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An Ontology for Apiculture Practices (Onto4API): Towards Semantic Interoperability and Knowledge Sharing in the Apiculture Community

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ABSTRACT: *This study presents the development of Onto4API, a domain ontology designed to support semantic interoperability and structured knowledge sharing in the field of apiculture. The ontology addresses the lack of standardized, machine-interpretable vocabularies that hinder knowledge integration and decision support in traditional beekeeping practices. Developed under the guidance of subject-matter experts from the Türkiye Apiculture Research Institute, Onto4API formalizes key concepts, relationships, and production practices in modern beekeeping. The ontology was built using OWL 2 and RDF/XML syntax, and includes 67 classes, six object properties, and 10 data properties. Following the METHONTOLOGY framework, our approach ensures methodological rigor from specification to implementation and evaluation, combining expert validation, reasoning-based consistency checks, and SPARQL-based functional testing. To demonstrate its practical utility, a web-based educational tool was implemented using ASP.NET MVC and dotNetRDF. This prototype enables users to explore apiculture knowledge through SPARQL-based queries in a guided question-and-answer format. By providing a reusable and extensible semantic framework, Onto4API lays the groundwork for future ontology-driven agricultural systems, including intelligent decision support, educational tools, and interoperable data services in apiculture and beyond.*

Keywords: *Apiculture practices ontology, beekeeping ontology, apiculture knowledge sharing, semantic interoperability.*

Arıcılık Uygulamaları için Bir Ontoloji (Onto4API): Arıcılık Topluluğunda Anlamsal Birlikte Çalışabilirlik ve Bilgi Paylaşımına Doğru

ÖZ: *Bu çalışma, arıcılık alanında anlamsal birlikte çalışabilirliği desteklemek ve yapılandırılmış bilgi paylaşımını kolaylaştırmak amacıyla geliştirilen Onto4API isimli alan ontolojisinin oluşturulma sürecini sunmaktadır. Onto4API, geleneksel arıcılık uygulamalarında bilgi entegrasyonunu ve karar destek sistemlerini engelleyen standart, makine tarafından yorumlanabilir ortak kavramların eksikliğine çözüm getirmeyi amaçlamaktadır. Ontoloji, Türkiye Cumhuriyeti Tarım ve Orman Bakanlığı Arıcılık Araştırma Enstitüsü'nden uzman araştırmacıların rehberliğinde geliştirilmiş olup, modern arıcılıkta kullanılan temel kavramları, ilişkileri ve üretim pratiklerini biçimsel bir yapıya kavuşturmuştur. OWL 2 ve RDF/XML sözdizimi kullanılarak oluşturulan Onto4API, 67 sınıf, 6 nesne özelliği (object property) ve 10 veri özelliğinden (data property) oluşmaktadır. Ontolojinin geliştirilme süreci, METHONTOLOGY metodolojisi temel alınarak yürütülmüş; bu sayede tanımlamadan uygulamaya ve değerlendirmeye kadar tüm adımlar metodolojik bütünlük içinde ele alınmıştır. Süreçte uzman doğrulaması, mantıksal tutarlılık kontrolleri ve SPARQL temelli fonksiyonel testler uygulanmıştır. Ontolojinin pratik yararını göstermek amacıyla, ASP.NET MVC ve dotNetRDF teknolojileri kullanılarak SPARQL tabanlı soru-cevap sistemiyle çalışan web tabanlı bir eğitim aracı geliştirilmiştir. Yeniden kullanılabilir ve genişletilebilir bir anlamsal çerçeve sunan Onto4API, yalnızca arıcılık alanındaki dijital dönüşüme katkı sağlamakla kalmayıp, gelecekte geliştirilecek karar destek sistemleri, eğitim platformları ve birlikte çalışabilir veri servisleri için de sağlam bir temel oluşturmaktadır.*

Anahtar Kelimeler: *Arıcılık uygulamaları ontolojisi, arıcılık ontolojisi, arıcılık bilgi paylaşımı, anlamsal birlikte çalışabilirlik.*

INTRODUCTION

In recent years, the health and sustainability of honey bees and other pollinators have garnered increased attention from both the scientific community and the general public. This growing interest stems from the recognition of their critical role in ecosystem functioning and food security, particularly within controlled agricultural systems (Potts *et al.*, 2010; Vanbergen *et al.*, 2013). Unlike many other model insects such as Drosophila, honey bees exhibit caste-specific social behaviour, remarkable phenotypic plasticity, and complex genetic traits. These features have made them a subject of extensive biological inquiry, including one of the earliest insect species to have their genome sequenced (Weinstock, 2006). Due to the inherently interdisciplinary and complex nature of apiculture research—spanning biology, ecology, entomology, agriculture, and environmental science—there is a pressing need for formalized knowledge representation systems. Ontologies play a central role in addressing this need by offering a structured and semantic framework for organizing and integrating knowledge related to honey bee biology and apicultural practices. By capturing domain-specific concepts and their interrelations, ontologies enhance knowledge discovery, data annotation, and interoperability across systems (Seeley, 2009; Steeves, 1999). To date, no comprehensive ontology dedicated to apiculture practices has been developed, particularly one tailored to traditional beekeeping activities. This absence creates significant limitations for data-driven innovation in the field. Practical beekeeping activities generate valuable knowledge; however, without standardized representations, it becomes difficult to collect, structure, and share this information in a reusable form. There is a growing need for digital platforms that can disseminate relevant and structured knowledge to beekeepers, researchers, and newcomers to the field. A well-designed ontology can guide such platforms in defining, organizing, and sharing meaningful content. In response to this need, we present Onto4API (Ontology for Apiculture Practices)—a domain-specific ontology designed to formalize traditional beekeeping knowledge. Onto4API was developed using the OWL (Web Ontology Language) standard with Protégé, incorporating insights and validation from senior researchers affiliated with Türkiye’s National Apiculture Research Center. The ontology focuses on modelling traditional apiculture practices and does not currently cover sensor-based or smart beekeeping systems. Onto4API aims to support a broad range of stakeholders, including beekeepers, aspiring apiculture entrepreneurs, academic researchers, and data scientists interested in agricultural knowledge representation. By providing a structured vocabulary and semantic relationships, the ontology fosters knowledge sharing, facilitates platform development, and promotes semantic interoperability in the apiculture domain (Hessel *et al*., 2018; Hughes *et al.*, 2008).

While there has been substantial progress in the digitalisation of agriculture, for the domain of apiculture coherent and interconnected platforms are still missing to enable structured data exchange. There is traditional knowledge that is widely spread in the form of handwritten notes or local guides etc., and it is difficult to formalize such information into a digital format. Besides the fragmentation of vocabularies and lack of semantic structure, it is also observed that tools for education, as well as management in apiculture usually do not have adequate support when working across systems. And, finally, without standardised ontologies and taxonomies that could be read by machines, it is very hard to include this knowledge into scalable systems. Onto4API addresses these challenges by providing a unified and reusable semantic layer over apiculture data.

The remainder of this study is structured as follows: Section 2 details the methodology used for developing Onto4API and the conceptualization process. Section 3 presents the practical application of the developed ontology through an illustrative use case. Section 4 concludes the study by summarizing the main findings and offering suggestions for future research.

METHODOLOGY

Overview

This section describes a summary of the methodology used to build Onto4API, an ontology that has been dedicated to traditional apiculture. METHONTOLOGY (Fernández López *et al.*, 1997) was followed which is a methodology proposed for ontology building, widely adopted and contains a systematic treatment targeting all steps involved in an ontology generation process—from specification to evaluation. Under this framework, the development process of Onto4API consisted of specification, knowledge acquiring, conceptualization, formalization, implementation and evaluation. The full ontology file and related documentation are publicly available at our GitHub repository: https://github.com/sahinaydin/onto4api.

Specification

The essential goal of Onto4API was to add semantic structure to traditional apiculture practices. The ontology is aimed at a wide user base including professional beekeepers, people new to beekeeping, researchers and data scientists interested in studying or sharing phenotypic descriptions related to bee biology. Onto4API includes a rich vocabulary of concepts related to different aspects of apiculture such as general beekeeping, honey (White, 1978) production, propolis (Ghisalberti, 1979) harvesting, pollen collecting (Huang, 2012), royal jelly extraction (Pavel *et al.*, 2011), beeswax (Tulloch, 1980) processing, bee venom (Khalil *et al.*, 2021) harvesting, and apilarnil (Sidor and Dżugan, 2020) production. By defining such vocabulary, Onto4API is targeted to promote semantic interoperability, knowledge reuse and information sharing in the apiculture community.

