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BEE - OPTIMA

INTERNATIONAL WORKSHOP ON ICT-ENABLED OPTIMIZATION
AND DIGITAL INNOVATION IN BEEKEEPING

January 12-13, 2026



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PRESS

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BEE-OPTIMA

International Workshop on

**ICT-enabled Optimization and
Digital Innovation in Beekeeping**

January 12-13, 2026

BEE-OPTIMA

International Workshop on ICT-enabled Optimization and Digital Innovation in Beekeeping

January 12-13, 2026

FMV Işık University INTALA LAB, Online, İstanbul

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Distinguished researchers, esteemed participants, sector representatives, and dear students,

On behalf of the Board of Trustees of FMV Işık University, I am delighted to welcome you to the proceedings of the **BEE-OPTIMA International Workshop on ICT-enabled Optimization and Digital Innovation in Beekeeping**, held on January 12–13, 2026, under the hosting of INTALA LAB at FMV Işık University.

The successful completion of this international workshop and the publication of the valuable studies presented throughout the event represent an important academic achievement for our university and all contributing stakeholders.

Today, beekeeping is no longer viewed solely as a traditional agricultural activity. It has become a multidisciplinary field where sustainability, food security, ecological resilience, and digital transformation intersect. As environmental challenges, climate change, and resource management issues continue to grow globally, the integration of advanced technologies into apiculture has become not only valuable but essential.

In this context, the BEE-OPTIMA Workshop has provided a remarkable international platform bringing together researchers, engineers, practitioners, and policymakers working on the future of smart and data-driven beekeeping systems. The workshop demonstrated how information and communication technologies, optimization methods, artificial intelligence, Internet of Things (IoT) infrastructures, GIS-based spatial intelligence, and data analytics can contribute to more sustainable, efficient, and resilient apiculture ecosystems.

The studies presented within this proceedings book clearly illustrate that digital innovation is transforming the future of beekeeping. From hive placement optimization and migratory route planning to sensor-based monitoring systems and intelligent decision-support models, the contributions gathered here reflect both scientific excellence and practical relevance.

As the Chairman of the Board of Trustees, I would like to emphasize that FMV Işık University strongly supports innovative, interdisciplinary, and socially impactful research initiatives such as BEE-OPTIMA. We firmly believe that the collaboration established between academia, technology developers, and sector stakeholders through this workshop will inspire future international partnerships and pioneering research efforts.

I would like to extend my sincere gratitude to **Dr. Şahin Aydın**, the entire **INTALA LAB** team, all national and international researchers, project partners, and participants who contributed to the success of this workshop.

I hope that the outcomes of BEE-OPTIMA will continue to guide future developments in sustainable and digitally empowered beekeeping worldwide, and that this proceedings book will serve as a valuable reference for researchers and practitioners alike.

With my highest regards,

Mehmet Serdar Sarıgül

Chairman of the Board of Trustees
FMV Işık University

I am delighted to write a foreword for the proceedings book of the BEE-OPTIMA Workshop, organized by Işık University INTALA LAB. Having closely followed the establishment and development of INTALA LAB, I believe that the Laboratory sets a highly valuable example by applying innovations in management information systems and information technologies to agricultural issues with a contemporary vision. This example is highly meaningful both in terms of the transformation of academia and in terms of contributing to a field of great importance for our country and humanity.

The application of scientific knowledge to current challenges in agriculture constitutes one of the most important academic fields of study today and for the future, particularly in relation to sustainability and food security. Considering climate change, the efficient use of natural resources, and environmental sustainability goals, the development of innovative solutions that will enhance the efficiency and sustainability of agricultural production has become more important than ever. At this point, research initiatives and collaborations that bring together different disciplines have also become an important part of universities' mission of social contribution.

In this regard, I sincerely congratulate the INTALA LAB team, all contributing researchers, and stakeholders who took part in the organization and realization of the workshop. I hope that this proceedings book, which brings together the papers presented within the scope of the workshop, will inspire new research in the relevant fields and make valuable contributions to the scientific literature.

Prof. Dr. Serhat Kolođlugil

Acting Rector
FMV Işık University

Dear Participants and Readers of the BEE-OPTIMA International Workshop Proceedings,

Our workshop “ICT-enabled Optimization and Digital Innovation in Beekeeping”, hosted by FMV Işık University, brought together researchers and practitioners on data-driven and digitally optimized beekeeping on January 12-13, 2026. Organized within the context of the BEE-OPTECH4Honey international project, the workshop and its proceedings represent an excellent example of the interdisciplinary and applied research that FMV Işık University and the Faculty of Economics, Administrative and Social Sciences proudly promote.

We are currently living in a world where we are becoming increasingly aware of the critical relationship and balance between nature and human beings, as well as the importance of ecological citizenship. The problems we face today force us to think and act in multidimensional and innovative ways. Critical issues such as climate change, biodiversity loss, and food security can only be tackled effectively in an interdisciplinary manner and through sustainable models.

The BEE-OPTIMA Workshop has been one such effort, hosting discussions on digitalization in apiculture, ecological analysis, optimization applications, and governance-based innovative approaches. The workshop served as a platform for sharing leading theoretical and policy-relevant research on utilizing digital technologies and optimization models to enhance both the environmental and economic performance of contemporary apiculture. This volume contains these debates and policy recommendations, constituting a valuable resource for experts and anyone interested in the topic.

I would like to express my sincere appreciation to our distinguished academic Dr. Şahin Aydın, whose efforts have been instrumental in the successful organization of this workshop. My sincere thanks also go to the INTALA LAB team at FMV Işık University, those researchers who contributed to the BEE-OPTECH4Honey project, and all the participants who enriched this collaboration.

Yours sincerely,

Prof. Özlem Kayhan Pusane

Dean, Faculty of Economics, Administrative and Social Sciences
FMV Işık University

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WORKSHOP PROGRAM

Monday, January 12, 2026		
Time	Speaker	Title
10:00 – 10:15	Dr. Şahin Aydın <i>Workshop Chair</i>	Opening Speech
10:15 – 10:30	Mehmet Serdar Sarıgül <i>Chairman of the Board of Trustees, Işık University</i>	Innovation, Research, and Global Collaboration at Işık University"
10:30 – 11:00	Şeref Cınbıroğlu <i>Director, Beekeeping Research Institute</i>	Activities of the Beekeeping Research Institute
11:00 – 11:30	Doç.Dr. Raşan İvgin Tunca <i>Muğla Sıtkı Koçman Üniversitesi</i>	Possible Effects of Global and Regional Temperature Changes on the Sustainability of Agriculture and Beekeeping in Türkiye
Lunch Break 11:30 - 12:30		
12:30 – 13:00	Dr. Ertuğrul Arda <i>Director, Aegean Agricultural Research Institute</i>	Research and Development Activities of the Aegean Agricultural Research Institute
13:00 – 13:30	Prof. Dr. Vedat Ceyhan	New Dynamics And Changing Priorities In Bee Product Industry
13:30 – 14:00	Prof. Dr. Ender Yarsan	Harmful Substances In Honey Bees, Contaminants and Pollutants In Bee Products
Coffee Break 14:00 - 14:30		
14:30 - 15:00	Filips Marks Amelkovichs	Status of the beekeeping in Latvia

15:00 - 15:30	Prof. Dr. Norberto Luis Garcia Dr. María Alejandra Palacio	Main Trends in the International Honey Market and Traceability as a Tool for Mitigating Fraud
Coffee Break 15:30 - 16:00		
Session 1 Session Chair: Dr. Sonya Javadi		
16:00 – 16:15	Hüseyin Deniz	Data-Driven Optimization of Migratory Beekeeping Decisions Through Floral Calendar and NDVI-Based Spatial Analysis
16:15 – 16:30	Busenur Türkali-Özbek, Demet Özgür-Ünlüakın, Sonya Javadi	Uncertainty in Beekeeping
16:30 – 16:45	Sonya Javadi, Demet Özgür Ünlüakın, Busenur Türkali-Özbek	Supply Chain Management in Beekeeping
16:45 – 17:00	Demet Özgür-Ünlüakın, Sonya Javadi, Busenur Türkali-Özbek	Multi-objective Optimization in Beekeeping
Tuesday, January 13, 2026		
Session 2 Session Chair: Dr. Aleksejs Zacepins		
10:00 – 10:15	Aleksejs Zacepins, Olvija Komasilova, Armands Kviesis, Janis Gailis	Exploring bee colony weight dynamics during passive wintering period
10:15 – 10:30	Daniels Kotovs, Aleksejs Zacepins	Identification of the Organic Beekeeping Sites by the Support of the GIS: case of Latvia

10:30 – 10:45	Wojciech Staszewski, Aleksejs Zacepins	Continuous In-Hive Monitoring Reveals Honeybee Thermoregulation and Behavioral Rhythms
10:45 – 11:00	Kirishanth Manivannan, Aleksejs Zacepins	IoT- based Autonomous Surveillance System for Real-Time Wasp Detection at Beehive Entrances
Coffee Break 11:00 - 11:15		
Session 3 Session Chair: Dr. Gülsüm Çiğdem Çavdaroğlu		
11:15 - 11:30	Gülsüm Çiğdem Çavdaroğlu	XAI-Powered Early Warning System for Honey Bee Colonies Based on Multimodal Sensor Data
11:30 - 11:45	Muhammet Emre Özkan	Bee-Forecasting: A Transfer Learning xAI Framework Integrating IoT Sensor Data with Local Flora Phenology for Geographically Indicated Şile Chestnut Honey
11:45 - 12:00	Gönül S.Tuzlu, Mehmet N. Aydın, Gökhan Akdeniz, Samet Okuyan	Digitizing Hazard Analysis in Honey Processing: From Conventional Thresholds to Synchronized Data Streams
12:00 - 12:15	Deniz Altıntaş	Multi-Criteria GIS Modelling for Beehive Site Selection
12:15 - 12:30	Göktürk Alperen Aytekin, Raşan İvgin Tunca, Uğur Bekçibaşı, Taylan Doğaroğlu, Nevin Güler Dincer	Sensor-Based Monitoring of Intrahive CO ₂ -Humidity-Temperature Profiles in the Muğla Ecotype Based on Brood and Total Frame Numbers in April, July, and October
12:30 - 12:45	Ekin Varol, Banu Yücel	Mobile Beekeeping Approach for Sensitive Beekeeping Technologies
Coffee Break 12:45 - 13:00		

