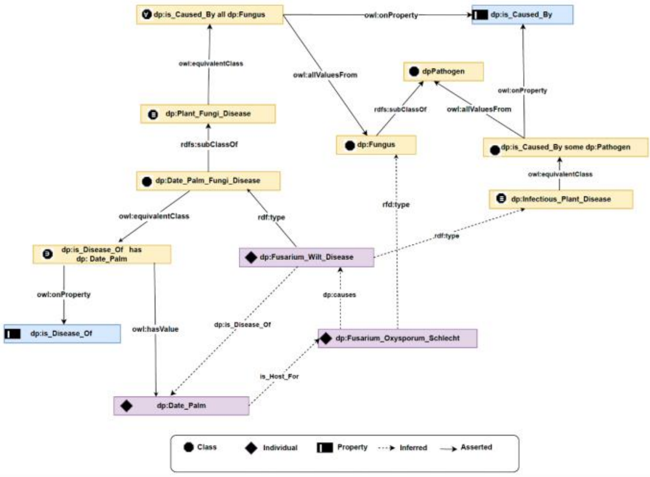


**Figure 3:** Asserted RDF triples to express logical definition of some classes in PDP-O, as well as the inferred RDF triples based on them in Manchester syntax

Therefore, we specified the inverse property of each object property in PDP-O, regardless of its *subPropertyOf* level. In addition, we restricted each object property by using *rdfs:domain* and *rdfs:range*. Furthermore, we attached characteristics to object properties, such as *Symmetric*, *Asymmetric*, *Functional*, *Inverse Functional*, *Transitive*, *Reflexive*, and *Irreflexive*. Figure 4 is a graphical display of inferences based on properties modeling in Manchester syntax. For example, it shows that the object property *is_susceptible_To* has the class *Plant_Variety* as its domain, and declares that the owl:inverseOf the object property is *is_Harmful_For*. In addition, the object property causes has as its class domain *Causal_Agent* and declares that the *owl:inverseOf* the object property is *is_Caused_By*. Furthermore, the object property is_Disease_Of has the class *Plant_Disease* as its range and defines the property as the *subPropertyOf influence*, which in turn declares that the *owl:inverseOf* the object property is *influenced_By*.

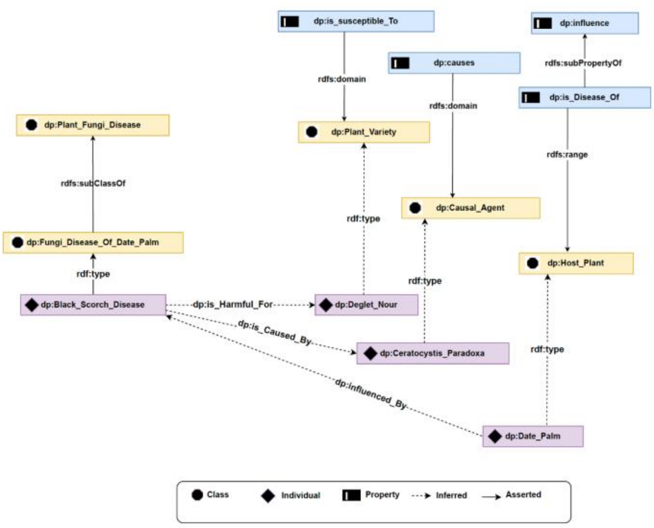


**Figure 4:** Inferences drawn from properties modeling in Manchester syntax

Based on properties definitions, the reasoner automatically infers new knowledge or facts when an individual or data item is added to these classes. For example, when this RDF triple is asserted (*Deglet_Nour is_susceptible_To Black_Scorch_Disease)* the reasoner automatically infers the following additional RDF triples based on the semantic property *is_susceptible_To*:

*Deglet_Nour rdf:type Plant_Variety.*
*Black_Scorch_Disease is_Harmful_For Deglet_Nour.*

### 4.3 Enhanced reasoning through SWRL rules

SWRL (Semantic Web Rule Language) is an OWL-based rule language for complex knowledge modeling. It allows deductive reasoning on the basis of user-defined rules and increases the expressivity of ontological models by permitting the definition of relations that cannot be defined through OWL DL. In the context of this work, these rules can be of huge benefit due to the complex relationships between the domain concepts. For example, the symptoms associated with a particular disease in fact refer to the effect that the pathogen causes when it infects the host plant. Based on such facts, the authors define the following SWRL rule:

$$\begin{array}{l} dp{:}Plant\_Disease(?pd1)\hat{} \\ \quad dp{:}is\_Caused\_By(?pd1,?ca1)\hat{} \\ \quad dp{:}is\_Effect\_Of(?sym,?ca1) \\ \quad -> dp{:}has\_Symptom(?pd1,?sym) \end{array} \tag{4}$$

$$\begin{array}{l} dp{:}Pest\_Damage(?pd1)\hat{} \\ \quad dp{:}is\_Caused\_By(?pd1,?ca1)\hat{} \\ \quad dp{:}is\_Effect\_Of(?sym,?ca1) \\ \quad -> dp{:}has\_Symptom(?pd1,?sym) \end{array} \tag{5}$$