Knowledge Acquisition

The training phase of Onto4API development was adapted from a METHONTOLOGY methodology and employed tacit and explicit instances of knowledge. Selected domain experts from Apiculture Research Institute (ARI), Republic of Türkiye Ministry of Agriculture and Forestry participated in the construction end ontological model development. The process began with a brainstorming session of ARI-experts and ontology-designers to identify the core concepts and limit the domain. Afterwards, an informal textual analysis of bee domain resources (i.e., books on beekeeping, manuals and technical guides) was made (Laidlaw and Page 1997; Winston 1991). The objective was to abstract the useful domain terms and discover some conceptual patterns needed for traditional apiculture. A formal textual analysis was performed afterwards in order to (semi-)automatically classify and structure the obtained knowledge, allowing analysis of hierarchical relations and definability of attributes. Finally, structured interviews with ARI experts and ontology engineers were conducted. This exercise assisted with the development of terminology, disambiguation and validation of entity relationships. The iterative character of the procedure allowed continuous feedback and improvement, which possibly added to the reliability and relevance of the ontology.

Conceptualization

The Onto4API ontology is organized according to three top-level classes, which represent fundamental components of apiculture in a traditional way. These are: Bee_Products which includes the extracted biological materials from honey bees; bee products, collected by beekeepers during hue harvest and trade applications, Beekeeping_Equipments that describes the devices, machines and apparatus used in apiculture technology at different stages of the process and Honey Bee modeling components managing all aspects related to colony function and product production. All three classes are directly classified under owl:Thing, according to OWL's default class hierarchy, and guarantee semantic coherence within the ontology. This "three-layer transition" has kept Onto4API conceptually clear and modular, thus enabling the software to be both extendable and domain-coherent. Subclasses of these upper-level classes further specialise the classes to present specific entities, processes or roles in the context of traditional beekeeping. The design is informed not only by domain semantics but also practical considerations for ontology reuse and scalability. Figure 1 illustrates the class hierarchy of the Onto4API ontology.

The Bee_Products class in Onto4API, intended to model formally the wide range of biological outputs flowing from honey bee activity, several being traditional apiculture merchandise. This class is additionally a subclass of the owl:Thing and serves as the main conceptual node gathering all edible, medicinal, or financially valuable products from a beehive. In addition, for semantic granularity purposes and compatibility with bio-categorisations, Bee_Products, is then broken down into three more specific subclasses: Apilarnil, Collected_Bee_Products and Secreted_Bee_Products. The product known as Apilarnil represents a specialized bee product with respect to its stage of development. It is the stage of male bee larvae that are 3-7 days old and have not yet been capped as a pupal cell. This product is mainly harvested for its excellent content of nutrition and hormone, usually for traditional medicine and as a dietary supplement. From an ontological perspective, Apilarnil will be also represented as a separate subclass because it has specific origin by emerging from drone brood, unique for production technique and biological classification in comparison to other collected products (pollen) or secreted substances (royal jelly). The proposed approach also allows such an ontologically anchored classification of bee derived products according to its origin (biological vs. behavioral) and the mechanism (acquiring modus), preventing failures in data annotation, automated reasoning and domain-wise query expansion.

The Collected_Bee_Products Class, is a class that is specifically one type of nonendogenously produced sub-type of substance: those gathered by bees from the environment and worked on in their hive. It forms a subclass of Bee_Products and consists of entities that are collected through foraging activity, while highlighting the ecological relationships between honey bees and flowers. This class includes three major subclasses: Honey, Pollen, and Propolis, which are essentially important for colony survival as well as in commercial apiculture. The subclass referred to as Honey is a metabolizable carbohydrate product converted through a complex biochemical reaction. Nectar foraging honey bees enzymatically convert plant nectar into smaller sugars, drying it down by removing water and storing it in honeycomb cells (Yang *et al.*, 2021). Honey serves as a long-term food source for the hive especially when there are no flourishing flowers. In Onto4API, Honey is modeled as a separate class due to its distinct formation process, storability, and its prominence as the most widely recognized bee product. Pollen, another key subclass, is represented as the primary nutritional source for bee larvae, collected and stored by honeybee foragers to nourish the colony with essential proteins, vitamins, and minerals. This concept is further refined through the subclass Bee_Bread (Kieliszek *et al.*, 2018), which refers to fermented pollen stored in honeycomb cells. This distinction enables the ontology to represent both the raw and biologically processed forms of pollen, which is significant for accurate nutritional characterization and scientific analysis. A third product, Propolis, is categorized separately. It is a sticky resinous substance that bees collect from plant exudates and use for its adhesive and antimicrobial properties. Propolis serves multiple functions within the hive, including sealing cracks, regulating airflow, and contributing to colony hygiene. Unlike honey and pollen, which are primarily linked to nutrition, propolis is defined in the ontology based on its functional role and material characteristics. This classification ensures a clear semantic separation within the broader category of collected hive products. On category sharing, because the collected substances vary with the environment and are mediated by behaviour, Onto4API semantically managed to represent these products under a common parent class as shared products. Such a structure keeps fine-grained questions (e.g. "Which bee products are fermentative? using observational data is improved, and it is consistent with ecological and behavioural foraging models.