Session 4 Session Chair: Dr. Selin Alihanoglu		
13:00 - 13:15	Gökhan Akdeniz	Honey Bee Genetic Resources of Türkiye: Conservation and Sustainable Use of Registered Races and Ecotypes
13:15 - 13:30	Engin Üçeş	Apitoxin: Biomedical Potential and Global Market Opportunities
13:30 - 13:45	Sebastian Ávila, Carina Requina, Emanuel Caluva, Virginia Avena, Geronimo Galvani	Advantages of using expanded polystyrene hives during over-wintering in <i>Apis mellifera</i> colonies installed in an oasis
13:45 - 14:00	Selin Alihanoglu, Esra Deniz Candan, Yasemin Karaagaç	Selective Antimicrobial Responses of Bee Pollen: Impact of Cell Wall Disruption
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Session 5 Session Chair: Dr. Şahin Aydın		
14:15 - 14:30	Matthew Calleja, David Mifsud	Preliminary results of physico-chemical and melissopalyno-logical analysis of wild thyme (<i>Thymbra capitata</i>) honey from Malta
14:30 - 14:45	Salim Aktürk, Gökhan Akdeniz, Habip Aydın, Güven Yılmaz, Süleyman Alparslan, Samet Okuyan, Özkan Ünal, Serhat Solmaz, Ahmet Emir Şahin, Saffet Sansar, Ahmet Kuvancı, Tunay Kılıçin, Alper Durgut	Increasing The Use of Bombus Bee (<i>Bombus Terrestris</i> L.) In Greenhouse Cultivation in DOKAP Provinces

14:45 - 15:00	Banu Yücel, Ekin Varol	Stress Factors In Honey Bee Colonies and Prevention Possibilities
15:00 - 15:15	Mutlu Bulut	Analysis of Honey Production and Honey Yield per Beehive in Türkiye Using an ARIMAX Model in the Context of Climate Change
Coffee Break 15:15 - 15:30		
Session 6 Session Chair: Dr. Gökhan Akdeniz		
15:30 - 15:45	Veli Öz	Using enzymatic analysis methods in separation of natural honey from imitated and augmented honey
15:45 - 16:00	Seyit Hasan Öztürk, Cevat Nisbet	Investigation of the Effect of Different Nutritional Groups on Bee Venom Production Capacity and Composition Under In Vitro Conditions
16:00 - 16:15	Burak Hangışı	Determination of Some Chemical Properties of Propolis Sam-ples Provided from Ordu Province
16:15 - 16:30	Fazıl Güney, Zekai Tarakçı	Optimization of Extraction and Encapsulation Parameters of Propolis and Its Application in Functional Food Systems

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Exploring bee colony weight dynamics during passive wintering period

Aleksejs Zacepins ^{1,*}, Olvija Komasilova ², Armands Kviēsis ¹ and Janis Gailis ²

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Highlights

What are the main findings?

- Bee colony weight during the passive wintering period shows a consistent gradual decline, primarily reflecting continuous consumption of stored honey reserves for thermoregulation and basic colony metabolism.
- Short-term weight fluctuations were detected and were associated with external temperature changes, suggesting that environmental conditions influence colony metabolic activity even during periods without foraging.

What is the implication of the main finding?

- Continuous colony weight monitoring can serve as a non-invasive indicator of winter colony status, enabling early detection of abnormal resource consumption or potential colony stress.
- Understanding winter weight dynamics can improve winter management strategies, allowing beekeepers and researchers to better estimate required food reserves and reduce overwintering losses.

Abstract

Honeybee (*Apis mellifera*) colonies are essential for maintaining ecological balance and enhancing agricultural productivity through their pollination services. Gaining insight into the internal conditions of a honeybee colony is crucial for evaluating its health, productivity, and seasonal dynamics. In the northern countries bee colony activity is divided into two periods: active summer and winter passive periods. This study focuses on a passive non-active period. Monitoring the weight of honey bee colonies provides valuable insight into their physiological status, food consumption, and survival potential during wintering. This study investigates the weight dynamics of bee colonies throughout the passive wintering period, aiming to better understand colony metabolism and resource utilization under low-activity conditions. Continuous weight measurements were recorded using electronic hive scales. The data were analyzed to assess temporal trends in colony mass loss and to identify environmental or management factors influencing these changes. Results showed a gradual decrease in hive weight corresponding to the consumption of stored honey, with the rate of loss varying in response to external temperature fluctuations and colony strength. These findings

contribute to improving winter management practices by providing quantitative parameters for assessing colony health and predicting overwintering success.

Keywords: Bee colony weight dynamics; Honeybee colony monitoring; Precision apiculture; Precision beekeeping; Passive wintering period.

Identification of the Organic Beekeeping Sites by the Support of the GIS: case of Latvia

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Highlights

What are the main findings?

- A GIS solution identifies organic and non-organic fields within a bee foraging radius.
- Spatial algorithms classify agricultural fields to determine plant species of potential interest to bees.

What is the implication of the main finding?

- Supports objective validation of apiary locations under EU organic regulations.
- Provides a practical tool for certification bodies, beekeepers, and consumers.

Abstract

Organic beekeeping is an environmentally responsible form of apiculture that prioritizes the health and sustainability of bee colonies. According to EU regulations, organic beehives must be located so that bees can forage primarily on organically cultivated crops, wild vegetation, or low-impact agricultural land within a 3-km radius. Ensuring compliance with these spatial requirements remains a challenge for certification bodies and beekeepers. This study proposes a spatial analysis-based GIS solution for identifying organic agricultural fields within the flight radius of bees and assessing their suitability for organic beekeeping. The analysis was conducted using Latvian agricultural field data for 2025, comprising 416,418 spatial units. A set of algorithms was developed to classify organic and non-organic fields based on a spatial attribute and to identify plant species of potential interest to bees. Spatial filters and analytical procedures were implemented to calculate the proportion of organic and non-organic fields relative to bee-attractive crops within defined foraging zones. The proposed method supports objective evaluation of apiary locations and can assist certification authorities in granting organic status. Additionally, it provides beekeepers and consumers with a practical tool for verifying compliance with organic beekeeping requirements and confirming the organic origin of bee products.

Funding: This research was funded by LBTU Doctoral Support and Development Initiative (ERAF project No. 1.1.1.8/1/24/I/002).

Keywords: Organic beekeeping; organic fields; Web-GIS; spatial processing; environmental analysis

Continuous In-Hive Monitoring Reveals Honeybee Thermoregulation and Behavioral Rhythms

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Highlights

What are the main findings?

- Continuous monitoring revealed stable brood-area temperature and reduced internal humidity variability despite strong external fluctuations.
- Hive weight showed repeatable diurnal cycles reflecting foraging activity and internal resource dynamics.

What is the implication of the main finding?

- Microclimate stability and weight dynamics provide operational indicators of colony functioning and early deviation detection.
- In-hive environmental sensing supports automated diagnostics and long-term monitoring in precision apiculture.

Abstract

This study investigates thermoregulation and activity rhythms in honeybee colonies (*Apis mellifera*) using continuous, non-invasive in-hive sensing under natural field conditions. Two managed colonies were monitored over a 30-day midsummer period using an Arduino–Raspberry Pi–based system recording brood-area temperature, internal and ambient air temperature and humidity, and total hive weight at 10-second resolution, aggregated to 1-minute intervals. Despite pronounced fluctuations in ambient conditions, brood-area temperature remained tightly regulated within a narrow range close to the optimal level for larval development, while internal humidity showed substantially reduced variability compared to external values. Hive weight time series exhibited repeatable diurnal cycles associated with foraging activity, nectar inflow, and internal resource processing, as well as step changes linked to management interventions. Monthly means and variability metrics for temperature, humidity, and hive weight provide quantitative reference ranges characterizing normal colony functioning. Rather than redefining established biological mechanisms, the study demonstrates how well-known colony processes can be expressed as stable, high-resolution time-series patterns suitable for automated detection and comparison. These operational indicators form a practical basis for early anomaly detection, long-term performance tracking, and decision-support tools in precision apiculture. The findings are based on a limited number of colonies and a single monitoring period but illustrate a scalable framework for data-driven colony assessment.

Keywords: Apiculture monitoring; Colony behavior; Hive weight dynamics; Honeybee thermoregulation; IoT sensing; Precision beekeeping.

IoT- based Autonomous Surveillance System for Real-Time Wasp Detection at Beehive Entrances

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Highlights

What are the main findings?

- Introduce a three-stage IoT-based system for real-time detection of wasps at beehive entrances.
- Employ background subtraction, lightweight classification and object detection in a unified pipeline to filter and confirm wasp events.

What is the implication of the main finding?

- Provide an affordable early-warning tool for wasp attacks on honeybee colonies.
- Facilitate adaptable precision beekeeping and allow future extension to other visual threats.

Abstract

Beekeeping in Latvia is increasingly affected by predators, climate variability and market pressures. Among these predators, wasps pose a significant threat to the bee colonies, leading to substantial losses in honey production if attacks go unnoticed. This research develops an IoT-integrated, three-stage autonomous surveillance system intended to detect wasps at the beehive entrance in real time and support timely protection of honeybee colonies. In the first stage, a background subtraction model, FBS-ABL, detects moving objects in downsampled hive-entrance video and produces cropped candidate regions. In the second stage, a lightweight classifier, MobileOne, categorizes each region as bee, wasp or background. Only regions classified as wasp are passed to the third stage, where an open-vocabulary detector, YOLO-World, operates on the full frame to localize and visually confirm wasp presence. A temporal decision rule then analyses a short sequence of subsequent frames and triggers an alert only when wasp classifications are consistently observed. This design reduces the number of expensive calls to the third stage and is intended for deployment on edge devices such as the Jetson Nano. The proposed system aims to provide an affordable and reliable early-warning tool that can be extended to additional visual threats, thereby supporting more resilient precision beekeeping practices.

Keywords: Precision beekeeping; wasp detection; autonomous threat detection; surveillance; small object detection; edge computing; affordable; IoT devices, object identification.

XAI-Powered Early Warning System for Honey Bee Colonies Based on Multimodal Sensor Data

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Highlights

This study demonstrates that multisensory hive data—combining temperature and humidity dynamics, acoustic stress indicators, and phenotypic colony measurements—can accurately predict honey bee colony weakening and overwinter loss when modeled using machine learning techniques. By integrating explainable artificial intelligence methods, particularly shapley additive explanations and counterfactual explanations, the proposed framework delivers transparent and actionable insights, enabling users to understand both why a colony is at risk and how this risk may be reduced. The results indicate that temperature variability, humidity instability, and indicators associated with Varroa pressure are among the most influential factors shaping overwinter loss predictions.

What are the main findings?

- A replicable and explainable framework that integrates multisensory hive data with machine learning to support precision apiculture.
- Identification of interpretable and biologically meaningful drivers associated with colony weakening and overwinter loss.
- Quantitative assessment of how targeted changes in key environmental and colony-related variables affect predicted survival outcomes.

What is the implication of the main finding?

- Beekeepers can access interpretable early-warning signals, allowing timely interventions before irreversible colony losses occur.
- Stabilization of thermal and humidity conditions, together with proactive Varroa management, emerges as critical levers for reducing winter loss risk.
- The framework is suitable for integration into real-world hive monitoring systems, providing transparent and trustworthy decision-support tools for sustainable, data-driven beekeeping.

