BeeSensorVET

Sustainable and smart beekeeping through sensors, AI, and IoT: Insights from Slovenia, Greece, and the EU

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1. Introduction

1.1 About the BeeSensorVET project

BeeSensorVET – Integrating Sensors into VET Training for Smart Beekeeping is an Erasmus+ project that aims to modernise vocational education and training (VET) in beekeeping and apiculture by integrating advanced sensor technologies, artificial intelligence (AI), and data-driven learning approaches. The project addresses pressing environmental, technological, and social challenges in beekeeping, including climate change, biodiversity loss, and limited access to modern training for small-scale and rural beekeepers.

By developing a hybrid, digitally enabled VET training programme with innovative learning content, BeeSensorVET empowers beekeepers, VET students, and trainers with practical skills in smart beekeeping, multisensory hive monitoring, and sustainable hive management. The project strongly promotes inclusion and accessibility by engaging learners from geographically remote and rural areas, women, unemployed individuals, and low-skilled learners. Through transnational cooperation between partners from Slovenia and Greece-combining strong beekeeping traditions, scientific expertise, and digital innovation-BeeSensorVET contributes to environmental sustainability, digital transformation of VET, and the long-term resilience of the European beekeeping sector.

1.2 Sustainable beekeeping and digitalisation in apiculture

Sustainable beekeeping is increasingly recognised as a key component of biodiversity conservation, agricultural resilience, and food security, particularly in Europe, where beekeeping is dominated by small-scale and family operations. Traditional beekeeping practices, while rooted in valuable experiential knowledge, rely heavily on manual hive inspections that are time-consuming, disruptive to colonies, and provide only momentary snapshots of hive conditions. As a result, early warning signs of colony stress, disease, or environmental pressures often remain undetected, contributing to avoidable colony losses [1,2]. In the context of climate change, habitat loss, and emerging pests and diseases, sustainable apiculture increasingly depends on data-driven approaches that enable early intervention, reduce unnecessary hive disturbance, and support long-term colony health and ecosystem services such as pollination [2,3].

Digitalisation offers transformative potential for sustainable beekeeping through the adoption of Internet of Things (IoT) technologies, sensor-based monitoring, and artificial intelligence (AI), often referred to as **Apiculture 4.0**. Smart hive monitoring systems integrate sensors measuring temperature, humidity, weight, sound, gas concentrations, and bee activity, transmitting real-time data to cloud platforms where advanced analytics convert raw signals into actionable insights for beekeepers [1,4]. These technologies reduce labour demands, improve decision-making, and enable non-invasive, continuous monitoring of colony dynamics, supporting both productivity and environmental sustainability [3,5]. At the same time, recent studies highlight that adoption remains uneven, influenced by cost, connectivity, digital literacy, and social factors, underscoring the importance of accessible training, user-friendly solutions, and knowledge-sharing

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networks to ensure that digital innovation benefits a wide range of beekeepers, including those in rural and geographically remote areas [2,4,6].

1.3 Structure and purpose of this e-book

This e-book has been developed within the BeeSensorVET project as a key knowledge resource to support the integration of advanced sensor technologies, AI, and IoT solutions into VET for sustainable beekeeping. Its purpose is to present the current state of smart beekeeping technologies, analyse their adoption in Slovenia and Greece, and showcase selected EU and international best practices. The publication is based on desk research, combining an in-depth review of scientific and professional literature, analysis of policy documents, EU and national project outputs, and identification of good practices. The research also included a review of formal education curricula from school centres in Slovenia and Greece covering beekeeping and apiculture, as well as non-formal training offered by beekeeping associations, universities, and faculties in veterinary, agriculture, tourism, and rural studies. Collected materials were synthesised into thematic clusters on technological innovations, educational practices and digital skills, sustainable beekeeping, and institutional/policy support, providing a solid knowledge base to inspire and guide VET educators, trainers, beekeepers, associations, policymakers, and other stakeholders, and to support the design of future hybrid training programs in smart beekeeping.



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2. Methodology

The preparation of this e-book was based on **desk research**, combining an in-depth literature review, analysis of policy and EU and national project documentation, and identification of good practices for integrating sensor technologies, artificial intelligence (AI), and Internet of Things (IoT) solutions into sustainable beekeeping. The purpose of this research was to collect and synthesise existing knowledge and experiences that can serve as inspiration and guidance for educators, researchers, policymakers, and practitioners in modern beekeeping.

Additionally, the research included a review of formal curricula offered by educational institutions in Slovenia and Greece, covering school and university programs in beekeeping and apiculture, as well as non-formal education and training provided by beekeeping associations, NGOs, lifelong learning centres, and relevant faculties. This review identified the key skills and knowledge required by modern beekeepers, particularly in sustainability and digitalisation.

2.1 Research approach

The research followed a qualitative and analytical approach, focusing on identifying:

- current trends and technologies applied in smart beekeeping;
- innovative training practices and learning approaches in the context of VET and lifelong learning;
- policy and strategic frameworks supporting digitalisation and sustainability in beekeeping.

Each project partner conducted desk research in their respective context: **MIITR** focused on the situation in **Slovenia**, **AKMI** analysed the **Greek** context, and **MPŠ** gathered and synthesised **international and EU** best practices. The findings were later compared and discussed to identify common challenges, transferable solutions, and exemplary initiatives that could support the design of future hybrid training programmes in smart beekeeping.

2.2 Sources and databases

The information was collected from diverse and credible sources, including:

- **scientific and academic publications** indexed in Scopus, Web of Science, and Google Scholar;
- **EU-funded project outputs** (Erasmus+, Horizon Europe, EIP-AGRI, Interreg, etc.);
- **professional and industry reports** from beekeeping associations, agricultural institutes, and VET networks;
- **policy and strategy documents** from the European Commission and national ministries focusing on digital transformation, green transition, and rural development;

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- **online case study databases** and open educational resources describing the use of AI, sensors, and IoT in beekeeping and related sectors;
- **curriculum and training analysis**, particularly official school and university programs as well as non-formal education and training in Slovenia and Greece, focusing on the skills and knowledge required for beekeepers in the areas of sustainability and digitalisation.

2.3 Selection criteria

To ensure consistency and relevance, the following selection criteria were applied when choosing materials and examples for analysis:

1. **Relevance** to smart and sustainable beekeeping, with emphasis on the integration of sensors, AI, and IoT;
2. **Geographical coverage**, prioritising Slovenia, Greece, and European Union countries;
3. **Recent and credible sources**, preferably from the period 2015–2025;
4. **Transferability and educational potential** of practices for use in VET or professional training;
5. **Sustainability dimension,** including energy efficiency, biodiversity protection, and climate resilience.

2.4 Data synthesis

After data collection, the materials were categorised into thematic clusters: Technological innovations and applications; Educational practices and digital skills development; Sustainable and ecological aspects of beekeeping; Institutional and policy support mechanisms. Each project partner contributed to the synthesis by summarising the most relevant and innovative examples. The comparative analysis of national and international practices provided the foundation for the chapters that follow, presenting insights from **Slovenia, Greece, and the EU**.

3. Current state of smart beekeeping technologies

This chapter deals with the technology, namely the sensors and sensor systems that can help beekeepers to better manage their hives. Numerous commercial sensor and sensor platform providers exist on the market. To avoid appearing to favour any provider, we will refrain from listing any particular brand or product names and focus on the technology itself. The graphs used for illustration were prepared using the data obtained in the research project WellBEEing, coordinated by one of the authors of the book [7].

Traditionally, before the arrival of electronics, beekeepers checked their hives manually, either by observing the behaviour of the bees at the hive entrance or by opening the hive and inspecting the interior. Sensors facilitate the management of a large number of beehives and are particularly useful when the hives are located in remote areas that the beekeeper

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cannot access daily. We first look at the individual sensors and next into sensor combinations. The last few years have seen the publication of several review papers that serve as a good starting point for exploring the state-of-the-art of smart beekeeping technologies [8–11]. As the review papers point out, while several sensors are already in use, it is time to start using advanced systems to generate new apiary knowledge.

3.1 Sensors

3.1.1. Scales

Scales measure the weight of a beehive and can offer beekeepers a real-time window into what's happening inside the hive without opening it. Typically, the scales are installed under the beehive over the season.

Tracking a hive's weight helps reveal nectar flow patterns, colony growth, food consumption, and even early signs of swarming. When the hive suddenly gains weight, it often means a strong nectar flow is underway; when it drops, the bees may be consuming stored honey or facing stress (for example, a colony may be experiencing loss of bees). These kinds of data let beekeepers make smarter decisions about feeding, planning harvests, or other interventions.