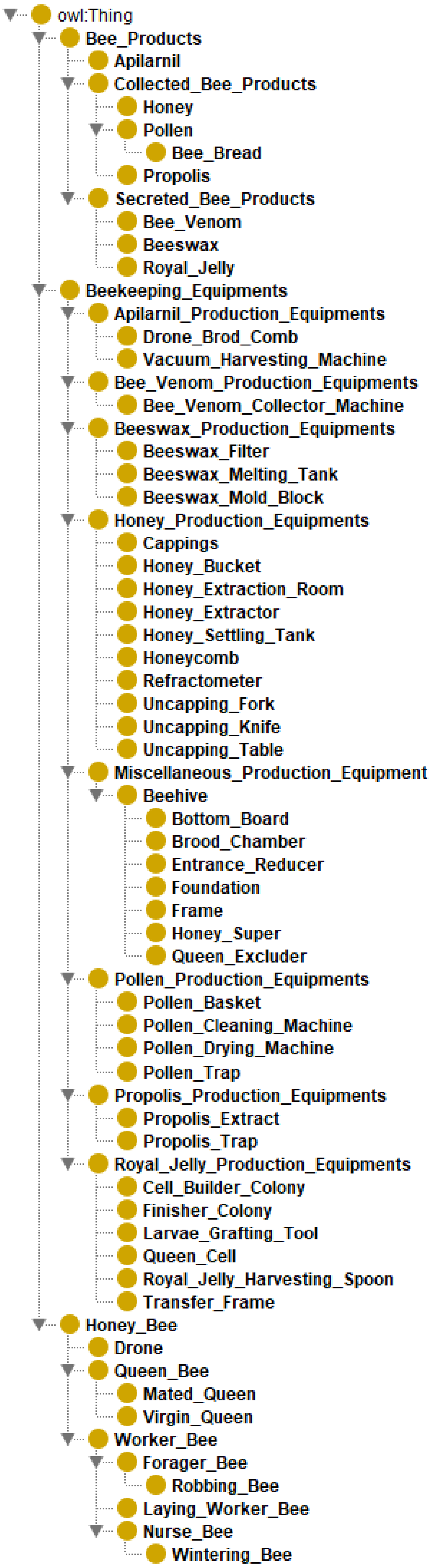

Figure 1. Onto4API Class hierarchy

The Secreted_Bee_Products class represents a category of substances that are biosynthesized and actively secreted by honey bees, primarily for intra-colony functions such as construction, nutrition, and defense. This class is modeled as a subclass of Bee_Products and serves to distinguish products that originate endogenously within the bee's physiology from those that are environmentally collected. Onto4API includes three key subclasses within this category: Beeswax, Bee_Venom, and Royal_Jelly, each characterized by distinct secretion pathways and functional roles in the colony's lifecycle. Beeswax is a lipid-based secretion produced by worker bees through abdominal wax glands. It is primarily used as a structural material for constructing the honeycomb, a central architectural element of the hive where honey, pollen, and brood are stored. In the ontology, Beeswax is treated as both a functional substrate and a biosynthetic output, making it critical to model not only as a product but also as a material with downstream dependencies (e.g., Honeycomb is constructed from Beeswax). Bee_Venom, in contrast, has solely a protective role. It is a clear, colorless liquid formed in venom glands and stored in the bee's sting apparatus. The bee injects this secretion as a form of defense against anything threatening the hive. Onto4API separates Bee_Venom ontologically into a unique substance, as shown by its peculiar pattern of usage, absence in the storage space within hive infrastructure, and different biochemistry compared to nutrient rich or structural secretions. Royal_Jelly is a nutritious and safely consumed product of the honey bee. It is the sole food for all larvae at least during the first few days, and for queen larvae throughout their development. Contrary to honey or pollen, Royal_Jelly is not stored nor modified after production – it is ingested right away upon being secreted. This temporal immediacy and functional specificity of Royal_Jelly as a short-lived, use-specific secretion that is essential for the ontogenetic division of labor in the colony is represented in our ontology. Together, the enumerated sub-classes depict the underlying biological complexity of the secretory behavior of honey bees and portray how this domain-specific knowledge is represented in Onto4API. This class organization facilitates semantic reasoning on production paths, functional roles and material exchange in the hive ecosystem.

The Beekeeping_Equipments class in Onto4API provides a high level abstraction of all material tools, instruments or machines utilized in traditional apicultural operations. It is a direct subclass of owl:Thing and is semantically disjointed from bees, to product-honey. This is because that category of class is very important to bring to life the practical side of beekeeping – things you can touch and use (collecting/processing, managing hive outputs). In order to enhance modularity and semantic relation mapping, BeeKeeping Equipments is decomposed into a set of domain-specific concept classes which correspondingly represent different types of the bee product or production phase. The eight main subclasses under Beekeeping_Equipments are: Apilarnil_Production_Equipments, Bee_Venom_Production_Equipments, Beeswax_Production_Equipments, Honey_Production_Equipments, Miscellaneous_Production_Equipment, Pollen_Production_Equipments, Propolis_Production_Equipments, and Royal_Jelly_Production_Equipments.

Tools that fit within a given production pipeline can all be grouped in this fashion. This class framework was derived from real practices of beekeeping in Türkiye, as revealed by national recommendations and expert interviews. It is also a modular structure that allows the scalability of our application. To this subclass, new tools or technology can be added since our domain can grow. From an ontological engineering perspective this enables targeted querying (e.g. "List all tools used in manufacturing of royal jelly), filtering based on classes for user interfaces, and possibly interlinking with IOT systems sharing data about tool usage in the field. What is more remarkable about the categorial definition of equipment as production type, however, is that it also enacts a world view; an ontological commitment to process oriented modelling that does not (merely) classify tools in terms of kinds of generic things but imputes them to the lifecyle of objects they realize. It enhances the semantics expressiveness and allows for ontology reusability in terms of a workflow-based applications in smart agriculture platforms.

The Apilarnil_Production_Equipments class represents a set of tools and devices used in the harvesting and processing of Apilarnil, a product derived from drone bee larvae. As a subclass of Beekeeping_Equipments, this class models not only the physical instruments involved but also captures the procedural context of apilarnil production, which is distinct from other beekeeping workflows due to its biological specificity and handling requirements. This class includes two core subclasses: Drone_Brood_Comb (Seeley, 2002) and Vacuum_Harvesting_Machine (van Toor and Littlejohn, 1994). The Drone_Brood_Comb is a structural component of the hive intentionally designed to encourage the queen to lay unfertilized eggs that develop into drone larvae. These combs serve as the primary biological substrate for apilarnil production, and their provision to the colony is a prerequisite for harvesting activities. Ontologically, Drone_Brood_Comb is classified as both a biological stimulus and a production-enabling artifact, reflecting its dual role in apicultural practice.

The Vacuum_Harvesting_Machine, on the other hand, is modeled as a mechanized apparatus used for the efficient and hygienic extraction of larvae from the comb. It operates by suctioning larvae out of the wax cells, minimizing manual contact and preserving the integrity of the product. This subclass is crucial for characterization of the technological mediation necessary in apilarnil extraction and also to support communication of Onto4API with prospective IoT applications which could track device usage, frequency or potential parameters. By unambiguously identifying these tools in terms of a particular production process, Onto4API also facilitates semantic distinction between different equipment classes and supports producer- and/or workflow-related reasoning – an essential feature for contemporary agricultural informatics systems. The Bee_Venom_Production_Equipments class encompasses the specialized technological infrastructure required for the safe and controlled extraction of bee venom — a highly bioactive secretion used for pharmaceutical and therapeutic purposes. As a subclass of Beekeeping_Equipments, it encapsulates equipment that facilitates this delicate and potentially hazardous process while ensuring minimal disruption to colony health and behavior. This class has a single but one of the most essential subclass, Bee_Venom_Collector_Machine (Ali *et al*., 2023). This apparatus is constructed to elicit antennal extension response from honey bees by applying weak electric pulses on a wire grid as they walk. The weak stimulation triggers a defensive reaction, causing the bees to sting the surface and inject venom, while retaining their stingers and lives. The venom is allowed to dry on a glass plate or film so it can be air-dried and collected later for further use.

Ontologically, Bee_Venom_Collector_Machine is considered by Reference Model as both a stimulus-generating machine and a bio-output medium with its distinctive logics of operation. This model enables Onto4API to represent both the physical aspects of apparatus, and also the ethological interaction that it elicits – a neglected but crucial modelling feature in existing knowledge representations of apicultural technology. The assignment of the class in the ontology enables further high-level reasoning on production conditions, animal welfare implications and device specific constraints, which are important topics in ethical and automated beekeeping. Furthermore, it establishes a base for combining with sensor-driven platforms recording venom yield or electric current parameters and behavioral reactions in situ.

The Beeswax_Production_Equipments class includes the tools and machinery which are used in extracting, purifying and shaping beeswax— a naturally-produced substance with dozens of apicultural and industrial uses. As a subclass of Beekeeping_Equipments, this class models the material processing workflow associated with converting raw, biologically embedded wax into a reusable commercial product. Onto4API defines three key subclasses under this category: Beeswax_Melting_Tank (Coggshall and Morse, 1984), Beeswax_Filter (Coggshall and Morse, 1984), and Beeswax_Mold_Block (Coggshall and Morse, 1984). The Beeswax_Melting_Tank is designed to melt such material from all four sides and from the bottom. An inner and outer jacket, between which there is an intermediate space for a circulation of water passes through the double wall around the cage and slowly melts even old and darkened material including larval casings, residual honey or propolis. The melting step removes the wax from non-wax residues and reduces it to a pourable substance for subsequent processing. In ontological terms, this class describes the point in production when wax is taken from solid to liquid and models its functional as well as performance aspects. The liquid wax is then run thru the Beeswax_Filter to remove any finer remnants or impurities. This class is added to the ontology in order for refinement steps in workflow models to be modelled, which can be monitored and improved with regard to wax purity and filtration quality. The strained wax is placed into a Beeswax_Mold_Block where it hardens again in blocks or sheets of the desired size. Representing this operation with ontology will allow to query for storage, stock, transport availability and feeding systems during wax foundation production process. From an engineering ontology viewpoint, this Beeswax_Production_Equipments class connects the steps in term of a processing chain via a set of transformations performed on them by their types of equipment. This architecture facilitates workflow alignment, sensor incorporation and automation. However, it allows Onto4API to support monitoring and traceability of tasks in smart apiculture applications.