Abstract

Winter losses in honeybee colonies pose a critical problem for the sustainability of beekeeping activities and ecosystem services. This study aims to predict the risk of winter loss in colonies using multi-sensor data collected during the active season and to interpret these predictions using explainable artificial intelligence methods. In this context, a multimodal feature set consisting of environmental, acoustic, and phenotypic indicators was created using the Multisensor Bee Phenotypic Dataset. An XGBoost-based supervised classification model was developed for winter loss prediction, and the model's ROC-AUC value was obtained as 0.94. Global and local explainability analyses were performed using the SHAP method to ensure the interpretability of the model outputs. Global analyses showed that environmental variables played a dominant role in the model's decision-making mechanism, while acoustic and phenotypic indicators provided complementary contributions. Local explainability analyses revealed that predictions in individual

colonies were formed by the combined effect of multiple variables. Furthermore, the quantitative impact of hypothetical improvements in specific variables on winter loss risk was evaluated through counterfactual analyses. The findings demonstrate that explainable and intervention-oriented AI approaches offer strong potential for developing early warning and decision support systems in precision beekeeping applications.

Keywords: colony health; explainable artificial intelligence; precision apiculture; machine learning for bee health

1. Introduction

Winter losses observed in honeybee colonies have become an increasing concern recently in terms of ecosystem sustainability and agricultural production. Increased colony losses result from the combined effect of numerous factors, including climatic fluctuations, disease and parasite pressure, environmental stressors, and management practices. This multi-dimensional structure makes it difficult to explain the phenomenon of winter loss with a single variable and necessitates holistic assessment approaches. Today, advanced sensor technologies allow for continuous and high-resolution monitoring of hive and environmental conditions. Time-series data such as temperature, humidity, and acoustic signals provide valuable information about the physiological state and behavioral responses of the colony. However, the high-dimensional and complex nature of such multi-sensor data makes it difficult to analyze effectively with traditional statistical methods. Machine learning-based approaches offer the potential to capture complex patterns by evaluating different data sources together. However, machine learning models used in application-oriented fields such as beekeeping do not focus solely on achieving high predictive accuracy. The inability to understand how models, often referred to as *black boxes*, make their decisions makes it difficult to adopt them in the field and use them as reliable decision-support tools. Especially in areas directly related to biological and environmental processes, such as colony management, it is critical that predictions are explainable and interpretable.

Explainable Artificial Intelligence (XAI) approaches address this need by aiming to quantitatively and visually reveal the reasons behind model outputs. Methods like Shapley Additive Explanations (SHAP) can illustrate the overall behavior of the model on a global scale and which variables drive individual predictions at the local level. Counterfactual analyses answer the question, "Which conditions, if changed, would also change the prediction result?" enabling models to play not only an explanatory but also a decision-supporting role.

Honey bees play a critical role not only in honey production but also in global food security and ecosystem sustainability. Potts et al. highlighted the multifaceted impacts of global decline in pollinator populations on agricultural production, biodiversity, and human well-being, emphasizing that monitoring and protecting bee health is a strategic priority. In this context, data-driven approaches that can predict colony losses at an early stage, provide explanations, and enable intervention are of great importance in developing sustainable beekeeping practices [1]. According to this, the proposed study aims to present an explainable machine learning framework that predicts the risk of winter loss in bee colonies using environmental, acoustic, and phenotypic data collected during the active season. The main objective of this study is to generate interpretable and applicable information for beekeeping practices by revealing the determining factors behind predictions at global, local, and counterfactual levels. In this respect, the study

proposes a transparent and reliable decision support approach based on the integration of multi-sensor data with XAI approaches.

2. Literature Review

Recent studies have emphasized the growing role of Internet of Things (IoT) technologies and Artificial Intelligence (AI) in precision beekeeping. A comprehensive survey by Jeong et al. systematically reviews IoT- and AI-based systems for enhancing honey bee colony strength, categorizing existing approaches according to sensor types, data modalities, and analytical methods [2, 3]. The study highlights the widespread use of environmental, acoustic, and biological data sources for colony monitoring and demonstrates the increasing adoption of machine learning techniques in apiculture.

However, the survey also points out that most existing approaches primarily focus on monitoring or short-term health assessment, often relying on black-box models with limited interpretability. For instance, an integrated system combining visual and acoustic data with deep learning models has been proposed to classify short-term colony health conditions [4]. While such approaches demonstrate the potential of multisensory monitoring, they primarily rely on black-box models and focus on immediate classification tasks. In contrast, long-term overwinter loss prediction and explainable decision-support mechanisms remain largely unexplored, motivating the approach adopted in this study.

In another study [5], the authors developed a deep learning-based forecasting and early warning system for honey bee colony population loss using temporal convolutional networks. By leveraging image-based bee traffic monitoring and environmental sensor data, the study successfully predicted daily colony loss rates and identified abnormal patterns using an isolation forest algorithm. While this approach provides valuable short-term forecasts and operational alerts, it focuses primarily on time-series prediction and does not explicitly address explainability or management-oriented intervention analysis. In contrast, the present study emphasizes explainable machine learning and counterfactual reasoning to not only predict overwinter loss risk but also to interpret the underlying drivers and evaluate potential mitigation strategies at the colony level.

Beyond population-level forecasting, other studies have focused on individual- and phenotype-level assessments. For example, Singh et al. proposed an IoT-based framework combining environmental sensing with convolutional neural networks to classify bee phenotypes and subspecies, as well as to assess hive health using image data. While such approaches provide valuable real-time monitoring capabilities and support individual-level health assessment, they primarily focus on short-term classification tasks rather than long-term colony-level outcomes [6].

Complementary to data-driven approaches, simulation-based studies have provided mechanistic insights into early warning indicators of colony loss. These studies have highlighted the critical role of brood-related indicators as early warning signals of honey bee colony decline. For instance, in a study, the authors used the BEEHAVE mechanistic model to demonstrate that brood metrics, such as capped brood cells and the brood-bee ratio, respond earlier to both environmental and biotic stressors than traditional indicators like adult bee abundance or honey reserves. Their results provide strong theoretical evidence that colony-level brood dynamics are among the most sensitive indicators of impending colony loss [7]. However, while such simulation-based approaches offer valuable mechanistic insights, they do not directly address how these indicators can be operationalized using real-world, multisensory hive data, nor how their effects can be explained at the level of individual colonies. The present study builds upon this conceptual foundation by integrating environmental, acoustic, and phenotypic

measurements with explainable machine learning, enabling both predictive accuracy and transparent, colony-specific interpretation.

A principled and physics-based framework for monitoring honey bee hive health through temperature series analysis was developed in another study [8]. The proposed approach models hive thermoregulation behavior using thermal diffusion and control theory, enabling accurate forecasting, segmentation, and proactive anomaly detection with a small number of interpretable parameters. Unlike black-box deep learning methods, this approach emphasizes explainability and parsimony. However, the method focuses primarily on temperature dynamics and does not directly address colony-level survival or overwinter loss outcomes. In contrast, the present study adopts a data-driven, multi-modal learning framework that integrates environmental, acoustic, and phenotypic indicators to directly predict overwinter colony loss, complementing physics-based approaches with explainable machine learning and counterfactual reasoning.

A significant milestone in the field of model explainability is the SHAP framework proposed by Lundberg and Lee [9]. This approach makes it possible to quantitatively express the contribution of each variable to the model output in a consistent and comparable way using Shapley values based on cooperative game theory. SHAP is widely used in machine learning-based decision support systems because it offers a common explanatory language for different model types and provides interpretability at both global and local scales. In this respect, SHAP increases the transparency of black-box models, allowing model outputs to become understandable to humans. For example, a study analyzing the key determinants of colony loss using machine learning with data from 179 colonies collected from three apiaries in the Extremadura region of Spain during 2020–2021, predicted mortality using a Random Forest model [10]. Variable contributions were first evaluated using permutation importance, and then the interpretability of individual predictions was ensured with Shapley/SHAP-based explanations. Importantly, unlike the present study, the analysis relied primarily on inspection-based biological and pathological measurements, rather than continuous environmental and acoustic sensor data collected during the active season. According to the model explanations, open/operculated brood, Varroa density, honey and pollen reserves, adult bee number, and DWV and Nosema load emerged as the main factors explaining colony loss. While this approach emphasizes the importance of intra-colony biological and pathogenic indicators, the presented study aims to address the same problem through environmental and acoustic sensor indicators obtained during the active season, generating actionable implications for field interventions through XAI and counterfactual scenarios. In decision support systems, it is not enough to simply explain why a prediction was generated; it is also critical to provide actionable information on how that prediction can be modified. Counterfactual explanations, as defined by Wachter et al., aim to reveal how minimal changes in the input space affect the output without interfering with the internal structure of the model [11]. This approach, particularly in application-oriented fields, increases the practical value of XAI by directly answering the question, "*What would have changed to produce a different result?*"

Taking together, existing review and empirical studies clearly demonstrate the growing role of AI and multi-sensor data in apiculture [2, 3]. However, despite these advances, the literature consistently reveals three critical gaps: (i) limited explainability at the colony level, (ii) insufficient integration of heterogeneous sensor modalities for long-term outcomes, and (iii) a lack of actionable intervention-oriented analyses. In this context, the present study directly addresses these gaps by integrating SHAP-based global and local explainability with counterfactual reasoning, enabling transparent, interpretable, and decision-oriented overwinter loss risk assessment at the individual colony level.

3. Methodology

This study develops a multimodal and explainable machine learning framework that combines environmental, acoustic, and phenotypic data to predict overwinter losses in honeybee colonies. The process begins with preprocessing and feature engineering multi-sensor data collected during the active season, transforming them into colony-specific integrated data vectors. The developed Extreme Gradient Boosting (XGBoost)-based prediction model classifies colony strength and survival status with high accuracy, while the XAI layer, which includes SHAP and counterfactual analyses, makes the decision-making mechanisms of the models transparent at both global and local scales. This holistic approach enables beekeepers to receive risk warnings, take action to reduce losses, and develop interpretable strategic insights. Figure 1 shows the proposed and implemented methodological framework in the study, along with its stages.

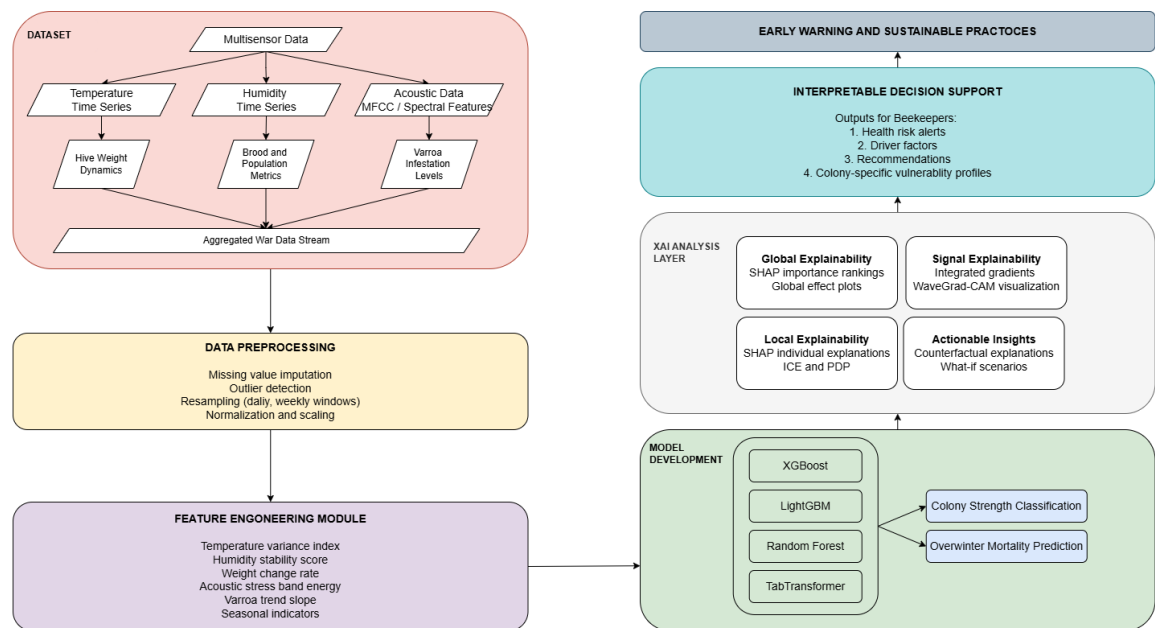


Figure 1. A framework for a honey bee colony health monitoring and early warning system based on multimodal sensor data and XAI.