Sampling rate is a very relevant parameter for scales. Several commercial products send the beekeeper an SMS containing the hive's weight once per day, typically in the evening. For an experienced beekeeper, this is usually enough to assess the hive's condition.

However, a single point per day without an appropriate context can be misleading. For example, an increase in mass in April without any additional information could correspond to a good harvest, several cm of snow on the beehive (snowfall in April does happen in Slovenia), or someone adding a weight on the top of the beehive for some reason. Looking at the time dependence of the weight of the hive can easily differentiate between the first and the third option (a good harvest is seen as a steady rise in mass, while adding extra weight is instantaneous), while combining the weight data with other sensors, such as temperature, can differentiate between the good harvest and the snowfall [12].

3.1.2 Temperature and humidity sensors

Bees work hard to keep the brood nest at a steady warmth—usually around 34–35°C—because even small fluctuations can affect larval development and colony health. When outside temperatures swing too high or too low, the colony must spend extra energy heating or cooling the hive, which can influence honey production and overall vitality. For beekeepers, monitoring temperature helps reveal whether the colony is thriving, stressed, or preparing for seasonal changes.
Bees actively regulate moisture levels by fanning their wings, evaporating nectar, and even bringing in or removing water as needed. If humidity climbs too high, nectar can't ripen into

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stable honey; if it drops too low, developing larvae can dry out. For beekeepers, paying attention to humidity trends offers clues about ventilation, colony strength, and seasonal pressures.

3.1.3 Sound

Sound inside a beehive is like a living diagnostic tool. It is a bit less straightforward than weight or temperature and requires pre-processing, but it can offer important insights into the colony's condition. A healthy colony produces a steady, low hum. Changes of sound, such as it becoming higher, sharper, or more erratic, can indicate situations where a beekeeper's intervention is required. Substantial research has been carried out in the assessment of swarming (when a beekeeper has to act fast to collect the swarm) [13], a queenless hive (which requires adding a new queen to assure the survival of the colony) [14,15], nectar robbing, or hornet attack [16].

3.1.4 Video

As you can see, we are moving from simpler to more complex technologies. Video from a camera placed in front of the hive entrance offers valuable insight into hive dynamics, including traffic flow, foraging intensity, guard-bee behavior, robbing attempts, and even subtle signs of stress. However, unlike some of the other sensors mentioned in this chapter, cameras generate much more data than, for example, temperature or humidity sensors. These data need to be stored and processed, which requires certain resources (bandwidth, server space, processing power). In addition, cameras require a stronger power source. It can only be placed outside the hive, which limits its usefulness in assessing the status inside the hive (if it were to be placed inside the hive, bees would most likely cover it with propolis; there is no space for a camera inside the hive, and it is dark, which further limits its usefulness). Finally, an exposed camera can easily get damaged by environmental factors or even get stolen.

3.1.5 VOC sensors

Sensors of volatile organic compounds (VOCs) are somewhat less explored than the sensors mentioned before. Nevertheless, monitoring VOCs in the hive can provide information about the colony's health. It is particularly useful in the treatment of bees with formic acid against varroa, where the beekeeper can monitor evaporation rates and ensure the treatment progresses according to the plan. Essential oils are sometimes also used for treatments.

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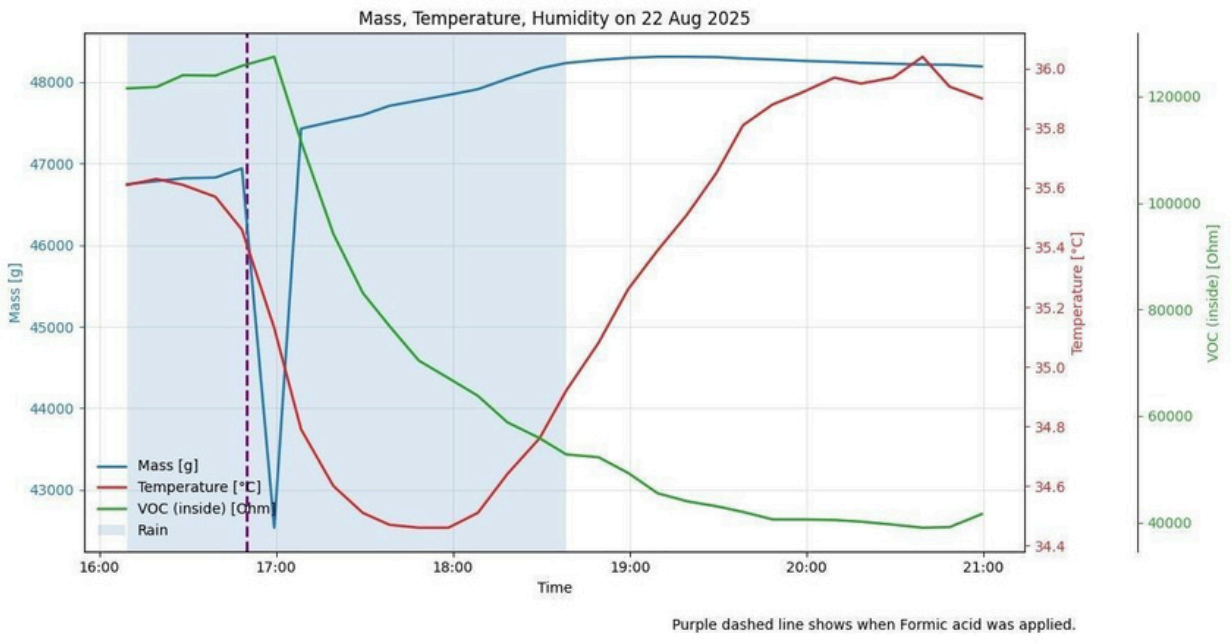


Figure: Example of sensor data when treating the bees with formic acid. Graphs for mass, temperature, humidity, and VOC concentration are shown, and the period of rain is indicated.

3.1.6 Connectivity and data analysis

Each sensor feeds its readings into a central hub or microcontroller inside or near the hive. That hub packages the information and sends it out via wireless protocols such as Wi-Fi, Bluetooth, LoRa, NB-IoT, or cellular networks, depending on how remote the apiary is. Once the data reaches the cloud, it's processed, stored, and translated into graphs, alerts, and trends that the beekeeper can view on a phone or computer in a dedicated app or a website. Alternatively, the data can be processed on the device itself (edge computing), with only aggregated data sent to the user. The advantage of this approach is that there is no need to store large amounts of data (especially in the case of audio and video), while the drawback at the same time is that the data is not stored, and it is thus impossible to check what was going on if the data processing results are not clear.

3.2 Trends - using AI toward precision beekeeping

We have so far discussed individual sensors; however, a true breakthrough occurs when we combine their outputs using methods of artificial intelligence to process them. Each sensor captures a different dimension of colony life, but instead of looking at isolated data points, AI can recognize patterns across multiple streams at once: a subtle rise in humidity combined with a drop in temperature and a shift in acoustic signatures might indicate brood-rearing stress; a sudden weight gain paired with increased forager traffic on video could signal the start of a major nectar flow. Over time, machine-learning models can learn the "normal rhythm" of each hive and flag deviations long before a human would notice them. This opens the door to true precision beekeeping, where interventions are timely, minimal, and tailored to each colony's unique behavior. As these systems mature,

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beekeepers will move from reactive management to predictive care, improving colony health, reducing losses, and making beekeeping more sustainable in a changing climate.

4. Case studies

4.1. Slovenia

4.1.1 Overview of the beekeeping sector in Slovenia

Beekeeping in Slovenia is widely recognised as both a traditional rural activity and a strategically important sector for biodiversity, food security, and cultural heritage. Slovenia is strongly associated with pollinator protection at the international level, including its leading role in establishing World Bee Day (20 May) as a United Nations-designated day [17].

4.1.2 Scale and structure of the sector

Slovenia's beekeeping sector is characterised by a large number of predominantly small-scale beekeepers, supported by strong organisational structures and public administration systems (e.g., registers, veterinary and food safety oversight, and sectoral interventions under agricultural policy). According to the national beekeeping topic portal, as of 31 October 2023 the register recorded 11,109 beekeepers, operating in 15,519 apiaries, with an average of 16.78 colonies per beekeeper; the same source reports 207,799 bee colonies in 2023 (including 7,865 in organic production) and a honey production figure of 285 tonnes for that year [18].

Earlier official statistical releases (SURS) similarly emphasise broad citizen participation and the nationwide distribution of beekeeping activity [19].

4.1.3 Cultural and identity dimension

Slovenian beekeeping is not only an agricultural activity, but also part of national identity and heritage. In 2022, "Beekeeping in Slovenia" was inscribed on UNESCO's Representative List of the Intangible Cultural Heritage of Humanity, reflecting a living set of knowledge and practices involving beekeepers, traditional equipment, and intergenerational transmission [20].