The Honey_Production_Equipments class comprises a semantically structured set of tools, devices, and spatial resources required to execute the complex, multi-phase process of honey harvesting in traditional apiculture. This class, defined under Beekeeping_Equipments, models a complete operational pipeline—from frame removal to honey storage—and plays a central role in representing the material and procedural ontology of honey production. The equipment instances are designed to mirror real-world workflows and facilitate the annotation of field data, IoT integration, and process optimization. At the preliminary stage, sealed honeycomb frames are removed from hives and transported using a Honey_Bucket (Martin *et al.*, 1980), which acts as a containment vessel to prevent honey leakage and facilitate transfer to the Honey_Extraction_Room (Martin *et al.*, 1980). The extraction room itself is conceptualized as an environment-level resource (Honey_Extraction_Room), designed to maintain bee isolation and hygienic standards during processing. Prior to honey extraction, the beeswax Cappings sealing the honey-filled cells must be removed. This task is performed using an Uncapping_Knife (Martin *et al.*, 1980) and Uncapping_Fork (Martin *et al.*, 1980) on an Uncapping_Table(Martin *et al.*, 1980), a designated platform that enables safe and ergonomic handling. The wax residues removed during this phase may yield Capping_Honey, which is separately collected and modeled as a byproduct of the uncapping process.

The uncapped frames are extracted in a Honey_Extractor (Martin *et al.*, 1980), a centrifuge which uses the principle of accelerating movement to throw off honey through spinning it rapidly. The extracted honey flows down and is collected from the bottom of a Honey_Setting_Tank (Martin *et al.*, 1980), where sedimentation takes place to remove particles such as wax, pollen and other impurities. It is possible to employ tanks of this type with heating for the purpose of decreasing the viscosity of honey and for facilitating separation from impurities. The water content of the processed honey is also determined with a Refractometer (Hidayat *et al.*, 2021) to meet the moisture limits for ripening and storage. This class model in Onto4API represents not only the functional taxonomy of apiarian equipment but also temporal, procedural dependencies among all devices. The ontology, therefore, supports, process-aware applications of production traceability, quality assurance monitoring and smart automation in honey processing environments. Modeling the equipment and inter-equipment links, this category becomes a very rich semantic grounding for reasoning, querying and visualization of honey harvesting life-cycle.

Miscellaneous_Production_Equipment class capturing generic infrastructure equipment and competing production workflow-requirements as well as colony-wide processes. This class in Onto4API is concerned with those appliances whose service is beyond a bee product and appears to function as a basic infrastructure of the whole apicultural ecosystem. Its only derived subclass, Beehive defines the fundamental architectural building block in which honey bees live, reproduce and create products – forming a biological system and modular structure, with several inside parts. The Beehive class is then broken down to the major components: Bottom_Board (Blackiston, 2019), Brood_Chamber (Blackiston, 2019), Entrance_Reducer (Blackiston, 2019), Foundation (Blackiston, 2019), Frame (Blackiston, 2019), Honey_Super (Blackiston, 2019) and Queen_Excluder (Blackiston, 2019). These sub-classes characterize the spatial and temporal structure of the hive in a manner that permits semantic annotation of how internal hive spaces support distinct/user/colorbox aspects of colony activity/productivity. The Bottom_Board is the base of the hive where the Brood_Chamber is supported. The Frame is the frame that holds the comb and allows manipulation of its contents—honey, pollen, eggs. Ontologically, Frame acts as a mediator between biological behaviour (combs being built), and human-apicultural management (cut out, inspection). The Foundation (thin hexagons sheets of wax) speeds up the building process as the bees can build upon it. This class is a great example of how we can scaffold within the framework of a hive and take human cues to make sense of what happens naturally. The Honey_Super, positioned above the brood chamber, constitutes the designated honey storage area, while the Queen_Excluder ensures reproductive segregation by restricting the queen’s access to this zone — a crucial factor in product purity and management. The Entrance_Reducer plays a defensive and environmental regulatory role by narrowing hive access, which is especially important during nectar scarcity when robbing behavior by bees from other colonies (Robbing_Bees) becomes a risk. Although spatially minimal, this categorization makes sense semantically in providing the relationship of the area and the space around it. By integrating these structural elements into Onto4API, the ontology not only models equipment as static objects, but also captures their roles in colony behavior regulation, product quality control, and environmental interfacing. Such high-level spatial description is a fertile ground to support the development of context-aware reasoning agents in situated interaction tasks, and tools for decision support in precision beekeeping.

This module Pollen_Production_Equipments which represents a collection of tools and biological compartments used for gathering, treating and quality control of pollen (which is also a very important beekeeping by-product full of proteins, vitamins and minerals). As a subcategory of Beekeeping_Equipments, this hierarchy includes physical mechanims for pollen collection and the methods used to process it into edible or industrial-quality products. Among its subclasses, the Pollen_Trap (Campos *et al.*, 2021) plays a central role in harvesting. It is strategically placed at hive entrances to remove pollen pellets from the hind legs of incoming worker bees. While the bees are allowed to enter, the trap's design gently dislodges the pollen from the Pollen_Basket (Campos *et al.*, 2021)—a biological structure located on the tibia of worker bees. By modeling this anatomical structure as a class within equipment, Onto4API recognizes the inseparable coupling of natural behavior and harvesting interface, a critical modeling feature for hybrid biological–technical systems. Once collected, pollen may contain impurities such as wax particles and debris. This necessitates post-harvest processing using a Pollen_Cleaning_Machine (Campos *et al.,* 2021) which performs physical separation based on particle size or density. Clean pollen is then subjected to moisture reduction in a Pollen_Drying_Machine. This device uses a controlled combination of airflow and thermal input to lower the water content, thus increasing shelf life and reducing microbial risk. From an ontological standpoint, these subclasses embody post-collection transformation stages, aligning with practices in food processing and bio-preservation. From an ontological standpoint, these subclasses embody post-collection transformation stages, aligning with practices in food processing and bio-preservation. By linking the biological to the technological, the internal with the external factors, Onto4API currently covers both foraging and hive entrance as well as trap or industrial readiness level in its representation of pollen life cycle. This model not only permits a more detailed traceability of the numerical predictions, but it also uses advanced questioning like "Which machines are responsible for influencing the pollen-moisture?" and automatic decisions for smart beekeeping application.

Propolis_Production_Equipments class represents a specialized subset of tools and techniques employed in the stimulation, collection, and post-processing of propolis. Propolis is a resinous bee product known for its antimicrobial, sealing, and structural properties within the hive. Since this category models both behavioral elicitation interfaces and chemical transformation systems, among the entire class Beekeeping_Equipments, this class is one of the most combined classes in Onto4API. One notable subclass is the Propolis_Trap (Bankova *et al.*, 2019) which shows examples of environmental manipulation for inducing a particular bee behavior. The trap, which usually is made of a pliable plastic sheet perforated with numerous small holes, creates airflow patterns that honey bees instinctively try to block for thermoregulation and sanitation purposes. This has the effect of causing bees to store propolis into a trap where it is eventually collected by beekeepers. From an ontological perspective, this class is both a stimulus device and a passive collection interface that links the two senses used in bee-environment interaction models. The other subclass, Propolis_Extract (Bankova *et al.*, 2019), is not a trapping device itself but rather downstream processing unit. After harvested raw propolis is solvent extracted (a typical solvent being ethanol), the bioactive substances it contains dissolve in this solution together with impurities and wax residues. The filtered final solution, referred to as propolis extract, is extensively employed in pharmaceutical, cosmetic and nutraceutical practice. This subclass is also ontologically relevant as it leads to the introduction of chemical post-treatment in the equipment hierarchy and therefore constitutes a substantial extension of Onto4API not only from mechanical tools to bioprocessing workflows. By integrating both the modulational and transformational biological inputs in the class Propolis_Production_Equipments, Onto4API can be used for inference about behaviour-triggered resource exploitation, macromolecular refinement and bioeconomics. This is particularly useful for smart beekeeping systems that want to align hive design and behavioral dynamics, as well as operations within the downstream value chain.

The Royal_Jelly_Production_Equipments (RJP) class at Onto4API is a very structured and biologically well correlated process for production of royal jelly which is the larval food and queen sustenance. In contrast to other bee products, royal jelly production is mainly characterised by intricate colony handling, temporal synchronisation and specific biological interventions. As a sub class of Beekeeping_Equipments in this hierarchy the tools and works must coexist, for generating an enriched semantic explanation for apicultural bioengineering. Production is initiated at the colony level, i.e., a Cell_Builder_Colony (Hu *et al.*, 2019) is introduced by withdrawing the queen-bee to induce queen-rearing activity. This colony is the environment for royal jelly production. Queen_Cells (Hu *et al.*, 2019) are grafted from larvae (1 day old) to plastic or wax cylinder cups, put in place via a Larvae_Grafting_Tool (Hu *et al.*, 2019), an instrumental device for biological transfer.