3.1. Data Acquisition and Preprocessing

This study utilized the Multisensor Bee Phenotypic Dataset (MSPB) [12]. MSPB dataset has a multi-source structure containing environmental, acoustic, and phenotypic characteristics of honeybee colonies during the active season and winter period. Environmental attributes are statistical attributes derived from temperature and humidity measurements representing intra-hive and environmental conditions. These attributes represent the level and temporal variability of thermal and humid conditions to which the colony is exposed. The acoustic component consists of frequency band and intensity-based indicators obtained from intra-hive sound recordings. These indicators provide signals sensitive to intra-colony behavioral activity, stress, and disorder. Phenotypic attributes include biological and structural indicators related to colony health. These indicators represent the biological status and resilience of the colony. Table 1 summarizes the three main components in the dataset.

Table 1. The MSPB dataset overview.

Component Type	Includes
Environmental Component	Mean, standard deviation, minimum, maximum.
Acoustic Component	Energy measurements for specific frequency bands (Hz), audio density, audio density ratio, density variation.
Phenotypic Component	Measurements associated with Varroa infestation include indicators relating to brood area and colony strength, as well as information on colony density and structure.

The dataset was created using sensor-based measurements and colony-based observations under real field conditions. Each observation corresponds to a specific colony, allowing for colony-level analysis. The dataset is divided into two main temporal periods:

- D1 Period (Active Season): Covering the spring-summer months, the period when the colony is active.
- D2 Period (Winter and Post-Winter): The period includes winter and post-winter measurements.

To prevent data leakage, only features from D1 period were included in the modeling process. Measurements from the D2 period were used only in the derivation of the target variable. Prior to modeling, feature-level data fusion was applied to the dataset. In this process:

- Raw sensor data were summarized at the time series level and converted into statistical features at the colony level.
- Environmental, acoustic, and phenotypic features were combined based on hive ID.
- A single observation row was created for each colony, resulting in a suitable tabular data structure for modeling.

As a result of this transformation, the dataset containing numerous raw measurements was reduced to a multidimensional but integrated feature vector representing each colony. The target variable (y_{loss}) used in the study is a binary class label representing the colony's state at the end of winter. This label is derived based on colony strength (number of frames covered with bees) measured in April 2021:

- Zero or missing frames \rightarrow colony loss ($y_{loss} = 1$)
- Positive frame count \rightarrow colony alive ($y_{loss} = 0$)

This approach provides a practical and direct definition of colony loss based on field data. Before modeling, the dataset underwent the following preprocessing steps:

- Descriptive fields and the target variable were removed from the model inputs.
- All features belonging to the winter period were excluded to prevent data leakage.
- Missing and infinite values were filled with the median value for numerical features. This approach offers a more robust preprocessing strategy against outliers.

The final dataset was stratified with a 75% training – 25% testing ratio to maintain class balance. The dataset obtained because of these processes has acquired a consistent structure that both represents high-dimensional multi-sensor information and is suitable for explainable machine learning analyses.

3.2. Modeling

This study employs a supervised learning approach to predict overwinter loss in bee colonies. A binary class label (y_{loss}) representing the end-winter colony status was used

as the target variable. This label was derived based on colony strength (number of frames covered with bees) measured in April 2021. Zero or missing values were defined as colony loss, while positive values were defined as survival. Only environmental, acoustic, and phenotypic indicators from the D1 period were used in the modeling phase. This prevented data leakage from post-winter measurements. In this context, the target variable (y_{loss}), descriptive identification fields, and D2 measurements from the winter period were removed from the feature set.

Missing or infinite values were filled with the median value for numerical features, thus employing a more robust preprocessing strategy against outliers. The dataset was divided using stratified sampling with a 75% training – 25% test ratio to maintain class balance. XGBoost algorithm was chosen as the estimation model. XGBoost is a powerful ensemble method based on decision trees and was deemed particularly suitable for this study for the following reasons:

- It can efficiently process heterogeneous feature sets (environmental, acoustic, and biological variables).
- It offers high performance in capturing nonlinear relationships.
- It can provide stable results even with relatively small sample sizes.
- It works in natural agreement with modern explainability methods such as SHAP.

With these features, XGBoost is a powerful option that offers high accuracy and XAI options together.

The model was structured with the following parameters to limit overfitting and increase generalizability:

- $n_estimators = 400$: More balanced learning was achieved by increasing the number of trees.
- $max_depth = 4$: Model complexity was controlled by limiting the tree depth.
- $learning_rate = 0.05$: Stable optimization is aimed for by enabling learning in smaller steps.
- $subsample = 0.8$ and $colsample_bytree = 0.8$: Variance is reduced by applying random sampling to each tree.
- $objective = "binary:logistic"$: Logistic loss function is used for the binary classification problem.
- $eval_metric = "auc"$: Model performance is evaluated with the ROC-AUC metric, which is insensitive to class imbalance.

The trained model is evaluated on the test data using ROC-AUC, a confusion matrix, and a classification report. The ROC-AUC metric is preferred to measure the model's discriminative power, especially in imbalanced and risk-driven problems such as colony loss. At this stage, the aim is to build a basic model that produces meaningful and explainable predictions, rather than achieving the highest accuracy. The ROC-AUC value was measured as 0.9411764705882353. Table 2 presents the classification report of the developed model.

Table 2. Classification report of the developed model.

	Precision	Recall	F1-Score	Support
0	0.85	1.00	0.92	11
1	1.00	0.88	0.94	17
Accuracy			0.93	28
Macro Avg	0.92	0.94	0.93	28
Weighted Avg	0.94	0.93	0.93	28

3.3. XAI

Systems like beekeeping, which intertwine ecological, biological, and environmental processes, limit the use of black-box models. Beekeepers often need to understand why and how decision support systems generate predictions. Therefore, XAI approach has been adopted to make the decision processes of the developed model transparent. XAI reveals the variable contributions behind the model outputs, making it possible to statistically, biologically, and managerially interpret the predictions. XAI methods were considered in this study with three main objectives:

1. to determine which variables and data modalities the model gives more weight to at the global level,
2. to reveal the dominant factors behind the predictions made for individual colonies, and
3. to examine the impact of possible intervention scenarios on the prediction results.

3.3.1. Global Explainability

In this context, the SHAP method was used to ensure the explainability of the decision tree-based XGBoost model. SHAP, thanks to its structure based on cooperative game theory, can quantitatively express the contribution of each feature to the model output at both global and local scales. The following section presents global XAI analyses that reveal the model's global behavior, followed by local explanations based on individual colonies (local XAI), and finally counterfactual analyses that evaluate potential management interventions. Figure 2 presents the global explainability results of the XGBoost model using SHAP, where panel (a) shows the global feature importance based on mean absolute SHAP values, and panel (b) illustrates the distribution of SHAP values across observations, highlighting both the magnitude and direction of each feature's contribution to overwinter loss predictions.

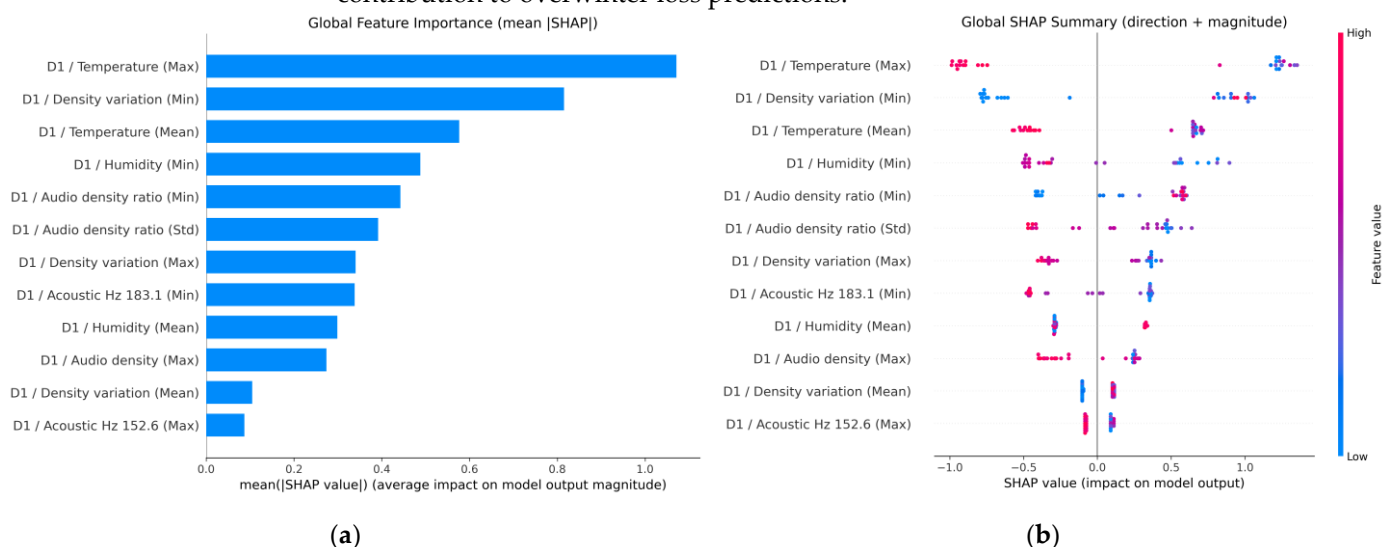


Figure 2. Global SHAP explainability results for the XGBoost model: (a) variable importance ranking based on mean absolute SHAP values and (b) SHAP scatter plot (beeswarm) showing the effect of variable values on the direction and magnitude of the prediction.

3.3.2. Modality-Based Contribution Analysis

As a complement to the global SHAP analysis, the variables contributing to the model's decision-making process were evaluated at the data modalities level at this stage. For this purpose, features were examined by considering them in three main groups: environmental variables (temperature and humidity statistics), acoustic indicators

(frequency bands and acoustic intensity measures), and phenotypic indicators (measurements related to *Varroa* infestation, brood area, and colony strength).