Government and official promotional sources connect this heritage to a wider set of contemporary practices such as apitourism and (more recently) urban beekeeping—where beekeeping activities also serve education, community engagement, and awareness-raising about pollinators [21].

4.1.4 Production, consumption, and market features

Honey production in Slovenia is variable and highly sensitive to weather, forage availability, and colony health. The national beekeeping portal reports that honey consumption in Slovenia is around ~1 kg per person per year, and provides a 2022 value of 1.27 kg per person; it also notes that average self-sufficiency over the last decade was 57%, and that self-sufficiency can fluctuate substantially between years [17].

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The same source highlights important market structure characteristics, including that Slovenian beekeepers sell more than 80% of honey “at home” (direct sale), which reflects the prominence of short supply chains and trust-based local markets [17].
Longer-term indicator reporting also points to challenges in maintaining honey self-sufficiency and notes a decreasing trend in honey self-sufficiency relative to some other animal products, underscoring the sector’s exposure to environmental and market pressures [22].

4.1.5 Institutions and sector coordination

Slovenian beekeeping is supported by structured coordination mechanisms, including a legally anchored registry framework and a recognised breeding organisation for the Carniolan honey bee (Apis mellifera carnica). The national beekeeping portal explicitly identifies the Slovenian Beekeepers’ Association (Čebelarska zveza Slovenije) as the recognised breeding organisation for the Carniolan bee [17].

In parallel, the Slovenian Beekeepers’ Association describes a broad network of regional and local beekeeping societies that provide training, advisory services, and community-based knowledge exchange [23].

4.1.6 Technological adoption and innovative beekeeping initiatives

Slovenia’s beekeeping tradition increasingly coexists with a measurable shift toward precision beekeeping and smart hive monitoring, reflecting broader European patterns: sensors and IoT systems are used to track colony weight (nectar flow/honey stores), internal temperature and humidity, acoustics/vibration signals, and environmental variables; these data streams can support decision-making in disease risk management, feeding, movement of colonies, and timing of harvest [8].
Within the Slovenian context, technology adoption is visible in three interconnected layers:

1. **Digital administration and advisory workflows** (e.g., web-based record keeping, sector reporting, and beekeeper support services). A concrete example is the eČebelar platform, operated through the national beekeeping association ecosystem, which is positioned as a digital tool for beekeepers [23].
2. **Field-deployed monitoring devices and networks** used to track nectar flows and honey yield potentials at scale. Slovenia has a long-running approach to automated honey-flow forecasting using hive-scale measurements, showing how instrumentation can support both individual beekeepers and advisory systems [24].
3. **Research and innovation projects** integrating IoT sensing, AI analytics, and multi-sensor approaches. Slovenian research highlights the move toward integrated “smart hive management,” combining sensing hardware with cloud processing and decision support [1].

This trajectory aligns closely with BeeSensorVET’s rationale (i.e., bridging traditional practice with sensors/AI/IoT through vocational training and competence tracking), as described in the official project application documentation.

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4.1.7 Examples of local good practices

Below are well-documented Slovenian good practices that illustrate how smart beekeeping technologies, research, education, and education–industry cooperation are being implemented.

1) National digital tools for beekeepers: eČebelar (association-driven digitalisation)

eČebelar is presented as a dedicated digital platform/tool for beekeepers within the ecosystem of the Slovenian Beekeepers' Association [23].

While the public-facing page is concise, it signals institutional support for digital workflows in beekeeping (e.g., record-keeping, access to services, and sector-level coordination).

Why it matters as a good practice.

- It demonstrates association-led digitalisation—important in a sector dominated by small-scale operators who benefit from shared infrastructure and standardised processes.
- It serves as an enabling layer for broader smart-beekeeping adoption, as digital tools reduce administrative friction and connect beekeepers with forecasting and advisory services.

2) Honey-flow forecasting and automated hive-scale monitoring (long-running field implementation)

Slovenia has an established practice of using hive scales to support honey-flow forecasting. The "Slovenian Honey Forecasting System" description states that the system has used more than 60 automatic scales for more than 14 years and supports monitoring and forecasting of honey yield [24].

Technology and implementation

A concrete Slovenian technology example for hive-scale monitoring is the TCM-13A measuring station by Ames d.o.o., described as a honey-collection control station using a beehive scale [25].

Ames also provides a technical brochure for the TCM-13A station, indicating a mature productisation pathway from measurement needs to deployable monitoring equipment [25].

Why it matters as a good practice.

- It is a rare example of sustained "smart monitoring" adoption over a long period, which is critical for building trust in technology among beekeepers.
- The network effect (multi-location measurements) supports both micro-level decisions (when to harvest, whether to move colonies) and meso-level advisory insights (nectar flow trends by region).

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- It creates a practical learning environment for VET and non-formal training: learners can interpret real data and link it to seasonal biology and management decisions.

3) BeeScales (Slovenian innovation recognised through sector channels)

BeeScales is a Slovenian bee-scale solution showcased as a "reference" and explicitly noted as a winner of a competition organised by the Slovenian Beekeepers' Association [26].

Why it matters as a good practice.

- It demonstrates sector-led innovation incentives: competitions and recognition mechanisms help steer technological development toward beekeeper needs and usability.
- It strengthens the domestic innovation ecosystem by connecting practitioners (associations and beekeepers) with product developers.

4) AI + urban beekeeping technology pilots: Urban Beekeepers (DIH4AI-funded development)

The Urban Beekeepers initiative describes an AI-powered bee monitoring system under development, framed as an innovation project supported within DIH4AI and focused on enabling beekeepers to optimise inspections and reduce environmental footprint through data-driven monitoring [27].

Why it matters as a good practice.

- It links smart beekeeping with urban sustainability agendas, where monitoring and transparency can support the coexistence of beekeeping, public safety expectations, and environmental education.
- It provides a high-visibility pathway for public engagement, helping translate "sensing and AI" into an understandable narrative for citizens.

5) Ljubljana's "Bee Path" and pollinator-friendly urban practice transfer (city-led good practice)

Ljubljana is widely recognised for its urban pollinator programme known as the Bee Path (BEE PATH), framed in European urban cooperation contexts. The Bee Path is listed as an URBACT good practice, highlighting city-level measures for pollinators and awareness building [28].

In addition, European Urban Initiative materials describe "Bee Path Cities" as a transfer and capacity-building effort around creating cities that are good for pollinators [29].

Why it matters as a good practice.

- It demonstrates municipal leadership and practical transferability to other cities.
- It creates a "living lab" for education: urban beekeeping, pollinator habitats, and citizen awareness can be integrated into school programmes and vocational learning.

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6) Research-based smart hive management: University of Ljubljana (IoT for hive management)

A Slovenian research output hosted in the University of Ljubljana repository (and associated with the EU project CODECS context on the repository page) addresses leveraging IoT technologies for smart hive management and sustainable beekeeping [1].

Why it matters as a good practice.

- It provides an evidence base for teaching and training (methods, architectures, and system considerations) that can be translated into VET learning content.
- It illustrates the research-to-training pathway: published results can be adapted into modules on sensors, data interpretation, and decision support.

7) WellBEEing: smart hive monitoring (Jožef Stefan Institute + partners; ARIS-supported project)

The aim of the WellBEEing project explicitly is to develop a smart hive monitoring honey quantity, harvest quality, and bee wellbeing, with project partners including the Jožef Stefan Institute, Senso4s d.o.o., and the University of Ljubljana, Veterinary Faculty [7].

The Jožef Stefan Institute's project listing identifies WellBEEing: monitoring bee colonies with smart sensors, including a project identifier and English subtitle indicating IoT monitoring in the presence of external stressors.

Why it matters as a good practice.

- It is a strong example of education–research–industry cooperation: a research institute, a company, and a university faculty collaborate on applied sensing.
- It supports VET relevance through clear "applied outcomes" (monitoring, quality, wellbeing) that map to practical skills (sensor deployment, data literacy, interpretation, preventive action).

8) National Institute of Biology (NIB): pollinator research and monitoring ecosystem

Slovenia's applied pollinator ecosystem includes substantial research capacity. The National Institute of Biology provides a directory of projects, including pollinator-related work [30].

One example is the NIB project page describing BEE(A)WARE and related work (as presented on the referenced project page), demonstrating ongoing research attention to pollinators and bee-related stressors [30].

Complementing institutional research, Slovenia has also published official reporting on monitoring wild bees, showing policy-relevant attention beyond managed honey bees [17].

Why it matters as a good practice.

- It shows that Slovenia's smart-beekeeping context is embedded in a broader pollinator science and biodiversity monitoring environment.