These queen cells are adhered onto the surface of a Transfer_Frame (Hu *et al.*, 2019), which is convenient to handle and infiltrate into the colonies. After 24–48 h inside the cell builder colony, grafted larvae are transferred to a Finisher_Colony (a strong two-story hive of bees divided by a queen excluder). The nurse bees are kept in the upper box and are motivated to do so by the fact they can secrete royal jelly into the cups. After 48 hours in the finisher colony, royal jelly is collected with a Royal_Jelly_Harvesting_Spoon (Hu *et al.,* 2019), a non-reactive apparatus that allows the royal jelly to remain uncontaminated. From an ontological point of view, this class is remarkable in its inclusion of colony-level behavioral configurations (Cell_Builder_Colony, Finisher_Colony) as equipment instances. It blurs the boundary between hardwarebased computing and the bio-inspired system, thereby enhancing expressiveness as well as adaptability of Onto4API. In addition, explicitly modeling tools like the Larvae_Grafting_Tool and Transfer_Frame can provide more accurate description of intermediate stages and relationships during workflow execution. In recording not just the bio-activities, but also doing justice to the spatial logistics and temporal sequences involved in royal jelly production, we have a full and semantically rich abstraction for reasoning, simulation and digital integration of royal jelly equipment production represented by the class Royal_Jelly_Production_Equipments. The Honey_Bee (Laidlaw and Page, 1997) class in Onto4API represents the core biological entity around which all apicultural practices are organized. As a subclass of owl:Thing, it models the taxonomic, behavioral, and social dimensions of the domesticated honey bee. This class is foundational to the ontology, providing the biological basis for interpreting apicultural processes, role distributions, and product generation. It is subdivided into three primary castes: Drone (Laidlaw and Page, 1997), Queen_Bee (Laidlaw and Page, 1997), and Worker_Bee (Laidlaw and Page, 1997), each with specialized roles and further subclassifications. The Drone subclass represents male honey bees whose sole biological function is to mate with a virgin queen. Drones do not engage in foraging, nursing, or hive maintenance, and their presence in the colony is regulated seasonally. Ontologically, they represent reproductive agents without colony-internal labor utility. The Queen_Bee subclass encapsulates the central reproductive and pheromonal control unit of the colony. As the only diploid egg-laying individual, the queen ensures genetic continuity and colony cohesion. This class is further divided into Virgin_Queen (Laidlaw and Page, 1997)—a newly developed queen bee that has not yet mated—and Mated_Queen (Laidlaw and Page, 1997), who has completed her nuptial flight and actively lays fertilized eggs. These distinctions are critical for modeling queen-rearing processes, colony establishment, and hive replacement cycles. The Worker_Bee (Winston, 1991) subclass constitutes the functional backbone of the colony. These sterile females perform all non-reproductive tasks, including product synthesis, brood care, foraging, and defense. This class is ontologically rich, containing the following functionally distinct subclasses:

- Nurse_Bee: Responsible for feeding and tending to larvae, including royal jelly secretion and cell cleaning. These bees operate within the brood chamber.
  - Wintering_Bee (Winston, 1991): A behavioral specialization of nurse bees adapted for overwintering conditions. They exhibit reduced activity, cluster behavior, and increased longevity to preserve colony temperature and cohesion.
- Forager_Bee: Adult worker bees that exit the hive to collect nectar, pollen, water, and propolis.
  - Robbing_Bee (Winston, 1991): A context-dependent behavioral variant of foragers. These bees engage in robbing behavior—invading other hives to steal honey—especially under conditions of resource scarcity.
- Laying_Worker_Bee (Winston, 1991): A rare behavioral state where worker bees begin to lay unfertilized eggs (which develop into drones) in the absence of a functioning queen. This state signals reproductive disorganization and often leads to colony collapse.

This detailed modeling of caste structure and sub-role dynamics allows Onto4API to support nuanced semantic queries, such as “Which bee type produces royal jelly under normal vs. emergency conditions?” or “What are the behavioral consequences of queen absence?” It also enables integration with simulation models and decision-support systems in precision beekeeping, colony health monitoring, and AI-driven hive management.

The ontology includes object properties that semantically link individuals from different classes, reflecting processes such as production, storage, and biological lineage. For instance:

- collectedBy associates bee products such as pollen and nectar with the forager bees responsible for their collection.
- housedIn links bees or bee-related equipment to physical hive components such as Brood_Chamber or Honey_Super.
- laidBy and rearedBy describe biological relationships in the reproductive cycle, such as eggs laid by a queen and larvae reared by nurse bees.
- secretedBy defines biochemical outputs (e.g., royal jelly, bee venom) and their corresponding producers within the colony.
- storedOn captures spatial relationships, such as bee products stored on Honeycomb or inside Queen_Cell.

These relationships are essential for modeling the workflow and life cycle dynamics within a beekeeping operation and enable rich querying over ontological data structures.

The data properties in Onto4API are used to attach quantifiable or descriptive attributes to individuals, capturing the measurable characteristics of bee products and equipment. Examples include:

- hasMoistureContent, hasPurity, and hasWaxPurity: used to represent quality indicators of products like honey and beeswax.
- hasStorageTemperature and hasShelfLife: describe environmental and temporal constraints for preserving products such as royal jelly or pollen.
- hasWeight and hasProteinContent: provide nutritional and compositional metadata essential for food quality analysis.
- hasBioactivityLevel: denotes the functional potency of biologically active substances like royal jelly or propolis.
- hasColorGrade: classifies honey based on color, relevant to product grading standards.
- hasHarvestingDate: records the temporal metadata for traceability and supply chain integration.

These data properties transform the ontology into a semantically interoperable and data-rich framework capable of supporting intelligent applications such as decision support tools, predictive models, and semantic retrieval systems in the domain of precision apiculture.

Formalization

The formalization of the Onto4API ontology was conducted using the OWL 2 Web Ontology Language, a W3C-recommended standard for representing rich and complex knowledge about things, groups of things, and relations between them. The ontology was developed using the RDF/XML syntax, ensuring compatibility with a wide range of semantic web tools and services. To facilitate the ontology design process, the open-source ontology editor Protégé version 5.6.1 was utilized. Protégé supports OWL-based modelling and provides a comprehensive environment for building, visualizing, and validating ontologies. The base IRI (Internationalized Resource Identifier) assigned to Onto4API is: http://www.intalalab.com/ontologies/2025/7/onto4api#

This IRI serves as a globally unique namespace for all entities defined within the ontology, ensuring semantic consistency and enabling potential integration with external ontologies or knowledge graphs.

The final version of Onto4API comprises:

- 67 classes representing key entities in apiculture, including bee products, beekeeping equipment, and bee castes,
- 6 object properties defining inter-class relationships (e.g., collectedBy, secretedBy, rearedBy),
- 10 data properties representing measurable and descriptive attributes (e.g., hasMoistureContent, hasStorageTemperature, hasBioactivityLevel).

To ensure semantic integrity and logical consistency, the ontology was validated using the HermiT reasoner embedded within Protégé. No inconsistencies or logical violations were detected during the reasoning process, confirming the internal coherence and structural soundness of the model.

Implementation

The implementation phase of the Onto4API ontology was realized using the Protégé 5.6.1 ontology editor, adopting the OWL 2 Web Ontology Language with RDF/XML serialization. The base IRI of the ontology is defined as:

http://www.intalalab.com/ontologies/2025/7/onto4api#.