The relative contribution of each modality to the model was summarized by calculating the average absolute SHAP values of the relevant features. This approach aims to reveal which types of data sources the model's overall decision-making behavior relies on more, regardless of the importance of individual variables. Table 3 presents the mean absolute SHAP values aggregated at the modality level, summarizing the relative contributions of environmental, acoustic, and phenotypic feature groups to the model's overwinter loss predictions.

Table 3. Average absolute contribution values at the SHAP-based modality level.

Modality Group	Mean Value
Environmental	0.30668774
Acoustic	0.028905448
Phenotypic	0.015063766

Explainability makes visible the information on "which variables are important" from the model's perspective. This analysis at the modality level allows understanding of which type of information is dominant in the prediction process. In this respect, the analysis highlights the importance of the holistic use of multi-sensor data in beekeeping practices and provides a contextual basis for the local XAI and counterfactual analyses presented in the following sections.

3.3.3. Local Explainability

Local explainability analysis was performed to reveal the variable contributions behind the model's prediction for a single colony. A representative colony in the test set, predicted in the winter loss class ($y_{loss} = 1$), was selected, and the prediction for this colony was examined using SHAP-based local explanation methods. For the selected colony, the contribution of each variable in the process from the model's base value to the final prediction value ($f(x)$) was visually shown; furthermore, the numerical equivalent of this information was presented through a table containing the variables with the highest impact. Thus, the explanation at the local level was documented both visually and numerically. Figure 3 presents the local SHAP waterfall explanation for a representative colony predicted as overwinter loss, illustrating how individual feature contributions cumulatively shift the model output from the base value to the final prediction. Table 4 presents the 10 most significant features with the highest absolute SHAP values for the selected colony, reporting the magnitude and direction of each feature's contribution to the model's local prediction.

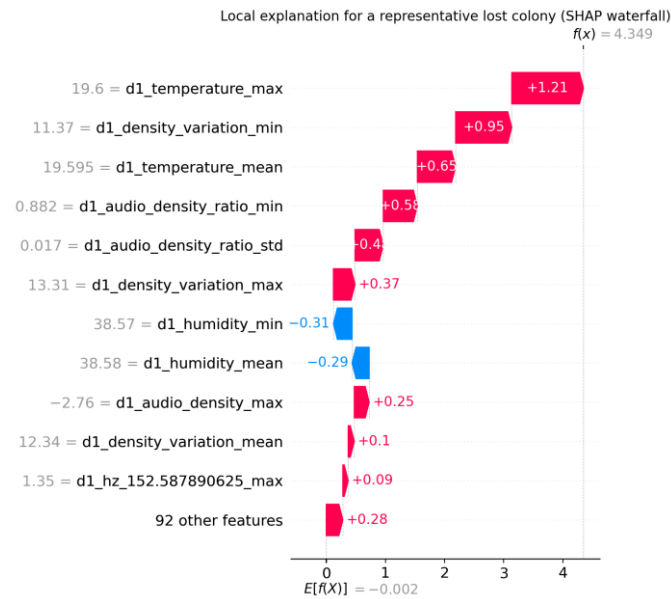


Figure 3. The local SHAP waterfall explanation for a representative colony predicted as overwinter loss.

Table 4. The 10 most significant features with the highest absolute SHAP values for the selected colony.

Feature	Shap_Value	Abs_Shap
d1_temperature_max	1.213562	1.213562
d1_density_variation_min	0.948866	0.948866
d1_temperature_mean	0.647700	0.647700
d1_audio_density_ratio_min	0.576596	0.576596
d1_audio_density_ratio_std	0.477879	0.477879
d1_density_variation_max	0.365468	0.365468
d1_humidity_min	-0.314928	0.314928
d1_humidity_mean	-0.290238	0.290238
d1_audio_density_max	0.252221	0.252221
d1_density_variation_mean	0.102952	0.102952

3.3.4. Counterfactual Analysis

A counterfactual analysis was applied to examine how the winter loss prediction generated by the model for a selected colony changes when hypothetical improvements are made to specific input variables. The analysis begins with the initial winter loss probability calculated for the relevant colony. Then, predefined intervention scenarios were created for specific variables considered biologically and environmentally significant. In these scenarios, the values of the selected variables were adjusted to distribution-based reference levels, corresponding to the lower (5th percentile) or upper (95th percentile) quantiles of the training data, depending on the direction suggested by local SHAP contributions. In each scenario, only the value of a single variable was changed, while all other features were kept constant. Thus, the effect of each variable on the prediction was isolated. For each counterfactual scenario, the updated input vector was fed into the model, and the resulting new winter loss probability was calculated. This process allows for the evaluation of the effect of changes in the input space on the prediction output without interfering with the learned parameters of the model. Table 5 presents the predicted overwinter loss probabilities obtained under single-feature and combined counterfactual intervention scenarios for a representative colony, reporting the resulting probability change and the number of decision tree leaf transitions associated

with each scenario. This table numerically documents how hypothetical interventions at the individual colony level affect the model output.

Table 5. Estimated winter loss probabilities under single and combined counterfactual scenarios.

Scenario	Feature	Old Value	New Value	Loss Probability	Delta	Leaf Changes
Set to q5 (decrease)	d1_density_variation_min	11.370000	2.011000	0.944246	-0.043000	35
Set to q5 (decrease)	d1_audio_density_ratio_min	0.882000	0.044600	0.970302	-0.016943	22
Set to q5 (decrease)	d1_density_variation_mean	12.340000	7.184016	0.984733	-0.002512	9
Set to q5 (decrease)	d1_audio_density_ratio_mean	0.894000	0.692874	0.985000	-0.002245	7
Set to q95 (increase)	d1_humidity_min	38.570000	66.540000	0.986638	-0.000608	1
Combined top 3 interventions	d1_density_variation_min, d1_audio_density_ratio_min, d1_density_variation_mean	-	-	0.842937	-0.144308	66

4. Results

4.1. Modeling Results

A supervised learning model developed to predict winter loss in bee colonies demonstrated high discrimination performance on the test data. By using only environmental, acoustic, and phenotypic indicators from the D1 period, representing the active season, in the modeling process, data leakage that could arise from post-winter measurements were prevented. This approach enabled the model to produce realistic and generalizable predictions. The ROC-AUC value of 0.94 obtained on the test set shows that the model has a high power to distinguish between colonies experiencing and not experiencing winter loss.

The classification performance of the developed model is presented in detail in Table 2. The overall classification accuracy was calculated as 93%. For the winter loss class ($y_{loss} = 1$), the model achieved a precision of 1.00 and a recall of 0.88. This indicates that all colonies predicted as lost were correctly classified, but a small portion of the actual losses were missed by the model. In contrast, the sensitivity value for surviving colonies ($y_{loss} = 0$) was measured as 1.00, indicating that all surviving colonies in the test set were correctly classified.

The macro-averaged F1-score of 0.93 shows that the model exhibits balanced performance for both classes and that the results are not driven by a dominant class. These findings demonstrate that the developed XGBoost model provides a reliable basis for XAI analyses and allows for the investigation of factors affecting winter loss at global, local, and counterfactual levels.

4.2. Global XAI Results

The model's global decision-making behavior was examined using the SHAP method. According to the global ranking of importance calculated based on the average absolute SHAP values of the variables given in Figure 2 (a), the temperature and density variables for the D1 period stand out as the features with the highest impact on the model output. In particular, the maximum temperature (D1 / Temperature (Max)) and density variation measures (D1 / Density variation (Min) and D1 / Density variation (Max)) are

among the variables that play a dominant role in the model's winter loss predictions. These are followed by average temperature and minimum humidity values.

Based on the beeswarm graph given in Figure 2 (b), it can be said that high and low variable values can affect the model output in different directions, and this effect varies among observations. Acoustic indicators, especially specific frequency bands and acoustic density measures, follow environmental variables in the global ranking of importance and make significant contributions to the model output.

Overall, the global SHAP results demonstrate that the model's decision-making mechanism does not rely on a single set of variables; environmental conditions, acoustic signals, and intensity-related indicators together shape the model output. These global explanations provide a contextual framework for the local explainability, and counterfactual analyses presented in the following sections.

4.3. Modality-Based Contribution Results

As a complement to the global SHAP analysis, data modalities were considered under three main groups. To quantitatively express the relative contribution of each modality to the model output, the average absolute SHAP values for the relevant variables were calculated and combined at the modality level. This approach aims to reveal which types of data sources the model relies on more in its overall decision-making behavior, regardless of the importance of individual variables.

Table 3 summarizes the average absolute SHAP values for the environmental, acoustic, and phenotypic variable groups and the relative contributions of these modalities to winter loss predictions. The results show that environmental variables provide the highest average contribution to the model output, followed by acoustic indicators and phenotypic variables. This modality-based explainability analysis makes visible which types of information are more dominant in the model's decision-making mechanism. Thus, the role of using multiple sensors and multiple data sources in predicting winter loss has been quantitatively revealed at the variable group level. These findings provide a contextual basis for the local XAI, and counterfactual analyses presented in the following chapters.

4.4. Local Explainability Results

Local explainability analysis revealed which variables drove the model's winter loss prediction for a single colony. The SHAP analysis performed on a representative colony in the test set, predicted by the model in the winter loss class ($y_{loss} = 1$), shows how the model output shifted from the baseline to the final prediction value. The SHAP waterfall diagram presented in Figure 3 reveals the variables that increased and decreased the model prediction for the selected colony, both in terms of direction and magnitude. Accordingly, maximum temperature ($d1_temperature_max$), minimum density variation ($d1_density_variation_min$), and average temperature ($d1_temperature_mean$) stand out as the variables that most strongly push the prediction towards winter loss. Each of these variables contributed to an increase in the probability of loss by shifting the model output upwards with positive SHAP values. Acoustic indicators also played a significant role in the local prediction. Specifically, the minimum acoustic density ratio ($d1_audio_density_ratio_min$) and the standard deviation of the acoustic density ratio ($d1_audio_density_ratio_std$) were among the variables that influenced the estimated winter loss. In contrast, the minimum humidity ($d1_humidity_min$) and average humidity ($d1_humidity_mean$) variables had a partially balancing effect on the estimate with negative SHAP values. Table 4 numerically summarizes the top 10 variables with the highest absolute impact on the local estimate for the selected colony. This table shows that temperature statistics, density variables, and acoustic indicators play a dominant role at

the local level. The variable with the highest absolute SHAP value, `d1_temperature_max`, was identified as the most decisive factor in the model decision for this colony. These local explainability results show that the model's decisions at the individual colony level exhibit a multidimensional structure and that environmental and acoustic indicators have a combined effect. Thus, the model's winter loss estimates are based not on a single variable, but on the combined effect of different complementary data sources.

4.5. Counterfactual Analysis Results

At the start of the counterfactual analysis, the initial winter loss probability calculated by the model for the colony in question indicates a high-risk level. Using this initial value as a reference, intervention scenarios were created for variables determined to be biologically and environmentally significant.

In the univariate counterfactual scenarios, the values of the selected variables were adjusted to reference levels based on the distribution of the training data. In line with the direction indicated by the local SHAP results, some variables were moved to the lower 5% percentile (q_5), and others to the upper 95% percentile (q_{95}). All other variables were kept constant, and the effect of only a single input was isolated in each scenario.