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- It supports evidence-based training: VET programmes can connect hive-level monitoring with broader ecosystem indicators and conservation measures.

9) Education and training: Slovenian Beekeeping Academy (KIS) and knowledge dissemination routes

The Beekeeping Academy of Slovenia (Slovenska čebelarska akademija) is presented by the Agricultural Institute of Slovenia (Kmetijski inštitut Slovenije) as a structured approach to beekeeping education and competence development.

An English-language page further introduces Slovenian beekeeping in this academy context [31].

Why it matters as a good practice.

- It institutionalises training and international knowledge exchange, supporting professionalisation and continuous learning.
- It offers a platform for integrating smart-beekeeping topics (sensor use, data interpretation, evidence-based management) as curricula modernise.

Supporting dissemination and experiential education (apitourism routes).

Government-hosted informational materials also frame beekeeping heritage and modern practice through apitourism routes and educational narratives, noting Slovenia as a “cradle of modern apitherapy” and positioning beekeeping as a living cultural and rural activity.

While not “sensor technology” itself, this is relevant for VET because it broadens employability pathways (tourism services, communication, product storytelling, quality presentation) that can complement smart monitoring competencies.

10) Connection to VET modernisation: BeeSensorVET as a structured skills pipeline (Slovenian-led dissemination and training)

BeeSensorVET is explicitly designed to integrate bee-monitoring sensors, AI, and IoT into beekeeping education, using a hybrid training model and competence tracking to support digital literacy and resilience among beekeepers and learners.

The project documentation also specifies planned outputs such as an e-book of best practices, interactive learning content, and workshops, including a practical workshop in Slovenia, and emphasises dissemination and stakeholder engagement.

As a Slovenia case study, this is a relevant “good practice in formation”: it demonstrates how Slovenia’s existing strengths (heritage + structured sector institutions + research capacity) can be operationalised into replicable VET training packages aligned with digital transformation.

4.1.8 Key challenges and opportunities

Key challenges.

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1. **High inter-annual volatility of honey production and self-sufficiency.** Official reporting notes strong fluctuations in self-sufficiency (e.g., large year-to-year variation), and an overall need to strengthen resilience and competitiveness.
2. **Environmental and biodiversity pressures.** Pollinator health is influenced by habitat change, climate pressures, and external stressors; monitoring wild bees and broader pollinator indicators signals that the challenge extends beyond managed honey bee colonies.
3. **Fragmentation and capacity constraints among predominantly small-scale beekeepers**. Small-scale structures can slow adoption of new technologies due to cost, skills gaps, and uncertainty about benefits. This is exactly the type of bottleneck that VET-oriented, practical, and data-driven training aims to reduce.
4. **Data integration and interpretability.** Smart beehive technology produces large data streams; research reviews emphasise that usefulness depends on robust models, standardisation, and actionable interpretation—not only sensor deployment [8].

Key opportunities.

1. **Strong institutional infrastructure and public recognition**. UNESCO inscription and national-level policy attention create a favourable environment for investment in skills, quality systems, and the diffusion of innovation [17,21].
2. **Existing "real-world" smart monitoring practice**. Long-running hive-scale monitoring for honey forecasting provides a credible basis for scaling broader sensor adoption [24].
3. **Research-to-practice pipeline.** Active projects (e.g., WellBEEing, IoT hive management research, and AI monitoring initiatives) show that Slovenia has the ingredients for innovation transfer into vocational curricula and beekeeper upskilling [1,7].

European alignment and funding leverage. EU-level work on monitoring methodologies and pollinator-related actions provides a policy and technical scaffold that Slovenia can use for standardisation and scaling [5].

4.2. Greece

4.2.1 Beekeeping in Greece: Context and character

In Greece, beekeeping isn't just a job; it's woven into rural life and culture over the years. Around 20,000 beekeepers tend roughly 1.5 million colonies, giving Greece one of the densest concentrations of hives in Europe and making the country a major honey producer. Pine forests are like the lifeblood of this industry. They supply about two-thirds of the national honey, while thyme, heather, and wildflowers add distinctive flavours [32]. Despite this bounty, average yields per hive are modest, so many beekeepers operate large, mobile apiaries that follow seasonal blooms. The honey they produce plays a role well beyond commerce: bees pollinate crops, underpin biodiversity, and their products feature prominently in Greek cuisine and medicine. Support for the sector includes a National Apiculture Programme, subsidies for training and disease control, and a digital register tracking hives and beekeepers to improve traceability and align with EU standards [33].

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4.2.2 Tradition meets technology

For generations, Greek beekeepers have relied on manual inspections and local knowledge. That is starting to change. A growing minority, about one in five professionals, use electronic hive scales or other sensors to monitor weight, temperature, and humidity remotely. These early adopters often manage hundreds of hives spread across the country, so digital tools save them countless hours and kilometres by sending alerts when something isn't right. Yet most beekeepers still find technology costly, internet service patchy, and digital interfaces intimidating. To bridge this gap, associations and universities are running "Apiculture 4.0" workshops, while projects like BeeSensorVET offer training in Greek and aim to demystify smart beekeeping for newcomers.

Local innovation is also gaining traction. Companies such as Beezon and ANEL have introduced apps and IoT platforms that enable beekeepers to scan QR-coded hives, dictate inspection notes, and store data in the cloud [34,35]. Start-ups like LIME Technology are piloting eHive—an integrated smart hive that uses multiple sensors and basic AI to detect brood disease and microclimate stress [36]. Universities and research institutes, meanwhile, are contributing tools like bee-traffic counters, acoustic monitoring systems, and data platforms through EU projects such as IoBee and B-THENET [37,38]. EU and national funds, including resources from the Recovery and Resilience Plan, are helping move these ideas from lab to apiary.

4.2.3 Examples of local good practices in Smart & Sustainable Beekeeping (Greece)

The following examples highlight key Greek good practices in smart and sustainable beekeeping. They were selected for their relevance to digitalisation, sustainability, education, and transferability to VET contexts, covering industry-led solutions, applied research, knowledge networks, and training initiatives.

1. Digital hive record-keeping: ANEL Beekeeper App

What it is: The ANEL Beekeeper App is a mobile and web-based application developed by a Greek beekeeping supplies company to replace traditional paper hive logs. Beekeepers can scan QR/NFC hive IDs, dictate inspection notes by voice, and store inspection data in the cloud, accessible through a web dashboard.

Why it matters: This is a practical example of industry-driven digitalisation tailored to everyday beekeeper needs. Its simple interface and voice input reduce barriers for older or less digitally confident users, while supporting traceability and data-driven decision-making. The tool is directly relevant for VET training on modern hive management and digital record-keeping.

2. IoT-based smart hive pilot: eHive project (Epirus)

What it is: The eHive project, developed by a regional Greek agri-tech startup and funded through Greece's Recovery and Resilience Plan, is piloting a fully integrated smart beehive. The system combines sensors (temperature, humidity, acoustics, and brood indicators) with IoT connectivity and basic AI to detect disease risks, environmental stress, and colony loss indicators in real time.

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Why it matters: eHive demonstrates how EU recovery funding can support applied innovation in rural regions. Its focus on early warning, prevention, and reduced hive disturbance aligns strongly with sustainable beekeeping goals. The pilot has high demonstrative value for VET learners, offering a tangible example of how IoT and AI can be applied in apiculture.

3. Research–industry cooperation: HMU and the IoBee project (Crete)

What it is: The Hellenic Mediterranean University (HMU) participated in the EU-funded IoBee project, contributing expertise in bioacoustics and ICT. The project developed tools such as bee traffic counters and smart hive systems, combining acoustic data, environmental sensors, and satellite information to assess colony health.

Why it matters: This case shows how Greek academic research feeds into practical beekeeping tools. HMU involved students and local apiaries in pilot testing, strengthening the link between higher education, VET, and practice. The outputs support non-invasive monitoring and evidence-based decision-making, directly applicable to smart beekeeping curricula.

4. Knowledge-sharing for sustainability: B-THENET Greek hub (Chalkidiki)

What it is: Within the Horizon Europe B-THENET project, Greece hosts a national hub coordinated by the Hellenic Institute of Apiculture. The hub collects, validates, and disseminates best practices for sustainable beekeeping through practice abstracts, workshops, and peer exchange, with a strong presence in a major beekeeping region.

Why it matters: B-THENET represents a bottom-up, practitioner-led innovation model in which beekeepers co-create and share solutions. Its materials are accessible and directly usable in training and lifelong learning. The hub strengthens links between research, advisory services, and education, making it highly relevant for VET exploitation.

5. Entry-level and youth training: "New Agriculture – New Generation" (Apiculture programme)

What it is: This programme offers free, structured apiculture training for young people and new entrants, combining classroom teaching with extensive hands-on practice in local apiaries. Delivered with university involvement, it covers both technical skills and basic entrepreneurship.