This IRI scheme guarantees global uniqueness and a clear semantics for all concepts, properties, and individuals defined in the ontology. For consistency checking, the ontology was internally tested by using the HermiT reasoner in Protégé. Reasoning revealed that the ontology is void of logical contradictions and semantic faults. Then the ontology was uploaded to a triple store (GraphDB), which is an RDF database with support for SPARQL querying and reasoning services for ontologies. The triggered ontology provides runtime querying and knowledge exploration by specifying SPARQL queries. The ontology was tested through some sample queries to check the feasibility of its structure and to illustrate its applicative usefulness. For example, the query below retrieves all object properties that are defined and displays their domain and range definitions:

```
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
SELECT ?property ?domain ?range WHERE {
  ?property a owl:ObjectProperty .
  OPTIONAL { ?property rdfs:domain ?domain . }
  OPTIONAL { ?property rdfs:range ?range . }
}
```

This query, above all, returns central object properties like collectedBy, storedOn and rearedBy to ontology engineers for confirming semantic dependence between the classes Bee_Products and Honey_Bee. Equally, ontology-defined data properties (e.g., hasMoistureContent, hasStorageTemperature) may be queried to identify the semantics of attributes:

:

```
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
SELECT ?property ?domain
WHERE {
  ?property a owl:DatatypeProperty .
  OPTIONAL { ?property rdfs:domain ?domain . }
}
```

These questions are especially useful to check the domain-property alignment correctness and that the ontology allows semantic data integration and attribute-based reasoning. Moreover, to obtain all classes that are defined in the ontology and to get an overview of its taxonomic structure it is possible to execute this query:

```
PREFIX owl: <http://www.w3.org/2002/07/owl#>
SELECT ?class
WHERE {
  ?class a owl:Class .
}
ORDER BY ?class
```

These implementations not only allow the structuration of evaluation on the ontology level, but also lay a foundation for advanced semantic applications, including intelligent search, rule-based reasoning and decision-support systems in apiculture.

Evaluation

Semantic correctness, consistency, completeness and usefulness of the Onto4API ontology were verified through validation with apicultural domains using five tests. Various hierarchical structural, logical and functional validation techniques were applied. In order to provide a sound evaluation strategy ensuring vocabulary coherence for Onto4API in terms of its semantics, structural coherence, application domain and pragmatic usage was pursued. For this approach we used logical validation by reasoning, structural metrics analysis, expert review sessions and SPARQL-based functional testing and interoperability checks.

Consistency and Logical Validation

The ontology was evaluated for semantic consistency using the HermiT reasoner integrated within Protégé 5.6.1. This included checks for class hierarchies, disjoint class definitions, and validation of domain and range specifications for both object and data properties. The reasoning process did not reveal any logical inconsistencies, suggesting that the ontology adheres to the formal requirements expected of OWL 2-based ontologies.

Structural Evaluation and Ontology Metrics

The ontology structure was analysed using a variety of qualitative measurements such as total classes, object properties, and data properties. These metrics demonstrate the modelling scope and level of detail of the ontology are presented in Table 1.

Table 1. Metrics of Onto4API

Metric	Value
Total classes	67
Object properties	6
Data properties	10
Subclass relationships	✓
Class annotations	✓

These quantitative results suggest that Onto4API offers a detailed characterization of the apiculture activities, including both biological and operational concepts in beekeeping.

Domain Expert Validation

The domain relevance and conceptual completeness of Onto4API were evaluated through a series of review sessions with senior researchers from ARI (Republic of Türkiye Ministry of Agriculture and Forestry Apiculture Research Institute). The review covered:

- Class and subclass definitions
- Appropriateness of relations
- Terminological consistency
- Applicability for decision-support and training purposes

Feedback confirmed that Onto4API accurately represents real-world apiculture processes, particularly those involved in the production of bee products (e.g., honey, pollen, royal jelly).

Functional Testing via SPARQL

To evaluate the functional correctness and usability of Onto4API, the ontology was deployed into GraphDB, and a set of SPARQL queries was executed. These queries were specifically designed to validate:

- Retrieval of class hierarchies
- Navigation across object properties (e.g., collectedBy, secretedBy)
- Filtering entities by data properties (e.g., hasMoistureContent, hasHarvestingDate)

All queries executed successfully, demonstrating that Onto4API is queryable and supports semantic retrieval operations.

In addition, to simulate realistic user interactions, a representative set of domain-specific questions was formulated. These include queries such as *"What equipment is required for royal jelly production?"* or *"What are the types of Queen Bee?"*, which are presented in Table 2 alongside their corresponding SPARQL forms and output results. These question-query-answer triplets demonstrate the practical utility of Onto4API for educational and exploratory purposes.

Thus, although formal usability testing was not conducted, the ontology underwent rigorous functional testing using simulated user scenarios, ensuring its operational validity and semantic alignment with the domain.

Potential for Reuse and Interoperability

The ontology's use of standard vocabularies (e.g., rdfs, owl, xsd) and its compliance with OWL 2 DL syntactic rules ensures interoperability across RDF-based systems. The IRI structure is globally unique and suitable for integration with external ontological resources and agricultural knowledge graphs.

Summary of Evaluation Results

Finally, we evaluated the Onto4API ontology with respect to structural coherence, semantic consistency, utility and technical reliability. The ontology includes 67 well-defined classes, 6 object properties and 10 data properties modelled by OWL 2 in RDF/XML syntax and evaluated by the HermiT reasoner using Protégé version 5.6.1. During the reasoning, no logical inconsistency was identified validating the internal consistency of the ontology. The deployment in GraphDB also confirmed the ontology's utility in semantic repositories, as well as its compliant support of SPARQL query functionality. A set of example queries were successfully implemented validating the capability to query semantic data, integrate it and infer knowledge. Additionally, Onto4API was developed in close cooperation with domain specialists from the Apiculture Research Institute, which provided the significance and correctness of selected concepts, relationships and properties. This expert participation, the strong validation process and a proprietary approach leads Onto4API to be a semantic rich and interoperable resource providers for knowledge sharing, decision support systems and the semantic web applications in apiculture domain.

Application of the Onto4API

Use Case Scenarios

The Onto4API ontology has been modelled not only as an abstract and conceptual description of the domain of apiculture but also with a view to being reused in real contexts. Its applications in various fields focus on different aspects of structured knowledge representation, integration and reasoning. A common application is data integration. Apiculture composes a very heterogeneous domain in terms of data sources, from paper methods used to manage/appraise hives, to sensor based monitoring systems. Onto4API introduces a common vocabulary and a formal semantics across the ontologies with the aim of reconciling (and making them interoperable) such diverse datasets, while also facilitating an improved analysis and decision making over multiple media outlets. Significant application is also found in the generation of educational and training material. The transparent class hierarchy of the ontology that Onto4API applies and its being completely for this domain in particular can support digital textbooks, e-learning and training simulations for novice beekeepers. This permits interpretation of complex apiculture knowledge in a more natural way to students and uniformity between concepts on different training course. Besides, Onto4API provides a reference for decision support systems dedicated to precision apiculture. Integrated with domain rules and inference, it provides intelligent recommendations for hive management, product collecting, equipment using in the smart farm scenario, etc. Onto4API also acts as a semantic backbone in web-based apiculture-information portals and platforms that target providing knowledge to the broadest variety of stakeholders (bee-keepers, agricultural advisors and researchers). Ontology can provide semantic richness to contents of applications, so that they may be findable and hence easily accessible through searches, and such links among related information sources may be improved. Finally it aids their integration into smart agriculture, such as IoT-based hive monitoring systems or geospatial analysis tools for migratory beekeeping. Its computable development allows for easy integration with other agri ontologies, facilitating inter-operability across agri-tech environments. These case studies indicate the possible capability of Onto4API to sustain applications that exceed the mere field of knowledge representation and contribute to operational, educational, and technological development in modern apiculture.

Use Case Implementation: Ontology-Based Educational Tool for SPARQL Learning

To illustrate the practical value of Onto4API, a lightweight ontology-based educational tool was developed using the ASP.NET MVC framework and the dotNetRDF library. This web-based prototype is designed as a question-and-answer system to support learning about apiculture practices through semantic querying. Rather than functioning as a generic SPARQL endpoint, the tool guides users—particularly students or domain learners—through predefined queries that retrieve relevant information from Onto4API. The aim is to combine semantic web technologies with an intuitive interface that facilitates domain-specific learning in beekeeping.

Table 2 presents a selection of these educational questions along with their corresponding SPARQL queries and example outputs, illustrating how Onto4API can be operationalized to support interactive learning and semantic exploration. These queries demonstrate the ontology's capacity to represent complex class hierarchies, production equipment, and bee-related concepts, enabling targeted information retrieval aligned with real-world apiculture practices. Figure 2 shows a screenshot of the ontology-based educational tool developed using ASP.NET MVC and dotNetRDF, where users can interact with predefined SPARQL queries to learn about apiculture practices.