The results presented in Table 5 show that the effect of single-variable interventions on the winter loss probability differed among the variables. Reducing the minimum density variation (`d1_density_variation_min`) to the lower 5% level resulted in the most significant reduction in the winter loss probability, decreasing the probability value from 0.987 to 0.944. This scenario also corresponds to a significant change in the model decision structure, with 35 leaf transitions occurring on the decision trees. Similarly, reducing the minimum acoustic density ratio (`d1_audio_density_ratio_min`) also reduced the probability of winter loss, but the magnitude of this effect remained more limited. In other univariate scenarios, interventions, especially those targeting the average density variation and the average acoustic density ratio, showed a relatively lower impact on the prediction probability. In the scenario targeting increasing the minimum humidity (`d1_humidity_min`), the change in the probability of winter loss was quite limited. In addition to individual interventions, the combined counterfactual scenario, which considered the three most effective variables together, produced the strongest change in the model output. When the variables `d1_density_variation_min`, `d1_audio_density_ratio_min`, and `d1_density_variation_mean` were improved simultaneously, the probability of winter loss decreased to 0.843, resulting in a total reduction of -0.144 . This scenario also represents the case where the largest structural change in the model's decision space occurs with 66 leaf transitions. These counterfactual results reveal that interventions with single variables produce limited but measurable effects, whereas multiple and simultaneous improvements can alter the model prediction. Thus, the model allows for the quantitative assessment of the impact of potential management interventions at the colony level on the prediction output.

Figure 4 presents the change in the predicted overwinter loss probability under different counterfactual intervention scenarios applied to a representative colony. The horizontal bars indicate the magnitude of probability reduction ($-\Delta$) resulting from each scenario, including single-feature adjustments and a combined top 3 intervention. Larger bars correspond to greater reductions in predicted loss risk, allowing a direct comparison of the relative impact of individual and combined hypothetical improvements.

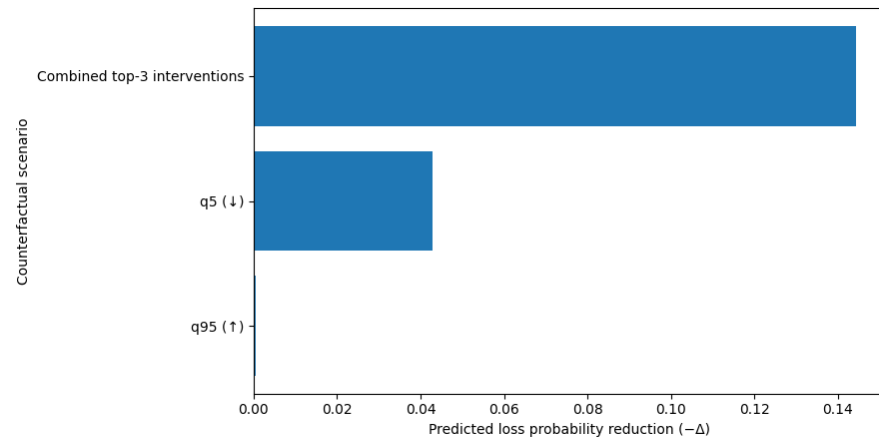


Figure 4. Counterfactual impact of single-variable and combined intervention scenarios on the predicted overwinter loss probability for a representative colony.

5. Discussion

This study demonstrates that an explainable machine learning model, developed using environmental, acoustic, and phenotypic data collected during the active season, can predict the risk of winter loss in bee colonies with high accuracy and reveal the reasons behind these predictions at a multi-scale level. The findings emphasize that winter loss cannot be explained by a single factor and that intra-colony and environmental dynamics must be considered together.

The modeling results show that even using only active season data, the risk of winter loss can be strongly predicted. This supports the importance of early warning and preventive interventions in the pre-winter period. In particular, the model's ability to identify lost colonies with high accuracy while distinguishing healthy colonies almost without error provides a strong foundation for risk-oriented decision support systems in practical beekeeping applications.

Global explainability analyses have shown that environmental variables play a decisive role in the model's decision-making mechanism. The dominance of temperature statistics and density variables suggests that colony health is strongly dependent not only on biotic factors but also on environmental stress conditions. This finding is consistent with studies in the literature highlighting the significant impact of temperature fluctuations and environmental imbalances on colony behavior and survival. However, the fact that acoustic indicators also make significant contributions at the global level supports the idea that intra-hive sound signals can be an important indirect indicator reflecting colony status.

Modality-based analyses quantitatively revealed that the model relies on multiple data sources in its decision-making process. Despite the dominance of environmental variables, acoustic and phenotypic information does not play a purely secondary role; rather, it offers a complementary structure along with environmental signals. This suggests that monitoring approaches based on a single sensor or a single data source may be limited, while holistic and multi-sensor-based systems can provide more reliable predictions. Local explainability results reveal that the model's decisions at the individual colony level are similarly multidimensional.

In counterfactual analyses, the limited effects of hypothetical improvements to individual variables suggest that winter loss cannot generally be explained by a single problem. However, the observation of a significant reduction in risk in the model output when multiple critical variables are improved simultaneously highlights the potential importance of holistic management strategies. This result provides strong quantitative

evidence that multidimensional improvement approaches may be more effective than individual interventions in beekeeping practices.

6. Conclusion

This study, which demonstrates that the risk of winter loss in bee colonies can be successfully predicted using XAI approaches with environmental, acoustic, and phenotypic data collected during the active season, shows that the developed XGBoost-based model exhibited high discrimination performance with only pre-winter information and that the phenomenon of winter loss can be predicted at an early stage. This finding offers significant potential for timely planning pre-winter interventions. One of the most important contributions of the study is that the model outputs are supported by multilayer explainability analyses in addition to accuracy metrics. Global SHAP analyses quantitatively showed that environmental conditions play a dominant role in the model's decision mechanism; modality-based evaluations showed that environmental, acoustic, and phenotypic data are used together and complementarily. Local explainability results revealed that model decisions at the individual colony level exhibit a multidimensional structure and that inter-colony heterogeneity should be considered. Counterfactual analyses show that the XAI approach can be used as a decision-supporting tool. While hypothetical improvements to individual variables produce limited effects, it has been quantitatively demonstrated that a significant reduction in the risk of winter loss can be achieved by simultaneously improving multiple critical variables.

Overall, this study indicates that explainable AI-based multi-sensor data integration offers a viable, reliable, and transparent decision support framework in the field of beekeeping. The presented approach goes beyond black-box prediction models, demonstrating that a system providing both predictive and actionable information to beekeepers and decision-makers is possible. In this respect, the study provides a strong foundation for future research aimed at supporting sustainable beekeeping practices and reducing colony losses.

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Advantages of using expanded polystyrene hives during overwintering in *Apis mellifera* colonies installed in an oasis

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Highlights

Superior Thermoregulation: EPS hives (EPS_h) maintained a significantly higher average internal temperature compared to traditional wood hives (Wh) throughout the overwintering period. EPS_h colonies exhibited substantially less weight loss compared to Wh colonies and finished winter with a greater capped brood area. The enhanced insulation provided by EPS material reduces thermal stress, allowing colonies to conserve energy, minimize honey consumption, and maintain a larger population/brood area vital for rapid spring build-up. Utilizing EPS_h in semi-arid regions with high thermal amplitude offers a practical solution to reduce overwintering losses and promote stronger colony status, significantly improving beekeeping efficiency and productivity in these challenging environments.

Abstract

In semi-arid regions with climate of high thermal amplitude, expanded polystyrene hives (EPS_h) has a superior insulation coefficient compared to wood hives (Wh), providing an advantage with great potential in beekeeping. We propose to evaluate performance of EPS_h compared to Wh and its relationship with indicators of the colony's status during overwinter. In a commercial apiary located in an oasis in Mendoza Province (Argentina), 10 colonies of *Apis mellifera ligustica* hybrids were used, 5 of equal population spent the winter in in standard Wh and 5 in EPS_h of 6 frames. From April to September, the internal temperature of the hives was recorded. Additionally, the variation in weight hives and the occupied area of capped brood were evaluated. The average daily hive temperature in EPS $27.5 \pm 0,3$ °C and cM 25.8 ± 0.3 °C. The weight loss was lower in EPS_h (1.9 ± 0.3 kg) compared with cM (6.4 ± 0.6 Kg). The capped brood area at the start of the post-winter period was higher in EPS_h ($4,215 \text{ cm}^2 \pm 1,547$) compared to Wh ($3,086 \pm 1075 \text{ cm}^2$). The results suggest that colonies inhabiting EPS boxes have lower thermal stress and therefore go through winter in better conditions.

Keywords: Semi-arid ambient; hive temperature; thermal stress

Supply Chain Management in Beekeeping

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Abstract

Apiculture plays an important role in agricultural sustainability by supporting honey production and pollination services. Supply chain management in apiculture involves the coordinated planning and control of production, processing, distribution, and marketing activities, as well as the management of material, information, and financial flows among beekeepers, cooperatives, beekeeping institutes, distributors, and retailers. In practice, the sector is characterized by fragmented production structures, limited information sharing, and weak integration among supply chain actors, particularly in migratory beekeeping systems where seasonal movements and capacity constraints add further complexity. These coordination failures lead to higher logistics costs, quality variability, market instability, and reduced responsiveness to demand fluctuations.

This study investigates miscoordination in the apiculture supply chain and reviews common solutions aimed at improving integration and value creation. Key coordination mechanisms include strengthening cooperative structures, adopting digital information-sharing platforms, implementing contractual partnerships, and promoting standardization and certification schemes. In addition, policy support and institutional coordination are highlighted as critical enablers of supply chain integration. The findings emphasize that improving coordination among stakeholders can significantly enhance operational efficiency, transparency, and the economic, environmental, and social sustainability of the apiculture value supply chain.

Keywords: Apiculture; Supply Chain Management; Coordination

Multi-objective Optimization in Beekeeping

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Abstract

Beekeeping systems involve multiple stakeholders having different conflicting objectives such as productivity, cost, environmental sustainability, and equity. Single-objective models are often insufficient to address these trade-offs and to explain decision problems specific to beekeeping. Multi-objective optimization addresses decision problems where multiple, and often conflicting objectives are considered simultaneously. Instead of producing a single “best” solution, these approaches aim to identify a set of efficient trade-off solutions offering a balance among objectives. Multi-objective optimization methods are widely used in diverse domains such as supply chain management, energy systems, environmental planning and healthcare to evaluate economic efficiency and operational performance along with social and environmental concerns. Various solution approaches have been developed in literature, including weighted sum, ϵ -constraint methods, goal programming, and evolutionary algorithms each offering different advantages in terms of interpretability, flexibility, and computational performance. This study focuses on multi-objective optimization in the context of migratory beekeeping and hive placement problems. The key stakeholders in beekeeping, their objectives and alternative solution approaches are discussed within the multi-objective modeling framework. Finally, it demonstrates how trade-offs between stakeholder objectives can be analyzed through Pareto-based solutions and points out the contributions of multi-objective optimization as a decision support tool in beekeeping practices.