Why it matters: The initiative addresses generational renewal and inclusion in Greek beekeeping. Its blended, practice-oriented approach aligns well with VET principles and provides a model for introducing sustainability, innovation, and business thinking into traditional sectors.

6. Urban awareness and education: Bee Path initiative (Nea Propontida)

What it is: Adapted from the Slovenian Bee Path model, the Nea Propontida initiative integrates urban beehives, school activities, citizen workshops, and apitourism, linking beekeeping with environmental education and local identity.

Why it matters: This example highlights the social and educational dimension of sustainable beekeeping, extending beyond production. It creates living labs for

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awareness, citizen engagement, and informal learning, complementing technological innovation with community-based approaches.

4.2.4 Key Challenges and Future Opportunities

Beekeeping in Greece faces substantial headwinds. Climate change has brought longer droughts, hotter summers, and devastating wildfires that destroy forage, especially pine trees. Pests such as Varroa destructor still cause major losses, while the sector's demographic is ageing and the digital divide remains wide. Rising feed and fuel costs, as well as competition from cheaper imports, squeeze margins.

At the same time, a wave of opportunity is building. EU policies like the Green Deal and Farm-to-Fork Strategy encourage pesticide reduction, habitat restoration, and support for sustainable beekeeping. Improvements in connectivity and falling sensor prices make basic monitoring more accessible for small and medium apiarists. Training initiatives—whether through BeeSensorVET, B-THENET, or local universities—are building the digital and environmental skills needed to thrive in "Apiculture 4.0." It is also scoped to diversify incomes through certified specialty honeys, propolis products, and apitourism. Inclusive training and cooperative models are attracting younger and more diverse participants, bridging the gender gap, and ensuring that traditional knowledge is passed down. In short, the future of Greek beekeeping will depend on blending time-honoured practice with smart technology and a strong support network—something projects like BeeSensorVET are designed to facilitate.

4.3. EU and international best practices

Across Europe and internationally, beekeeping is experiencing a technological revolution. Advanced sensors, artificial intelligence, and data-driven monitoring systems are enabling beekeepers to manage hives more efficiently, detect colony stress early, and optimize pollination services, while simultaneously supporting biodiversity and sustainable agriculture. This chapter presents an overview of EU-funded projects, innovative companies, and educational initiatives that are leading the way in precision and digital apiculture. The chapter also highlights practical strategies for transferring knowledge and technologies from these initiatives to VET institutions and beekeeping education programs.

4.3.1 EU and Erasmus+ projects in apiculture

BestHONEY Project (Erasmus+) is a transnational initiative with partners from Türkiye, Italy, France, and Spain, designed to improve hygiene, processing, packaging, and quality standards in honey production according to EU regulations. The project unites scientific institutions, public authorities, and technical experts to develop harmonized training materials, practical guidelines, and innovative approaches that strengthen professional competencies in beekeeping. Key areas include colony health management, post-harvest quality control, food safety, traceability, product characterization, and sustainable production practices. BestHONEY supports the modernization of VET curricula, aligning learning outcomes with EU regulatory frameworks and integrating scientific research with practical field experience, thus fostering professionalization, safety, competitiveness, and sustainability in the European honey sector [39].

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BeeLieve – European Centres of Vocational Excellence (CoVE) in Apiculture is a four-year Erasmus+ initiative aimed at transforming beekeeping education and promoting sustainable practices across Europe. Partner countries include Poland, Bulgaria, Italy, Slovenia, and Greece. BeeLieve establishes regional centers of excellence that combine practical, industry-linked learning with research. The project develops customized curricula encompassing fundamental beekeeping knowledge, entrepreneurial and digital competencies, and green skills. BeeLieve emphasizes sustainability, eco-friendly beekeeping, biodiversity preservation, and regenerative practices aligned with EU green goals. Practical training—apprenticeships, internships, and on-site beekeeping experience—is central to the project, while open online courses (MOOCs) broaden access to knowledge and lifelong learning [40].

B-GOOD (Horizon 2020) focuses on improving honeybee health and the sustainability of beekeeping through advanced digital technologies. Led by Ghent University, researchers across 13 European countries developed a "smart hive" with integrated sensors to monitor hive weight, temperature, gases, vibrations, pollen flow, bee numbers, pesticides, viruses, and other colony health indicators (HSI). Machine learning algorithms analyze data in real-time, providing beekeepers with actionable alerts and guidance, particularly reducing winter losses. The project also created a European knowledge-sharing platform connecting beekeepers, researchers, and policymakers. Its continuation, **HIVEOPOLIS,** develops digital hives with active heating and even robotic bees for hive communication. These initiatives mark a breakthrough in high-tech apiculture, enabling precise monitoring, early stress detection, and improved bee survival, underpinning Europe's food security and pollination needs [41].

SENSORBEES investigates the use of bee colonies as sensor networks to monitor key ecological parameters, including pollination services and flowering plant diversity. Equipped with advanced sensors, hives track queen and worker activity, brood development, and inter-bee interactions. Data on bee behavior, hive production, and environmental conditions across a foraging radius of up to 10 km (~314 km^2) allows the evaluation of colony health, pest presence, and local floral resources. Integrating data across hives identifies potential problem areas, supporting sustainable beekeeping management and biodiversity conservation [42].

B-THENET – Sweet Innovation for Sustainable Beekeeping aims to modernize the European beekeeping sector by promoting innovation, digitalization, and knowledge sharing. The project implements a multi-actor approach, engaging beekeepers, advisors, researchers, policymakers, industry, and consumers to collect best practices and research findings for practical application. Through digital platforms and 13 national sub-networks, it provides resources in 15 EU languages, guidelines for advisors, online and practical training, and transnational events to harmonize sustainable beekeeping practices across Europe [38].

BeeUrban – Buzzing Futures (Erasmus+) develops urban beekeeping curricula, interactive online courses, textbooks, case studies, and best practices for university students, researchers, and educators. By fostering digital skills and entrepreneurship, the project enhances urban pollination initiatives and community engagement [43].

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BeeHome integrates AI, robotics, and automated climate/pest management for modular commercial apiaries. Managing up to 40 hives, the system automates feeding, thermoregulation, pest control, and honey harvesting while providing real-time monitoring and alerts. Field tests in Israel demonstrated increased colony survival, honey production, and pollination efficiency, addressing colony collapse and supporting sustainable agriculture [44].

ENFORCE (Erasmus+) strengthens the sustainability and resilience of beekeeping by introducing innovative business models, experiential farming, gamification, and sensory analysis of honey. It combines practical training with new marketing and communication strategies to improve honey quality, income stability, and consumer-oriented practices [45].

BeeGen (Erasmus+) promotes youth engagement in beekeeping through gamified, technology-supported learning. The project combines classroom theory with practical visits to local beekeepers and hands-on activities, introducing students to hive operations, honey production, and entrepreneurship in value-added products [46].

"Bees Give Us Food and Health" (Erasmus+ KA210-VET) connects Slovenian and Czech beekeepers, students, and apitherapy experts to exchange knowledge and best practices. Participants gain practical skills, explore apitherapeutic applications, plant pollinator-friendly plants, and develop a multilingual online classroom for sustainable beekeeping and health education [47].

4.3.2 Companies and educational initiatives

BeeLife (Brussels, since 2013) protects pollinators and biodiversity across Europe. The organization promotes sustainable farming practices, public awareness, and policy development while making pollinator data publicly accessible [48].

Sens4Bee employs miniaturized RFID-based sensors attached to hives and individual bees. Developed by Microsensys GmbH, Fraunhofer IZM, and Helmholtz UFZ, the system tracks temperature, humidity, vibration, light, acoustic signals, and flight activity. Micro-battery and energy-harvesting technologies power sensors weighing 2–10 mg without affecting bee behavior. Data is analyzed in the cloud, linked to environmental events, and used to provide beekeepers actionable insights [49].

HoBBIT (Norway) equips standard hives with cameras, microphones, scales, and climate sensors to monitor honeybee behavior and environment. AI analyzes data to detect early stress, disease, or queen loss, enabling regenerative, pollinator-friendly farming practices and supporting ecosystem health [50].

B**ee Analytics & Business course (RUN-EU SAP)** combines AI, beekeeping, and entrepreneurship. Students from Finland, Spain, and Belgium analyze hive sensor and video data, model bee behavior, and develop business solutions. Using Design-Based Education, students gain technical and entrepreneurial skills to innovate in precision beekeeping [51].