Rule (4) states that if a plant disease is caused by a specific causal agent that produces an effect on the host plant, we refer to its effect as a symptom of the disease caused by that causal agent. Rule (5) is closely related to Rule (4), but concerns pest damage, and states that if pest damage is caused by a specific pest that produces an effect on the plant, we refer to its effect as a symptom of the damage caused by this pest.

These rules can improve the ability of the ontology to diagnose a disease or pest, as they distinguish between similar symptoms produced by differing causal agents. Once a disease has been diagnosed by the rule-based engine, such as Pellet and Hermit, it obtains all possible diseases. We present a usage scenario to demonstrate how these rules enhance the reasoning power of our ontology to provide accurate disease identification in the following section.

## 5. Results and Discussion

PDP-O is an open-access ontology of plant pests and diseases that aims to serve as a knowledge base to facilitate their identification and control. It works to capture, represent, and model unstructured knowledge relating to plant diseases and pests in a machine-understandable format. The PDP-O knowledge base contains information that can support agricultural stakeholders' decision-making and defines an in-depth computationally enriched schema that could play an essential role in simplifying data integration from heterogeneous sources and enable the development of agricultural intelligent systems.

In this section we illustrate how the PDP-O and its associated inference mechanisms can be used to solve complex problems intelligently and support agricultural decisions. First, we describe an example scenario to demonstrate its ability to identify a plant disease. Next, the experimental results are shown and discussed. Finally, a preliminary assessment of PDP-O based on its automated tools is provided to demonstrate its validity.

### 5.1 Ontology Usage Scenario

This section focuses on an exemplary scenario of how PDP-O and its associated inference mechanisms can be used to advance decision-making in the management of plant pests and diseases. For this purpose, Snap SPARQL Query and Pellet reasoner in Protégé are used to query our ontology and obtain results. It must be noted that we used the Snap SPARQL Query tab that works with the reasoner and returns inferred results, rather than the SPARQL Query tab that does not. For demonstration purposes, we present and discuss the following exemplary scenario:

*'Suppose the palm inflorescence is covered with white powder; what does this symptom indicate? And what is the causal agent that cause this problem?'*

This scenario represents a situation in which a single symptom is observed on a date palm. The problem identification step starts when the SPARQL query gets the resource from the PDP-O that directly matches the graph patterns specified by the *WHERE* clause of SPARQL query, as shown in Figure 5. The SPARQL query in Figure 5a searches for the disease or pest that affects a plant with the scientific name *Phoenix dactylifera* and produces a 'white powder' symptom that appears on a plant part of 'palm inflorescence'. It finds what this symptom indicates and also which causal agent causes this symptom. The results retrieved from this query are shown in Figure 5a in the red rectangle. PDP-O was able to determine what this symptom indicates. We can note that there is a single defined problem associated with the 'white powder' symptom, namely *Inflorescence_Rot_Disease.* Furthermore, the results indicate that the causal agent that produces this symptom and, in turn, causes *Inflorescence_Rot_Disease*, is *Mauginiella_Scattae.*

It is important to know the logical formalism that guides the reasoner engine to reach this conclusion. The object property *has_Symptom* has the union of (*Pest_Damage* and *Plant_Disease*) as its domain and *Symptom* class as its range. It is also declared that the *owl:inverseOf* the object property is *indicate.* Therefore, although there is no explicit statement that states that 'white powder' indicates *Inflorescence_Rot_Disease*, the reasoner deduces this on the basis of the definition of the property *has_Symptom*. In addition, Rule 1 (defined in section 5.3) states that if a plant disease is caused by a specific causal agent, refer to the effect produce by this causal agent as a symptom of the disease caused by this causal agent. On this basis we can see from Figure 5a that the reasoner deduces that 'white powder' is a symptom indicative of *Inflorescence_Rot_Disease* since this symptom is an effect of the causal agent *Mauginiella_Scattae*, although other causal agents also cause *Inflorescence_Rot_Disease*.