Keywords: migratory beekeeping; multi-objective optimization; trade-off analysis

Data-Driven Optimization of Migratory Beekeeping Decisions Through Floral Calendar and NDVI-Based Spatial Analysis

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Highlights

- Combines NDVI indicators and floral calendar data for spatial-temporal suitability assessment.
- Ranks regions and periods to support migratory beekeeping decisions.
- Provides a decision support framework that may be applicable to different agricultural contexts.

What are the main findings?

- Integration of satellite-derived NDVI data with comprehensive floral calendar information (463 plant species across 20 provinces) enables spatial-temporal suitability assessment for migratory beekeeping routes using 60-40 weighted scoring (NDVI-flowering).
- Development of an interactive decision support system combining spatial analysis, route optimization algorithms, and visualization tools demonstrates potential cost reduction (26% in one Spring Late scenario) through improved route efficiency.

What is the implication of the main finding?

- The framework provides beekeepers with quantitative spatial-temporal information for migration timing and location selection, though field validation would be necessary to assess actual impacts on production efficiency.
- The methodology demonstrates potential scalability for regional beekeeping associations and may be adapted to other agricultural migration scenarios requiring spatial-temporal optimization.

Abstract

Migratory beekeeping contributes substantially to both apicultural economics and pollination services. Although an individual worker honeybee carries only a small amount of pollen, this seemingly minor contribution significantly enhances genetic diversity, floral reproduction, and the quality of agricultural products. Moreover, pollination supports the continuity of the food chain and forms the foundation of a balanced ecosystem that preserves biological diversity. These cumulative biological effects, which operate at the ecosystem scale and are difficult to quantify directly, represent one of the key factors that make migratory beekeeping essential. In addition to its ecological importance, migratory beekeeping provides supplementary income and employment opportunities for rural communities, facilitating the exchange of knowledge and experience among beekeepers. In this way, it fosters a cooperative social structure that strengthens the interaction between agriculture and nature. Our study introduces a digital optimization framework that combines a calendar of flowering periods at the provincial and district levels with NDVI (Normalized Difference Vegetation Index) analysis to transform decision-making in migratory beekeeping into a systematic, data-driven process. Flowering periods were divided into six temporal windows (Winter, Spring Early, Spring Late, Summer, Autumn, Late Autumn) for temporal analysis, and

NDVI values were derived from Sentinel-2 satellite imagery to characterize vegetation condition across regions. Province-level suitability was then calculated by combining flowering intensity scores with normalized NDVI values using weighted criteria (60% NDVI, 40% flowering). This integration enabled the systematic ranking of locations and periods according to their potential for migratory beekeeping operations.

Keywords: migratory beekeeping; NDVI; remote sensing; floral calendar; spatial optimization; route planning; decision support system; Sentinel-2; Google Earth Engine; precision agriculture

1. Introduction

Migratory beekeeping involves the seasonal translocation of colonies to exploit spatially and temporally distributed floral resources. This practice enhances honey production and supports crop pollination [1,2]. In Turkey, approximately eight million colonies are moved annually, producing over 100,000 tons of honey [3]. Despite widespread adoption of migratory practices, route selection and timing decisions remain challenging. Beekeepers must consider multiple factors, including floral resource availability, vegetation health, local environmental conditions, and the economic feasibility of long-distance transport. Nectar availability varies considerably across space and time, complicating route planning decisions. Flowering patterns differ among plant species and are influenced by climate, altitude, and weather conditions [4,5]. Most beekeepers continue to rely on personal experience and informal knowledge exchange when deciding where and when to migrate. While this approach functions adequately in familiar areas, it can result in missed opportunities or unnecessary costs when environmental conditions shift unexpectedly.

Despite the economic importance of migratory beekeeping in Turkey, route selection remains predominantly experience-based rather than data-driven. Advances in satellite remote sensing and spatial analysis offer opportunities to formalize migration planning through quantitative assessment of vegetation condition and phenology. The primary motivation for this study arises from the gap between available technological capabilities and current field practices. Integrating vegetation condition and flowering phenology enables a more accurate assessment of production potential. In this context, the main objective of this study is to transform migratory beekeeping into a data-driven decision support process that enhances efficiency and optimizes resource use. Satellite remote sensing tools provide methods to address these challenges [6,7]. The Normalized Difference Vegetation Index (NDVI) is widely used to quantify vegetation health and biomass, which correlate with nectar production potential [8]. Sentinel-2 satellites provide high-resolution imagery at sufficient temporal frequency to track vegetation dynamics across diverse landscapes [9]. Floral calendars, which document flowering periods for plant species across regions, facilitate the identification of potential nectar sources [10,11].

However, most studies analyze satellite vegetation data and floral calendars independently [12,13]. They also rarely incorporate practical considerations such as migration routes, travel distances, and costs, despite the importance of these factors for beekeepers using decision-support tools.

This study addresses a gap in the literature by integrating satellite-based vegetation indicators with floral calendar data within a unified decision-support framework for migratory beekeeping. Unlike previous studies that consider NDVI and phenological information separately, the proposed approach evaluates these two ecological dimensions jointly to represent nectar availability more realistically. In addition, practical constraints

such as migration routes, travel distances, and transportation costs are explicitly incorporated into the analysis. Consequently, the study moves beyond descriptive assessment and presents an application-oriented decision support system. The proposed suitability scoring and route optimization framework enables more informed, cost-efficient, and spatially optimized migration decisions. This study presents a decision-support system to assist migratory beekeepers in identifying optimal relocation sites. The system integrates NDVI data from Sentinel-2 satellites with detailed floral calendars to represent both vegetation health and blooming periods. The system uses Google Earth Engine to process satellite data from 20 provinces in Turkey and includes flowering records for 463 plant species across 221 districts. It also offers route planning and cost analysis to support transportation decisions. The system is available as interactive maps and a web dashboard, facilitating practical application.

The main objectives of this study are to:

- Integrate satellite-derived vegetation indicators with floral calendar data within a unified framework
- Develop a suitability scoring mechanism to rank potential migration sites
- Incorporate route optimization techniques to minimize transportation costs
- Provide accessible and user-oriented visualization tools for beekeepers
- Assess the spatial-temporal patterns of suitability across Turkish beekeeping regions

2. Materials and Methods

2.1. Study Area and Time Periods

This study focused on 20 provinces in Turkey recognized for their significance in beekeeping: Adana, Adıyaman, Afyon, Ağrı, Aksaray, Amasya, Ankara, Antalya, Artvin, Aydın, Balıkesir, Bingöl, Burdur, Çanakkale, Çorum, Erzurum, Hatay, Isparta, Mersin, and Muğla. These provinces were selected to represent the climatic gradient from coastal Mediterranean zones to continental and mountainous regions, collectively encompassing the majority of Turkey's beekeeping zones. The selected 20 provinces represent regions where migratory beekeeping is intensively practiced and where honey production is of strategic importance in Turkey. The selection criteria aimed to capture diverse climatic conditions, including Mediterranean, continental, and mountainous regions, as well as variations in elevation and vegetation structure. This approach allowed the inclusion of both extended flowering periods in coastal areas and shorter but intensive nectar flows in inland and high-altitude regions. In addition, the selected provinces represent a substantial proportion of Turkey's active hive population and migration movements. This selection strategy enables testing the proposed framework under different ecological conditions and supports the generation of results that may be generalizable at the national scale.

The year 2024 was divided into six time periods corresponding to major flowering seasons:

- Winter (Jan 1 - Feb 29)
- Spring Early (Mar 1 - Apr 15)
- Spring Late (Apr 16 - May 31)
- Summer (Jun 1 - Jul 31)

- Autumn (Aug 1 - Sep 30)
- Late Autumn (Oct 1 - Nov 30)

These periods correspond to the typical blooming times of various plant species at different elevations.

2.2. NDVI Data Acquisition and Processing

2.2.1. Satellite Data Source

NDVI data were extracted from Sentinel-2 Level-2A surface reflectance products accessed through Google Earth Engine (GEE) [14]. Sentinel-2 provides multispectral imagery at 10-meter spatial resolution with a 5-day revisit frequency, offering optimal spatial and temporal characteristics for vegetation monitoring at regional scales. Level-2A products include atmospheric correction, ensuring consistency across acquisition dates and geographic locations.

2.2.2. NDVI Calculation Process

For each province and time period, satellite images were processed in Google Earth Engine as follows:

1. Filtering images: Sentinel-2 images were selected based on appropriate dates and locations, retaining only those with less than 20% cloud cover.
2. Removing clouds: The quality band (QA60) was used to mask clouds and shadows, minimizing their impact on the results.
3. Calculating NDVI: NDVI was calculated using the near-infrared and red-light bands as follows:

$$NDVI = (NIR - Red) / (NIR + Red)$$

- Higher NDVI values indicate healthier and denser green vegetation.
- Combining images: For each time period, the median value from all cloud-free images was used to obtain a representative NDVI value.
- Statistical analysis: For each province, the average NDVI, standard deviation, and number of pixels analyzed were calculated.

One of the main challenges encountered during satellite data processing was cloud cover, particularly during winter and early spring periods. To mitigate this issue, only Sentinel-2 images with less than 20% cloud cover were included in the analysis. Cloud and shadow effects were further reduced using quality band-based masking procedures. In cases where the number of cloud-free images was limited, a median compositing approach was applied to preserve temporal representativeness. These steps improved the consistency and spatial comparability of the NDVI calculations.

2.2.3. Data Quality Control

NDVI values were validated through the following quality control procedures:

- Removal of pixels with $NDVI < -0.2$ or > 1.0 (physically unrealistic values)
- Verification of pixel counts to ensure adequate spatial coverage (>100,000 pixels per province)
- Cross-validation with MODIS NDVI products for consistency assessment
- Visual inspection of temporal profiles to identify anomalies

The final dataset comprised 114 province-period combinations with mean NDVI ranging from -0.010 to 0.697 (overall mean: 0.386, SD: 0.149).

2.3. Floral Calendar Data Collection and Processing

2.3.1. Data Source

Floral calendar data were compiled from the Twenty Provinces Flowering dataset, a comprehensive database documenting flowering periods for melliferous plant species across Turkish provinces [15]. The dataset includes information on plant species, geographic location (province and district), flowering start and end dates, and associated metadata.

2.3.2. Data Cleaning and Validation

R oral calendar data underwent systematic cleaning and validation:

1. **Date Parsing:** Flowering dates were standardized to ISO 8601 format, with manual correction of inconsistent date formats.
2. **Temporal Validation:** Records were checked for logical consistency ($\text{start_date} \leq \text{end_date}$), with 13 problematic records flagged for review.
3. **Geographic Standardization:** Province and district names were standardized to uppercase and matched against official administrative boundaries.
4. **Duplicate Removal:** Duplicate entries (same province-district-species-date combinations) were identified and removed.
5. **Missing Data Handling:** Records with missing critical fields (province, plant type, or dates) were excluded from analysis (92 records removed).

The cleaned dataset contained 1,106 valid flowering records representing 463 unique plant species across 20 provinces and 221 districts.