Fondazione Bruno Kessler (FBK) & Melixa – AGRIBEE AI harness AI to assess human and agricultural impacts on biodiversity. By combining real-time and historical hive data,

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weather, and agricultural datasets, beekeepers receive precision tools for monitoring hive health, improving productivity, and reinforcing bees' role as environmental sentinels [52].

BeeHero leverages in-hive and in-field sensors with machine learning to monitor colony health and pollination efficiency at scale. Their global collaborations include research on Varroa, bee genetics, invasive species, and biological pest control [53].

Ubees integrates AI-powered sensors, real-time monitoring, and data analytics to optimize pollination, improve crop yields, and support biodiversity. Apps provide real-time insights and tailored recommendations, creating regenerative agricultural ecosystems [54].

Bee Smart Technologies (Bulgaria) develops remote monitoring systems like BeeBot and Hivebase for hive temperature, humidity, and acoustic monitoring. Data analysis platforms allow long-term tracking, early interventions, improved colony health, and integration with e-commerce to support local beekeepers.

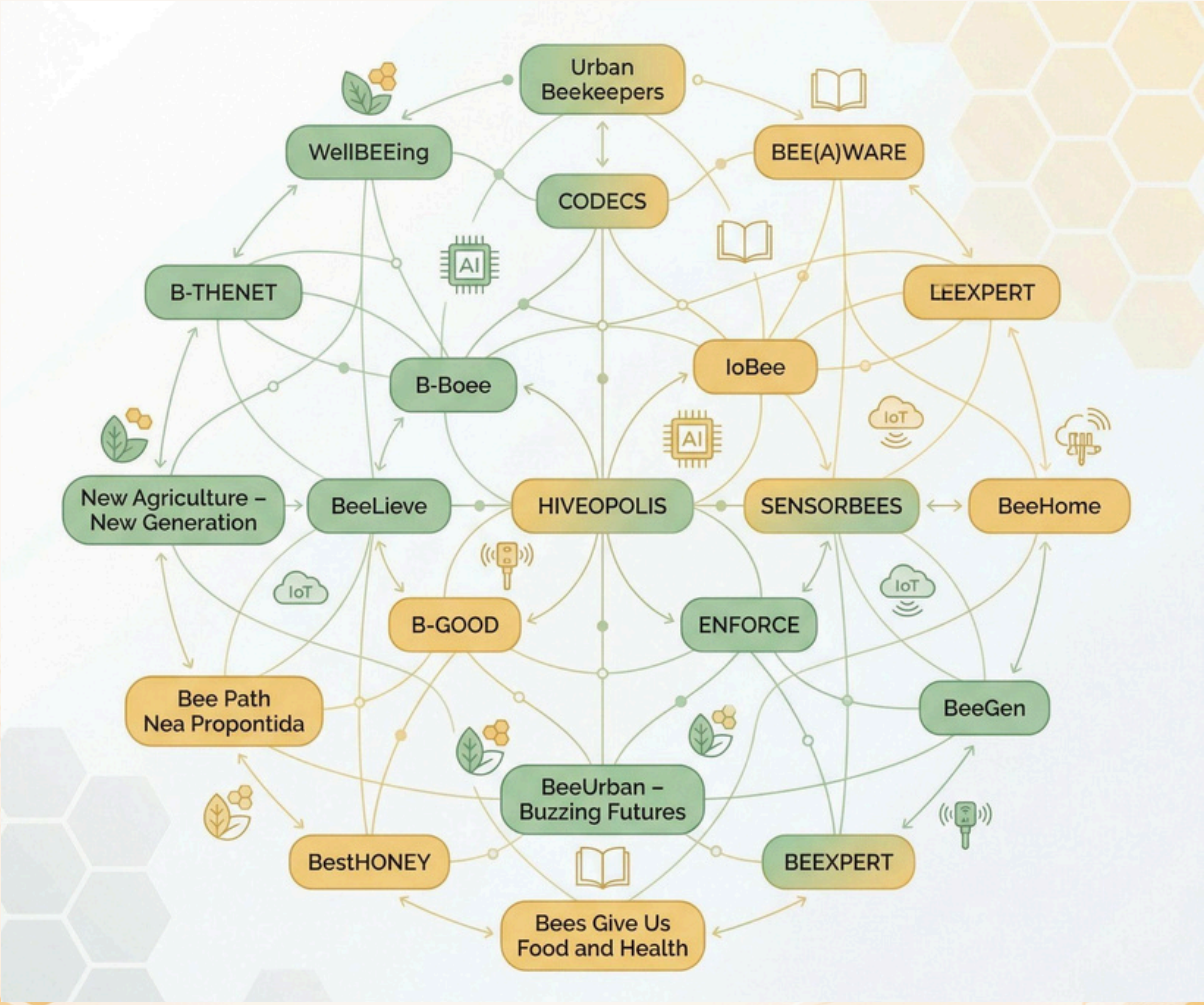


Figure. Network overview of innovative beekeeping projects in the EU, highlighting interconnected initiatives integrating AI, IoT, sustainability, digital monitoring, and vocational education to advance smart and data-driven apiculture ecosystems.

4.3.3 Guidelines for transferring knowledge to VET and beekeeper education

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The rapid development of AI, sensor technologies, and digital solutions in beekeeping offers a unique opportunity to modernize VET programs. By integrating insights from EU projects, international research, and innovative companies, VET institutions can equip future beekeepers with the skills, knowledge, and mindset needed for precision apiculture. Effective knowledge transfer requires not only technical training but also interdisciplinary collaboration, sustainability awareness, and practical experience to ensure students and professionals can apply these innovations in real-world contexts.

A publication on European beekeepers' attitudes toward digital technology highlights the gradual adoption of digital hive monitoring tools (DBMT), a trend referred to as "Apiculture 4.0." A survey of 844 beekeepers across 18 European countries shows that while 79.1% still rely primarily on traditional methods, an increasing number—especially professional beekeepers—are adopting digital tools, such as hive scales, resulting in improved hive management, healthier colonies, reduced winter losses, and time savings. At the same time, approximately a quarter of respondents remain uncertain about the benefits of these technologies, emphasizing the need for further education and awareness-raising. Personal attitudes, social influence, and a sense of control are key factors in technology adoption, and European beekeeping is approaching a "social tipping point" of 25% usage, which could trigger broader digital transformation and contribute to a more resilient, productive, and sustainable future for the sector [2].

The image below illustrates 10 key guidelines for transferring knowledge from these projects into practical beekeeper education and VET programs, providing a clear roadmap for implementation.

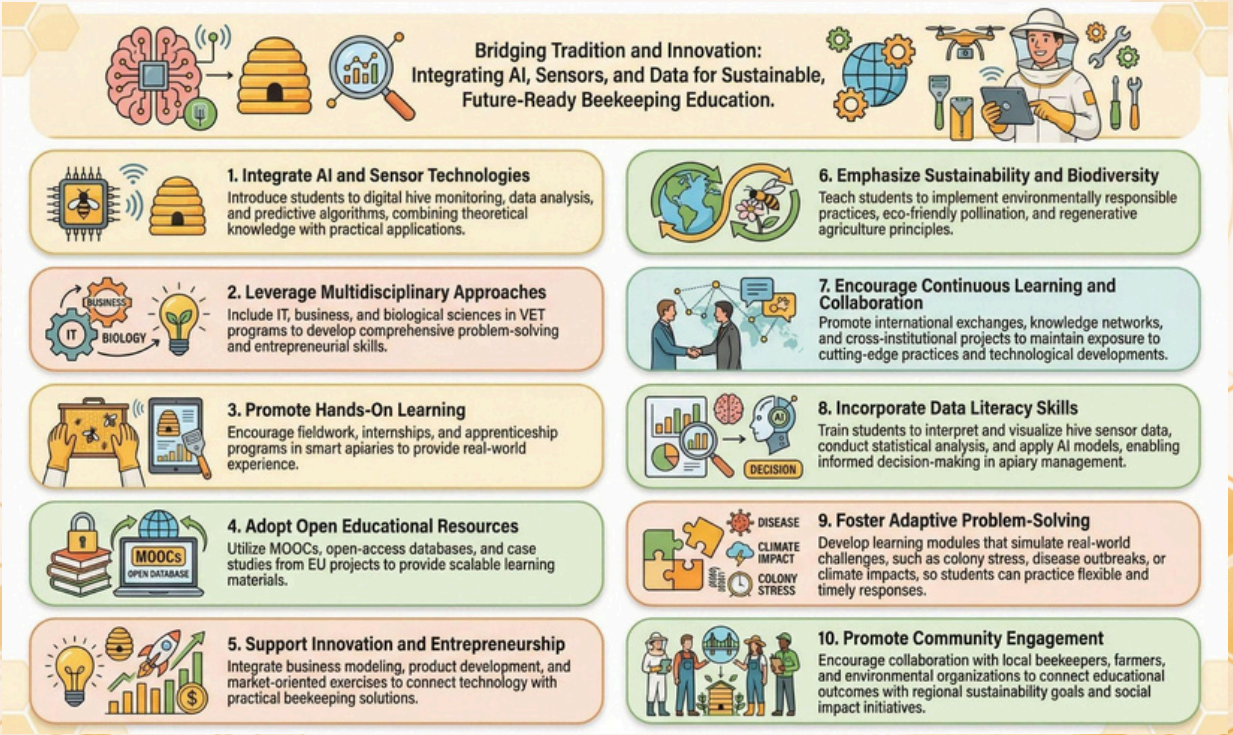


Figure: Strategic framework for future-ready beekeeping education, illustrating ten key pillars for integrating AI, sensor technologies, data literacy, sustainability, entrepreneurship, and community engagement into vocational training for smart and resilient beekeeping.