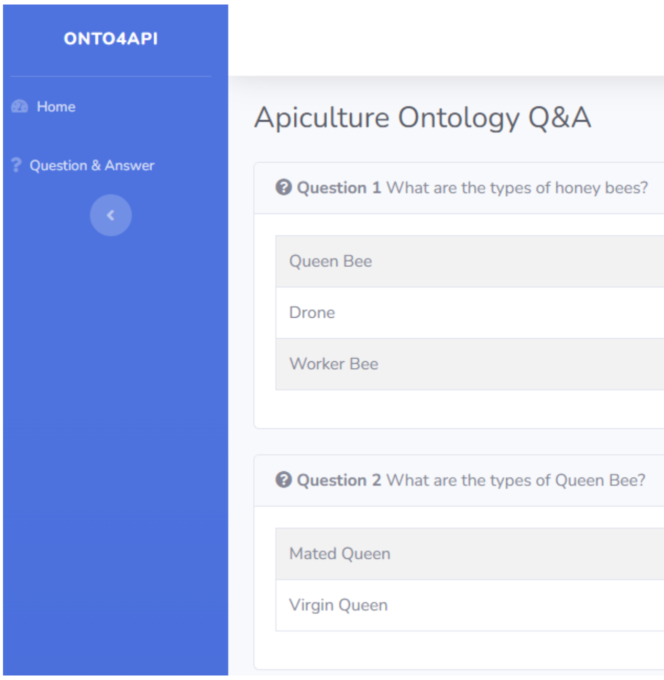

Figure 2. Screenshot of the implemented tool.

Table 2. Sample apiculture practices questions, their SPARQL queries and outputs.

Question	SPARQL	Output

What are the types of honey bees?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	PREFIX owl: <http://www.w3.org/2002/07/owl#>
	SELECT (REPLACE(STR(?type), "http://www.intalalab.com/ontologies/2025/7/onto4api#", "") AS ?HoneyBeeType)
	WHERE {
	?type rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Honey_Bee> .
	}
		Queen_Bee
		Worker_Bee
		Drone

What are the types of Queen Bee?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	SELECT (STRAFTER(STR(?type), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?QueenBeeType)
	WHERE {
	?type rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Queen_Bee> .
	}
		Mated_Queen
		Virgin_Queen

What are the types of Worker Bee?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?beeType), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?BeeType)
	WHERE {
	?beeType rdfs:subClassOf+ <http://www.intalalab.com/ontologies/2025/7/onto4api#Worker_Bee> .
	}
		Forager_Bee
		Laying_Worker_Bee
		Nurse_Bee
		Robbing_Bee
		Wintering_Bee

What are the fields or domains of activity in beekeeping?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?field), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?BeekeepingField)
	WHERE {
	?field rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Beekeeping_Equipments> .
	}
		Apilarnil_Production_Equipments
		Bee_Venom_Production_Equipments
		Miscellaneous_Production_Equipment
		Beeswax_Production_Equipments
		Honey_Production_Equipments
		Royal_Jelly_Production_Equipments
		Pollen_Production_Equipments
		Propolis_Production_Equipments

What equipment is required for honey production?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?equipment), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?HoneyProductionEquipment)
	WHERE {
	?equipment rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Honey_Production_Equipments> .
	}
		Cappings
		Honey_Bucket
		Honey_Extraction_Room
		Honey_Extractor
		Honey_Settling_Tank
		Honeycomb
		Refractometer
		Uncapping_Fork
		Uncapping_Knife
		Uncapping_Table

What equipment is required for propolis production?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?equipment), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?PropolisProductionEquipment)
	WHERE {
	?equipment rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Propolis_Production_Equipments> .
	}
		Propolis_Extract
		Propolis_Trap

Table 1. Continued.

What equipment is required for pollen production?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?equipment), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?PollenProductionEquipment)
	WHERE {
	?equipment rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Pollen_Production_Equipments> .
	}
		Pollen_Basket
		Pollen_Cleaning_Machine
		Pollen_Drying_Machine
		Pollen_Trap

What equipment is required for royal jelly production?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?equipment), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?RoyalJellyProductionEquipment)
	WHERE {
	?equipment rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Royal_Jelly_Production_Equipments> .
	}
		Cell_Builder_Colony
		Finisher_Colony
		Larvae_Grafting_Tool
		Queen_Cell
		Royal_Jelly_Harvesting_Spoon
		Transfer_Frame

What equipment is required for beeswax production?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?equipment), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?BeeswaxProductionEquipment)
	WHERE {
	?equipment rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Beeswax_Production_Equipments> .
	}
		Beeswax_Filter
		Beeswax_Melting_Tank
		Beeswax_Mold_Block

What equipment is required for bee venom production?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?equipment), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?BeeVenomProductionEquipment)
	WHERE {
	?equipment rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Bee_Venom_Production_Equipments> .
	}
		Bee_Venom_Collector_Machine

What equipment is required for apilarnil production?	PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
	
	SELECT (STRAFTER(STR(?equipment), "http://www.intalalab.com/ontologies/2025/7/onto4api#") AS ?ApilarnilProductionEquipment)
	WHERE {
	?equipment rdfs:subClassOf <http://www.intalalab.com/ontologies/2025/7/onto4api#Apilarnil_Production_Equipments> .
	}
		Drone_Brod_Comb
		Vacuum_Harvesting_Machine

This prototype implementation demonstrates the practical usability of the Onto4API ontology in a real-world educational context. By integrating semantic querying with an intuitive user interface, the system supports interactive learning and promotes ontology literacy among learners and practitioners in the apiculture domain. The success of this application suggests that ontology-based educational tools can play a significant role in bridging the gap between structured knowledge representation and domain-specific training needs. Future work may expand this platform by incorporating multilingual support, user-driven query generation, and integration with live sensor data from smart beekeeping systems.

DISCUSSION AND CONCLUSION

This paper explains custom development of Onto4API, a domain-specific ontology aimed at capturing the key body of knowledge, practices, and tools used in apiculture nowadays. The ontology was developed in OWL 2 using RDF/XML syntax and constructed using Protégé 5.6.1. Onto4API offers an ontological conception to model the relationships of numerous kinds of bee species, hive products, and production equipment using a systematic process that includes specifications, conceptualization results, formalizations, implementations and evaluations. Furthermore, a rigorous procedure of evaluation was performed comprising reliability and logical consistency check, treemap analysis with ontology metrics and expert review. These steps ensured the conceptual correctness, structural consistence and conformance with the real-world use of Onto4API. While the ontology itself was technically developed by the author, provision of domain knowledge and justification for its accuracy was monitored in consultation with experts of Türkiye Apiculture Research Institute. This collaboration has facilitated a real world reconciliation of the ontology with actual practices and terminologies. In order to show the usability of Onto4API, a small educational web-based application was constructed by ASP. NET MVC and the dotNetRDF library. This first prototype provides its users with an intuitive query-answering interface, which is based on SPARQL queries querying ontologies containing the apiculture knowledge. The validation experiment was conducted on a set of SPARQL queries executed against GraphDB. These questions tested the ontologies' support for class hierarchies and object property navigation, as well as filtering by data properties. Results of all the test cases worked as expected showing that, OnTo4API can be used semantically for search and real life applications. In its educational aspect the ontology-driven interface could facilitate stakeholder farmers, developers of apiculture applications, researchers and policy makers providing a structured approach on access to domain knowledge that can be employed in informed decision making as well as semantic data interoperation to use between apiculture focused applications. The learning tool serves as an example for supporting semantified agricultural exchanges. Being universal and versatile, we expect that Onto4API will serve as a general semantic base for other advanced beekeeping applications such as decision support systems in smart bee keeping and farming systems and data integration platforms. By standardization and knowledge transfer, these ontologies are an enabler for digital transformation in beekeeping chain. In the future, we want to increase the interoperability of Onto4API by aligning its key concepts and properties with known agricultural ontologies such as AGROVOC. This will also increase its capacity for integration within linked data ecosystems and semantic agricultural KBs. Such integration would additionally increase the usefulness of Onto4API for semantic web infrastructure, such as cross-domain reasoning and linkage with other agricultural, food and environment ontologies in Linked Open Data environments. Overall, the results of the evaluation show that Onto4API is technically valid, semantically complete and effectively applicable to various educational and training use cases in the apiculture domain.