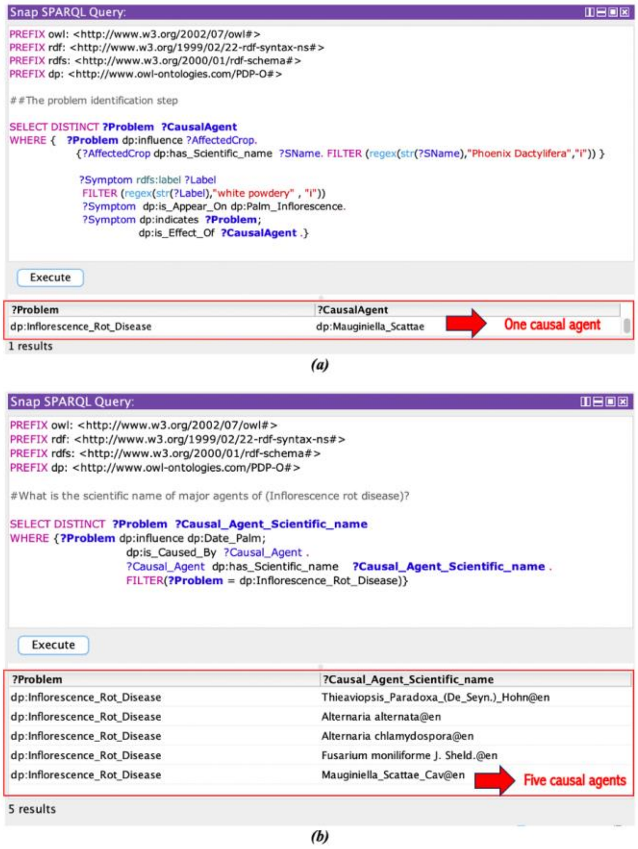


**Figure 5:** Sample of SPARQL queries: (a) identify the problem associated with 'white powder' symptom; (b) identify causal agents that cause inflorescence rot disease of date palm

Figure 5b shows the SPARQL query written to retrieve all possible casual agents of *Inflorescence_Rot_Disease*. We can see from the result in Figure 5b in the red rectangle that there are five casual agents of *Inflorescence_Rot_Disease* and that each produces similar symptoms yet of different colors. For example, *Inflorescences_Covered_With_Pink_Powder* is the symptom when the *Inflorescence_Rot_Disease* is caused by *Fusarium_Moniliforme*, and *Inflorescences_Covered_With_Black_Powder* is the symptom produced when the same disease is caused by *Thieaviopsis_Paradoxa*. Therefore, based on the classification and properties definition and SWRL rules, PDP-O successfully differentiates between various symptoms associated with a single disease caused by differing causal agents.

### 5.2 Ontology Evaluation

Ontology evaluation is the last step in the methodology presented in this work for computational ontology design and development. It is a vital step in the process to assess its quality and suitability for a particular application domain. Developing a high-quality ontology is essential since it impacts the overall system quality and user satisfaction [36, 37]. It is evident that a good-quality ontology is necessary to ensure an overall usable ontology-based DSS. Therefore, before deploying an ontology in a system it is essential to assess its quality at the level of content and structure [38]; however, there is as yet no consensus approach to assessing


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ontology, and researchers have suggested several methods over time.

Ontology evaluation means technically assessing ontologies, their associated software environments, and documentation on the basis of a frame of reference such as a set of competency questions or requirements [39]. Gruber [40] defines five design criteria for ontologies' evaluation: clarity; coherence; extendibility; minimal encoding bias; and minimal ontological commitment. Gómez-Pérez [39] also established five criteria for ontology evaluation. Some overlap with Gruber's criteria, such as consistency and expendability, which are similar to Gruber's coherence and extendibility. In this work, we carried out automatic consistency checking as a preliminary validation of PDP-O.

#### 5.2.1 Criteria-Based Evaluation

The criteria-based evaluation method is based on predefined criteria. In this work, two important criteria are used to evaluate the PDP-O: consistency and coherence. Conciseness, as defined by Gómez-Pérez [39], means that definitions should be concise, clearly stated, and unambiguous. Coherence, as defined by Gruber [40], means that the ontology should support inferences that are logically consistent with the formal definitions (the defining axioms) and have no contradictions. Also, concepts described informally should be coherent, which means that no statement inferred from a formal definition contradicts a definition given in natural language. As the OWL ontology is based on DL, it has strong expressive capability under the premise of computational decidability and computational completeness, thus enabling reasoning mechanisms such as consistency checks of OWL ontologies. Therefore, Pellet reasoner 2.2.0 (Protege plugin) was constantly used to check that the ontology is logically consistent at the level of structure and syntax (e.g., classes are arranged in the correct hierarchy and correctly relate to each other's via binary relations, and correctly define their instances' characteristics and constraints). For example, we declared that the object *has_Symptom*, which means that a disease or disorder X presents symptom Y in a host plant, as asymmetric. Thus, if we accidentally related Y to X using the *has_Symptom* property, an inconsistency would be detected automatically by the reasoner, as shown in Figure 6, because the asserted RDF statement does not satisfy the semantic definition of the *has_Symptom* property. Once inconsistencies were no longer detected in the PDP-O, knowledge reasoning could be performed. Furthermore, we used OntoDebug 0.2.2 (an interactive ontology debugging in Protégé) to check the ontology's coherence and consistency. The result of this test is presented in Figure 7, showing that the PDP-O is both coherent and consistent.