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5. Educational perspectives

5.1 Educational practices in Slovenia

5.1.1 Introduction: History and significance of beekeeping education in Slovenia

Beekeeping is one of the oldest and most recognized traditional activities in Slovenia, deeply intertwined with the country's cultural and natural heritage. Slovenia is home to the native Carniolan honeybee, a legally protected species valued for its productivity, calm temperament, and resilience. The foundations of modern beekeeping education were laid in the 18th century by Peter Pavel Glavar and Anton Janša, who established the first beekeeping schools and developed methods for rearing and managing bees that remain fundamental today. Janša, as the first official beekeeping teacher, systematically transferred knowledge and documented practices, creating a basis for both formal and non-formal education in beekeeping.

Today, beekeeping education in Slovenia encompasses both classical theoretical instruction and hands-on learning, focused on preserving Carniolan bee genetics and promoting sustainable hive management. Over 11,000 Slovenian beekeepers acquire skills through schools, associations, courses, and seminars, while top experts advance their competencies by obtaining the title of Beekeeping Master. Education not only transfers knowledge but also fosters responsibility, perseverance, respect for nature, and pedagogical skills for mentoring new generations of beekeepers.

5.1.2 Strategies, legislation, and regulations in beekeeping education

Beekeeping education is strongly regulated through national legislation and bylaws, such as Regulation 3244 on staffing and technical requirements for non-formal beekeeping education. The regulation specifies that educators must provide properly equipped premises, access to an apiary, offices, meeting rooms, and all necessary beekeeping tools, while ensuring the safety and health of participants. It also defines staffing standards: educators must be a program leader or a beekeeping instructor, with higher levels requiring a university degree, several years of experience, active knowledge of Slovenian and English, and pedagogical competence.

Intervention SI01 – Knowledge Transfer in Beekeeping within the framework of the Common Agricultural Policy 2023–2027 represents a key systemic mechanism for strengthening knowledge, expertise, and competitiveness in Slovenian beekeeping. It includes three sub-interventions: training in beekeeping techniques, education in bee health management, and the maintenance of teaching apiaries for knowledge transfer. The programs are designed as a combination of theoretical and practical work and are aimed at both beginners and experienced beekeepers. Special emphasis is placed on technological development, the recognition and management of varroa, the transfer of best practices, the enhancement of pedagogical competencies among instructors, and interinstitutional and international cooperation, including field trips and hosting of foreign experts. The programs also support the development of research activities, such as the characterization of bee products, testing technologies for efficient and sustainable hive management, and monitoring of bee health.

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These interventions aim to improve the professionalism of beekeepers, promote innovation, enhance product quality, and increase the competitiveness of the sector, while also contributing to biodiversity conservation and the sustainable development of beekeeping in Slovenia [55].

5.1.3 National professional qualifications: beekeeper and beekeeping master

Slovenia recognizes two key professional qualifications in beekeeping. **The National Professional Qualification (NPK) Beekeeper** equips individuals with comprehensive knowledge and skills for hive maintenance, bee colony management, and production of bee products such as honey, wax, pollen, propolis, royal jelly, and bee venom. Candidates acquire theoretical knowledge about bee biology, health management, breeding, feeding, disease control, and product hygiene, alongside practical skills in queen rearing, honey extraction, and product preparation. Beekeepers also learn planning, hive transportation, recordkeeping, and adherence to hygiene and ecological standards [56].

The Beekeeping Master (NPK Beekeeping Master) represents the highest professional level, requiring mastery of advanced technical, business, and pedagogical competencies. Masters oversee the planning, organization, and supervision of beekeeping operations, manage multiple bee colonies, produce complex bee products, and mentor apprentices or students. Achieving this title involves passing a rigorous master's examination, which includes practical work, written and oral theoretical tests, business and economic assessments, and pedagogical demonstration. This dual qualification system ensures that Slovenian beekeepers are skilled across all levels, from foundational colony management to advanced operational leadership and mentoring, promoting sustainability, professionalization, and knowledge transfer within the sector [57].

5.1.4 Innovative learning approaches and examples of good practice

Modern beekeeping education combines theoretical knowledge with hands-on learning and project-based approaches. Methods include practical apiary work, demonstrations of beekeeping techniques, project planning, mentoring, independent study, written and oral assessments, and digital learning. Digital learning supports monitoring hive conditions, online exam registration, access to literature, remote teaching via videoconferences, and administration, complementing practical and classroom instruction.

Examples of good practice include:

- **Beekeepers' Association of Slovenia** – organizes seminars, workshops, and national-level events, supports mentors, promotes good beekeeping practices, and facilitates knowledge transfer across generations.
- **Slovenian Beekeeping Academy** – provides non-formal education for foreigners, teachers, and the general public; coordinates practical training, digital learning tools, and international knowledge exchange [23].
- **Anton Janša Beekeeping School** – provides systematic training for all levels of beekeepers, licenses instructors, and emphasizes both theory and practical skills.

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- **Posavje Beekeeping Mosaic regional center** – connects local beekeeping associations, producers, and the public through interactive exhibits, workshops, and practical demonstrations [58].
- **Beginner courses for foreigners** – urban beekeeping programs in Ljubljana and other locations, combining theoretical knowledge with practical work at city apiaries [43].
- **School beekeeping activities** – engage children and teenagers in hands-on learning, competitions, summer camps, and practical beekeeping skills.
- **Beekeeping center Gorenjska** – connects the world of beekeeping with research, education, and community engagement; offers workshops, lectures, and interactive programs to raise awareness about the Carniolan honeybee and sustainable beekeeping practices.
- Beekeeping **center of the Biotechnical faculty, University of Ljubljana** – integrates research, teaching, and professional expertise; focuses on bee physiology, behavior, genetics, health, hive technology, and ecosystem management; participates in international research projects [59].
- **Veterinary Faculty, University of Ljubljana** – organizes specialized training and workshops on bee health, diseases, pests (like Varroa mite), and biosecurity; supports both novice and experienced beekeepers with evidence-based veterinary knowledge [60].
- **BEEXPERT project** – develops EU-level standardized training frameworks, promotes digital tools for beekeeping, and supports professionalization and knowledge transfer.
- **World Bee Day (May 20th)** – educational events, workshops, and media campaigns to raise awareness of the importance of bees and pollinators for ecosystems and food production.
- **Slovenian Breakfast** – national initiative promoting healthy, local, and bee-related products in schools, teaching children about bees, pollination, and the value of local food production.
- **SI01 intervention (Common Agricultural Policy 2023–2027)** – provides comprehensive training in bee health, hive management, and good beekeeping practices, targeting both beginners and experienced beekeepers.

Emphasis is placed on transferring knowledge from experienced beekeepers to new generations, training mentors, promoting safe and sustainable practices, and integrating beekeeping tourism and ecological awareness into learning processes.

5.1.5 Opportunities for smart technologies and AI in beekeeping education

In Slovenia, there have already been initial attempts to introduce artificial intelligence into beekeeping education, particularly through pilot projects and targeted workshops that demonstrate the use of digital and multisensroy monitoring systems. Training on sensor technologies and data analysis is often connected to national and European initiatives, which provide structured guidance on monitoring hive temperature, humidity, weight, and bee activity. In addition, the Slovenian Beekeepers' Association plays a key role in practical AI education, organizing targeted workshops on using AI tools, such as ChatGPT, for marketing, promoting, and selling high-quality honey, as well as supporting business decisions, report preparation, and presentations (AI orodij). These programs are designed without technical

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jargon and use real-life beekeeping examples, allowing participants to create their own prompts and personal AI assistants for independent work [61].