Data and Ontology Availability

The Onto4API ontology developed and utilized in this study is publicly accessible via GitHub:

https://github.com/sahinaydin/onto4api

REFERENCES

Ali, E., A. Saad, M. Younis, and A. Metwally. 2023. Using Sensing Technology Inside Beehive to Determine the Optimal Conditions Affecting the Demand for Bee (*Apis mellifera* L.) Venom Collector Device. International Journal of Engineering Science and Technology 12: 76–85.

Bankova, V., Bertelli, D., Borba, R., Conti, B. J., da Silva Cunha, I. B., Danert, C., Eberlin, M. N., I Falcão, S., Isla, M. I., Moreno, M. I. N., Papotti, G., Popova, M., Santiago, K. B., Salas, A., Sawaya, A. C. H. F., Schwab, N. V., Sforcin, J. M., Simone-Finstrom, M., Spivak, M., … Zampini, C. (2019). Standard methods for Apis mellifera propolis research. Journal of Apicultural Research 58(2): 1–49. https://doi.org/10.1080/00218839.2016.1222661

Blackiston, H. 2019. Building Beehives For Dummies. John Wiley & Sons.

Campos, M.G., O. Anjos, M. Chica, P. Campoy, J. Nozkova, N. Almaraz-Abarca, L.M.R.C. Barreto, J.C. Nordi, L.M. Estevinho, A. Pascoal, V.B. Paula, A. Chopina, L.G. Dias, Ž.L. Tešić, M.D. Mosić, A.Ž. Kostić, M.B. Pešić, D.M. Milojković-Opsenica, W. Sickel and N.L. Carreck. 2021. Standard methods for pollen research. Journal of Apicultural Research 60(4): 1–109. https://doi.org/10.1080/00218839.2021.1948240

Coggshall, W. L., and R. A. Morse. 1984. Beeswax: Production, Harvesting, Processing, and Products. Wicwas Press.

Fernández-López, M., A. Gómez-Pérez, & N. Juristo. 1997. Methontology: From ontological art towards ontological engineering. Spring Symposium on Ontological Engineering, AAAI Technical Report SS-97-06, 33–40. http://aaaipress.org/Papers/Symposia/Spring/1997/SS-97-06/SS97-06-005.pdf

Ghisalberti, E. L. 1979. Propolis: A Review. Bee World. https://www.tandfonline.com/doi/abs/10.1080/0005772X.1979.11097738

Hessel, E. V. S., Y. C. M. Staal, and A. H. Piersma. 2018. Design and validation of an ontology-driven animal-free testing strategy for developmental neurotoxicity testing. Toxicology and Applied Pharmacology 354: 136–152. https://doi.org/10.1016/j.taap.2018.03.013

Hidayat, S. A., A. Susilo, and D. Masyithoh. 2021. Effect of change in moisture content of Sumatra Forest Honey on total sugar, electrical conductivity and color. IOP Conference Series: Earth and Environmental Science 788(1): 012107. https://doi.org/10.1088/1755-1315/788/1/012107

Hu, F.-L., K. Bíliková, H. Casabianca, G. Daniele, F.S. Salmen Espindola, M. Feng, C. Guan, B. Han, T.K. Kraková, J.-K. Li, L. Li, X.-A. Li, J. Šimúth, L.-M. Wu, Y.-Q. Wu, X.-F. Xue, Y.-B. Xue, K. Yamaguchi, Z.-J. Zeng, … and J.-H. Zhou. 2019. Standard methods for Apis mellifera royal jelly research. Journal of Apicultural Research 58(2): 1–68. https://doi.org/10.1080/00218839.2017.1286003

Huang, Z. 2012. Pollen nutrition affects honey bee stress resistance. https://doi.org/10.1163/187498312X639568

Hughes, L. M., J. Bao, Z.-L. Hu, V. Honavar, and J. M. Reecy. 2008. Animal trait ontology: The importance and usefulness of a unified trait vocabulary for animal species. Journal of Animal Science 86(6): 1485–1491. https://doi.org/10.2527/jas.2008-0930

Khalil, A., B. H. Elesawy, T. M. Ali, and O. M. Ahmed. 2021.Bee Venom: From Venom to Drug. Molecules 26(16): 4941. https://doi.org/10.3390/molecules26164941

Kieliszek, M., K. Piwowarek, A. M. Kot, S. Błażejak, A. Chlebowska-Śmigiel, and I. Wolska. 2018. Pollen and bee bread as new health-oriented products: A review. Trends in Food Science & Technology 71: 170–180. https://doi.org/10.1016/j.tifs.2017.10.021

Laidlaw, H. H., and R. E. Page. 1997. Queen rearing and bee breeding. Wicwas Press. https://cir.nii.ac.jp/crid/1970586434903872183

Martin, E. C., Oertel, E., Nye, N. P., and others. 1980. Beekeeping in the United States (Agriculture Handbook No. 335). U.S. Department of Agriculture.

Pavel, C.I., L.A. Mărghitaș, O. Bobiș, D.S. Dezmirean, A. Șapcaliu, I. Radoi ve M.N. Mădaș. 2011. Biological activities of royal jelly—Review. Scientific Papers: Animal Science and Biotechnologies 44(2): 108–108.

Potts, S. G., J. C. Biesmeijer, C. Kremen, P. Neumann, O. Schweiger, and W. E. Kunin. 2010. Global pollinator declines: Trends, impacts and drivers. Trends in Ecology & Evolution 25(6): 345–353. https://doi.org/10.1016/j.tree.2010.01.007

Seeley, T. D. 2002. The effect of drone comb on a honey bee colony's production of honey. Apidologie 33(1): 75–86. https://doi.org/10.1051/apido:2001008

Seeley, T. D. 2009. The Wisdom of the Hive: The social physiology of honey bee colonies. Harvard University Press.

Sidor, E., and M. Dżugan. 2020. Drone Brood Homogenate as Natural Remedy for Treating Health Care Problem: A Scientific and Practical Approach. Molecules 25(23): 5699. https://doi.org/10.3390/molecules25235699

Steeves, H. P. 1999. Animal Others: On Ethics, Ontology, and Animal Life. State University of New York Press (SUNY Press)

Tulloch, A. P. 1980. Beeswax—Composition and Analysis. Bee World. https://www.tandfonline.com/doi/abs/10.1080/0005772X.1980.11097776

van Toor, R. F., and R. P. Littlejohn. 1994. Evaluation of hive management techniques in production of royal jelly by honey bees (Apis mellifera) in New Zealand. Journal of Apicultural Research 33(3): 160–166. https://doi.org/10.1080/ 00218839.1994.11100864

Vanbergen, A.J., M. Baude, J.C. Biesmeijer, N.F. Britton, M.J.F. Brown, J. Bryden, G.E. Budge, J.C. Bull, C. Carvell, A.J. Challinor, C.N. Connolly, D.J. Evans, E.J. Feil, M.P. Garratt, M.K. Greco, M.S. Heard, V.A.A. Jansen, M.J. Keeling, W.E. Kunin, … ve G.A. Wright. 2013. Threats to an ecosystem service: Pressures on pollinators. Frontiers in Ecology and the Environment 11(5): 251–259. https://doi.org/10.1890/120126

Weinstock, G.M., E. Elhaik, R. Wright ve Honeybee Genome Sequencing Consortium. 2006. Insights into social insects from the genome of the honeybee *Apis mellifera*. Nature 443(7114): 931–949. https://doi.org/10.1038/nature05260

White, J. W. 1978. Honey. pp. 287–374 *In* C. O. Chichester (Ed.), Advances in Food Research (24). Academic Press. https://doi.org/10.1016/S0065-2628(08)60160-3

Winston, M. L. 1991. The Biology of the Honey Bee. Harvard University Press.

Yang, S., S. Deng, H. Kuang, D. Zhou, X. Gong, and K. Dong. 2021. Evaluating and Comparing the Natural Cell Structure and Dimensions of Honey Bee Comb Cells of Chinese Bee, Apis cerana cerana (Hymenoptera: Apidae) and Italian Bee, Apis mellifera ligustica (Hymenoptera: Apidae). Journal of Insect Science 21(4): 1. https://doi.org/10.1093/jisesa/ieab042