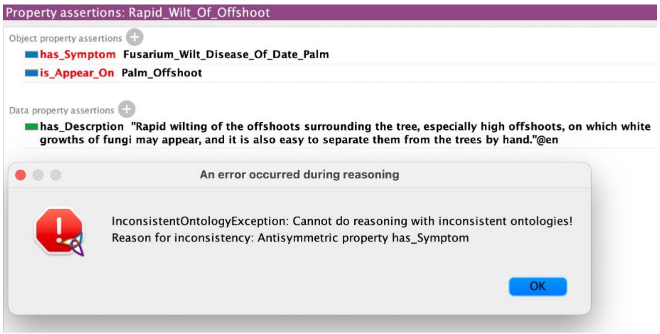


**Figure 6:** Example of ontology inconsistencies error detected by Pellet reasoner when asserting RDF statement that is logically incorrect

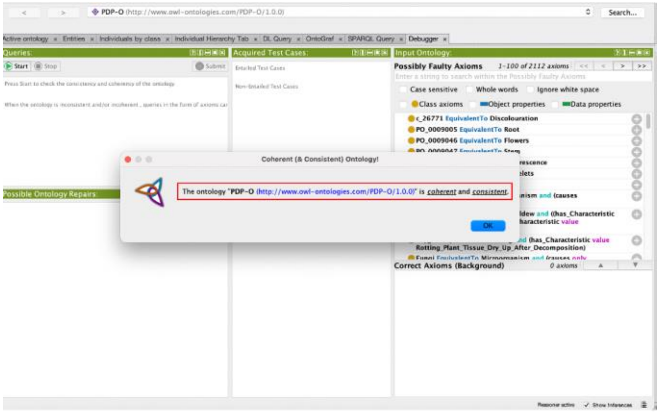

**Figure 7:** Result of PDP-O ontology syntactic test using OntoDebug in Protégé

## 6. Conclusions and Future Work

Identifying the type of insect pest or disease that is affecting a crop is a complex decision- and knowledge-handling problem. To manage pests and diseases effectively and make informed decisions, agricultural practitioners (i.e., farmers or farm owners) need to access the right information in a timely manner. However, information about pest and disease management practices is scattered across heterogeneous and human-oriented formats such as PDF, HTML, CSV files, and Excel worksheets. This situation makes the extraction of valuable insights for decision-making challenging. Semantic technologies have proven effective for data integration and representation from heterogeneous sources. Ontologies constitute the pillars that support the effective functioning of semantic applications. Additionally, they offer an alternative solution to static knowledge bases for decision-support systems (DSSs) by facilitating the execution of reasoning and inference from the knowledge.

Several ontologies and semantically enhanced tools have been built in the domain of agriculture, specifically concerning pests and diseases identification and control. However, they have several limitations, primarily as they present less formal representation models (lightweight ontologies). In other words, they lack the in-depth formalism required to support complex decisions (i.e., identifying the insect pests or diseases that affect a crop). To this end, we present PDP-O, an ontology of the domain of plant pests and diseases. This ontology is expected to serve as a knowledge base to enable the development of an intelligent decision-support system to assist decision-making regarding plant pests and diseases identification and control. We describe the construction of PDP-O, with a detailed description of the design process including the creation of the class hierarchy, properties, and individuals.

To address the limitations of previous works and empower the system to use this ontology to become more intelligent, we introduce an approach based on three strategies for enhanced reasoning, mainly: (1) enhanced reasoning through the logical class description; (2) enhanced reasoning through relationship modeling; and (3) enhanced reasoning through SWRL rules. A use case is presented, with real-life data regarding date palm pests and diseases, to demonstrate the efficiency of PDP-O and its associated reasoning in providing accurate results. As a preliminary validation, we show the logical consistency of PDP-O through automated tools in the Protégé environment, and the results show that the PDP-O is both coherent and consistent.

Finally, although PDP-O shows promising results, further enhancements are required if it is to handle large data sets. For instance, the current version of PDP-O is centered on the date palm, and it is unable to deal with diseases and pests affecting other crops. This is due to the manual instantiation of the ontology, which led to the insufficiency of the data and rules covered by the PDP-O. Future work should explore other approaches to ontology population from structured, semi-structured, and unstructured data sources. Such approaches may allow for automatic ontology population and also help to keep the knowledge up to date.

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