However, it is important to recognize that the average Slovenian beekeeper is close to 60 years old, and their experience with these digital tools is generally limited. At the same time, various initiatives are increasing the number of younger beekeepers, who are more inclined to adopt innovative technologies, including sensors and AI, in their practice, bridging the gap between traditional knowledge and modern digital approaches. To fully leverage these technologies, beekeepers must develop competencies in data literacy, digital communication, project management, and pedagogical methods. Learning approaches include a mix of practical work, simulations, mentorship, e-learning, and project-based tasks, allowing students to understand complex processes, enhance problem-solving skills, and prepare for modern challenges in beekeeping.

The integration of digital technologies and artificial intelligence into formal and non-formal beekeeping education enables optimization of operations and development of key competencies. Sensors and digital systems monitor temperature, humidity, hive weight, and bee activity, while AI analyzes this data to detect early signs of disease, assess colony health, and optimize production. Generative AI can assist in preparing educational content, interpreting data, planning queen rearing, or developing innovative products.

5.2 Educational practices in Greece

5.2.1 A tradition that is slowly changing

In Greece, beekeeping has never been just a technical occupation. It is something people grow up with. In many rural areas, children see hives from an early age, they watch their parents prepare frames, load trucks at night, move colonies to follow the blooms. Knowledge usually passed from one generation to the next, not through manuals, but through experience. You learn by doing, by making mistakes, by losing a colony and trying again the next season.

Greece has one of the highest densities of beehives in Europe, and honey production remains important both economically and culturally. Pine honey in the north, thyme honey on the islands, heather and wildflower varieties — these are not just products, they are part of local identity. But the environment around beekeeping has changed. Summers are hotter. Droughts last longer. Wildfires destroy forage areas that took decades to grow. Diseases remain persistent [62].

So education cannot remain exactly as it was. Experience is still central, but it is no longer enough on its own.

5.2.2 The institutional setting

Several public bodies shape beekeeping education in Greece. The Ministry of Rural Development and Food manages the National Apiculture Programme and supports training connected to disease control, modernization and sustainability. The Ministry of Education oversees vocational training structures.

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ELGO-DIMITRA plays a particularly visible role. It organizes seminars, short courses, and practical sessions for both new and experienced beekeepers. These trainings often focus on hive management, Varroa treatment, hygiene rules, product quality and compliance with EU regulations. Many participants attend because they want to improve, others because participation helps when applying for subsidies.

There is no mandatory professional license strictly linked to formal studies. Anyone can register and start beekeeping. That flexibility encourages entry into the sector, but it also means the level of formal qualification varies significantly. Some beekeepers are highly trained, others rely entirely on traditional knowledge.

National policies increasingly reflect European priorities such as sustainability and digital transition. In practice though, translating those priorities into structured curricula takes time. Change does not happen overnight.

5.2.3 Beekeeping within vocational education

In formal vocational education, beekeeping usually appears inside broader agricultural programmes. Students in plant production, organic farming or agricultural technology modules learn the basics: bee biology, hive structure, honey extraction, food safety standards.

Practical work depends very much on facilities. In some regions students can visit apiaries, observe inspections, even participate in extraction. In others, the experience remains mostly theoretical. This unevenness is one of the structural weaknesses of the system.

Digital tools are not yet systematically integrated. Some instructors introduce remote hive scales or monitoring examples on their own initiative, sometimes through European projects. But there is no consistent national module focused on smart hive management or data interpretation.

For many Greek beekeepers, continuing education matters more than initial schooling. Short seminars organized by ELGO-DIMITRA, universities or local associations provide updates on queen rearing, disease management, organic certification or market standards. These trainings are practical and appreciated. Still, they vary widely in depth and structure. There is no unified framework that defines learning outcomes across providers.

5.2.4 Universities and research: knowledge that does not always reach the field

Greek universities conduct important research in apiculture. Researchers study bee health, environmental pressures, acoustic monitoring and digital applications in agriculture. Through European projects, they test monitoring systems and field technologies under real conditions.

The knowledge exists. What is not always clear is how this knowledge reaches vocational learners and small-scale beekeepers. Scientific outputs remain in research circles unless someone translates them into accessible training material.

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Stronger collaboration between universities and vocational institutions would help. If students could work with real data from Greek apiaries, analyze seasonal patterns, or compare traditional observation with digital monitoring results, learning would become more concrete. At the moment, these connections happen occasionally, not systematically.

5.2.5 Teaching culture and everyday practice

Beekeeping education in Greece still relies heavily on direct observation and hands-on practice. An experienced beekeeper opening a hive, explaining what they see, pointing out subtle changes in brood patterns - this kind of learning cannot be replaced by slides. It requires proximity, patience and time.

At the same time, online seminars and hybrid workshops have become more common, especially in regions where distance makes regular attendance difficult. Island and mountainous communities benefit from this flexibility.

However, digital simulations, structured data analysis exercises or interactive dashboards are rarely part of regular training. When they appear, they usually come through pilot initiatives or temporary projects. There is room for improvement here. Not to replace tradition, but to complement it.

5.2.6 The gradual digital shift

Some professional beekeepers in Greece already use electronic hive scales, temperature sensors or mobile applications. These tools allow them to monitor colonies remotely and reduce unnecessary disturbance. They can see weight changes overnight, detect unusual temperature drops, react earlier than before.

Still, adoption remains uneven. Equipment costs matter. Connectivity in remote areas remains inconsistent. And many older beekeepers feel more comfortable relying on instinct rather than screens. This is understandable.

Education can support this transition. When trainers demonstrate clearly how monitoring tools connect to practical decisions - when to harvest, when to feed, when to inspect - skepticism decreases. Step by step, confidence grows. The key is to present technology as support, not as replacement of experience.

5.2.7 Challenges and possibilities

Beekeeping education in Greece faces several difficulties. Climate instability increases complexity. Training provision remains fragmented. The average age of beekeepers is relatively high. Access to structured programmes differs between regions. Yet there are strong opportunities. European funding encourages sustainable agriculture. Equipment prices gradually decrease. Younger entrants show more interest in entrepreneurship, specialty honey production and value-added products. They are often more open to combining traditional practice with new tools.

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The real challenge lies in balance. Greece should not abandon its strong experiential learning culture. That is one of its strengths. But it must also create clearer pathways for digital literacy and structured competence development.

If education manages to connect heritage with innovation - field observation with data awareness - Greek beekeeping can remain resilient. Not because it rejects change, but because it learns to shape it.

Educational practices in Greece stand somewhere between continuity and transformation. The foundations are solid: long experience, active associations, and committed practitioners. What remains is to integrate modern approaches in a more structured way, without losing what already works. With stronger links between vocational education, research institutions and sector needs, and with gradual introduction of monitoring tools and data-based learning, Greece can strengthen both the sustainability of its beekeeping sector and the professional confidence of future beekeepers.

6. Conclusions

In summary, the key findings of the BeeSensorVET e-book confirm that sustainable beekeeping in the 21st century depends on the balanced integration of traditional apicultural knowledge with digital and data-driven solutions. Case studies from Slovenia and Greece, together with European and international initiatives, show that sensor technologies, IoT connectivity, AI-based analytics, and smart monitoring systems are increasingly accessible and applicable in real beekeeping environments. However, the research also highlights persistent challenges: climate change pressures, biodiversity loss, small-scale production structures, limited digital literacy, and unequal access to training opportunities. The evidence clearly demonstrates that technology delivers meaningful impact only when embedded in structured education, supported by institutional frameworks, and adapted to local contexts and beekeepers' real needs.

The next steps for the BeeSensorVET project therefore focus on translating these insights into practical, high-quality VET resources and hybrid training models. This includes developing modular learning materials, strengthening digital and entrepreneurial competencies, piloting sensor-based learning scenarios, and fostering collaboration between VET providers, researchers, technology developers, and beekeeping associations. Particular attention will be given to accessibility and inclusion, ensuring that both experienced and novice beekeepers—especially those in rural and remote areas—can benefit from digital innovation. By promoting transnational cooperation and aligning with EU green and digital priorities, BeeSensorVET aims to create a scalable and transferable training framework that bridges the gap between research, technology, and everyday beekeeping practice.

Looking ahead, the vision of BeeSensorVET is to contribute to a resilient, sustainable, and data-driven beekeeping education ecosystem. In this vision, future beekeepers are not only skilled in traditional hive management but are also confident users of digital tools, capable of interpreting data, making evidence-based decisions, and responding proactively to environmental and market challenges. Sustainable apiculture education will combine precision monitoring, environmental responsibility, innovation, and entrepreneurial thinking

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within lifelong learning pathways. By empowering beekeepers with both knowledge and digital competence, BeeSensorVET supports the transition toward Apiculture 4.0—where technology enhances, rather than replaces, human expertise, and where sustainability, biodiversity protection, and economic viability are pursued in an integrated and responsible way.

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