2.3.3. Temporal Period Mapping

Flowering records were mapped to six predefined temporal periods based on their flowering start and end months. Each record was assigned to the corresponding seasonal period, and records overlapping multiple periods were included in all relevant periods. This approach ensured that extended flowering durations were accurately represented, enabling more realistic capture of temporal variations in nectar availability.

2.4. Data Integration and Suitability Scoring

2.4.1. Flowering Intensity Calculation

For each province-period combination, flowering intensity was quantified based on the number and diversity of flowering plant species:

$$\text{Flowering Intensity} = (\text{Plant_Count} / \text{Max_Plant_Count}) \times \text{Coverage_Factor}$$

where:

Plant_Count: Number of unique plant species flowering in the province-period

Max_Plant_Count: Maximum plant count observed across all combinations (normalization factor)

Coverage_Factor: Proportion of districts within the province with recorded flowering activity (0–1 range). This metric captures both species richness and the spatial extent of flowering, providing a concise indicator of nectar availability.

2.4.2. Combining NDVI and Flowering Data

We combined NDVI and flowering intensity into a single suitability score:

$$\text{Suitability Score} = (0.60 \times \text{NDVI}) + (0.40 \times \text{Flowering Intensity})$$

NDVI was assigned a weight of 60% and flowering intensity a weight of 40%.

The 60–40 weighting scheme applied to NDVI, and flowering intensity was selected to balance continuous remote sensing information with species-based phenological data. NDVI was assigned a higher weight due to its spatial coverage and temporal consistency. Flowering intensity, while directly representing nectar potential, was weighted lower because of its more limited data coverage. Alternative weighting combinations were tested, and the overall spatial patterns remained stable across scenarios.

Both values are normalized to the 0–1 scale before combining, so the final score is also between 0 and 1, with higher scores indicating locations with greater potential for beekeeping. The 60–40 weighting scheme should be considered a methodological assumption rather than a strictly empirically validated parameter. While this configuration reflects a balance between spatially continuous vegetation indicators and species-level phenological data, the relative importance of these components may vary depending on ecological conditions and specific beekeeping objectives.

2.4.3. Data Integration Workflow

The integration process was implemented in Python using the following workflow:

- Load NDVI data (CSV format) and floral calendar data (Excel format)
- Standardize province names and temporal periods
- Calculate flowering intensity for each province-period
- Normalize NDVI values to 0-1 range
- Compute weighted suitability scores
- Generate integrated dataset with all metrics
- Export results for analysis and visualization

The final integrated dataset contains 114 records with the following fields: province, period_label, mean_ndvi, std_ndvi, pixel_count, plant_count, flowering_intensity, flowering_coverage, and suitability_score.

2.5. Spatial Analysis and Visualization

2.5.1. Interactive Mapping

Interactive maps were generated using the Folium library to visualize the spatial distribution of suitability scores. Province-level markers were created using centroid coordinates and color-coded according to suitability levels. Basic interactive elements were included to allow temporal filtering and on-demand display of key indicators. All maps were exported as standalone HTML files for web-based visualization and sharing.

2.5.2. Statistical Visualizations

Statistical visualizations were produced using Matplotlib and Seaborn to summarize suitability scores and their spatial–temporal patterns. The figures include distribution plots, period-based comparisons of NDVI and flowering intensity, province–period heatmaps, and scatter plots illustrating the relationship between vegetation vigor and flowering activity. In addition, ranked bar charts were used to highlight the highest-scoring locations. All figures were generated at 300 DPI resolution to ensure publication-quality output.

2.6. Route Optimization

2.6.1. Distance Matrix Calculation

Inter-province distances were calculated using the Haversine formula applied to province centroids:

$$d = 2r \times \arcsin \left(\sqrt{\sin^2 \left(\frac{lat^2 - lat^1}{2} \right) + \cos(lat^1) \times \cos(lat^2) \times \sin^2 \left(\frac{lon^2 - lon^1}{2} \right)} \right) \quad r = 6,371 \text{ km (Earth's radius).}$$

The resulting distance matrix (20×20) provides the basis for route optimization.

2.6.2. Cost Modeling

- Transportation costs were estimated using the following parameters:
- Fuel consumption: 0.35 L/km (typical for beekeeping transport trucks)
- Fuel price: 35 TL/L (2024 average diesel price in Turkey)
- Driver cost: 500 TL/hour (including wages and overhead)
- Average speed: 60 km/h (accounting for road conditions and stops)
- Total cost for route segment (i → j):

$$Cost_{ij} = (Distance_{ij} \times 0.35 \times 35) + (Distance_{ij} / 60 \times 500)$$

2.6.3. Traveling Salesman Problem (TSP) Optimization

Optimal migration routes were determined by formulating the problem as a Traveling Salesman Problem to minimize total travel cost while visiting high-suitability locations within a given season.

1. Graph Construction: Create weighted directed graph with provinces as nodes and costs as edge weights
2. Heuristic Solution: Apply greedy nearest-neighbor algorithm for initial solution
3. Local Optimization: Improve solution using 2-opt swaps
4. Constraint Handling: Ensure routes respect temporal sequencing (visit provinces in order of seasonal suitability)

The algorithm outputs optimal visitation order, total distance, total cost, and estimated travel time.

2.7. Decision Support Dashboard

To facilitate practical use of the proposed framework, an interactive decision-support dashboard was developed to provide access to integrated suitability analyses and route optimization results. The dashboard enables users to explore spatial and temporal patterns of migratory beekeeping suitability through an intuitive web-based interface, without requiring specialized expertise in geographic information systems or data analysis. The dashboard allows users to filter results by province, seasonal period, and suitability thresholds, while dynamically visualizing key indicators such as NDVI, flowering intensity, and overall suitability scores. Interactive maps and graphical summaries support exploratory analysis and comparison across regions and seasons. In addition, the dashboard incorporates route planning functionality, enabling users to specify starting locations and generate cost-optimized migration routes based on suitability rankings. Results can be exported in common data formats to support offline analysis and reporting. By integrating visualization, filtering, and optimization capabilities within a single interface, the dashboard bridges the gap between analytical outputs and real-world decision making, potentially enhancing the accessibility and applicability of the study framework for migratory beekeepers.

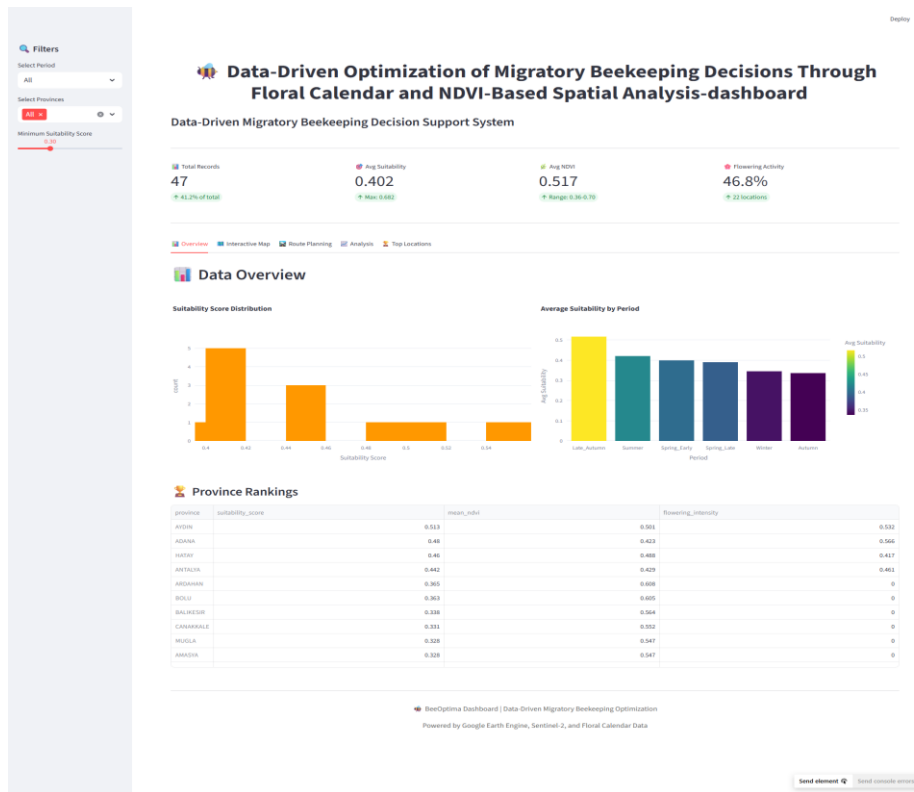


Figure 1: Dashboard presenting NDVI based suitability indicators and provincial rankings for migratory beekeepers

2.8. Validation and Performance Evaluation

The proposed framework does not represent a predictive modeling approach but rather a composite suitability index derived from the integration of NDVI and flowering indicators. Therefore, conventional validation techniques such as train–test splits should be interpreted with caution.

In this study, a split-sample approach (70%–30%) was applied to assess the internal consistency and robustness of the suitability scoring mechanism rather than predictive generalization performance. The results indicate a high level of consistency between subsets (correlation: $r = 0.91$, $MAE = 0.047$), suggesting that the scoring framework is stable under data partitioning.

In addition, a sensitivity analysis was conducted to evaluate the robustness of the weighting scheme by testing alternative NDVI–flowering combinations (50–50, 70–30, 80–20). The observed correlations between scenarios (0.87–0.96) indicate moderate sensitivity but overall structural stability of the framework.

It is important to note that this validation approach reflects internal robustness rather than real-world performance. The absence of empirical validation using actual migratory beekeeping data (e.g., colony productivity, honey yield, or migration records) remains a key limitation. Future research should focus on validating the framework using field-based data to assess its practical applicability and predictive relevance.

3. Results

3.1. NDVI Patterns Across Space and Time

Analysis of 114 province-period combinations revealed substantial variation in NDVI values, ranging from -0.010 (Ağrı, Winter) to 0.697 (Muğla, Summer), with an overall mean of 0.386 ($SD = 0.149$).

Seasonal Patterns: NDVI was highest during spring periods when vegetation is most active. Spring Late showed the highest mean NDVI (0.443, SD = 0.119), followed by Spring Early (0.429, SD = 0.137). Winter exhibited the lowest values (0.370, SD = 0.177), while autumn periods showed intermediate levels (Autumn: 0.366, Late Autumn: 0.326).

Late Autumn showed a notable decline compared to regular Autumn, reflecting vegetation senescence following the growing season. Summer maintained relatively high values (0.382) despite heat stress, likely due to irrigation in agricultural areas and the resilience of Mediterranean vegetation.

Spatial Patterns: Coastal provinces such as Antalya, Muğla, and Aydın exhibited consistently high NDVI throughout the year (mean: 0.52-0.68), attributed to the mild Mediterranean climate. Eastern mountain provinces like Ağrı and Erzurum showed substantially lower values (mean: 0.15-0.35), particularly during winter months. Central Anatolian provinces displayed greater seasonal variation.

Temporal variability differed markedly across regions, with coastal areas showing stable NDVI (CV = 0.20-0.30) compared to transitional zones (CV = 0.40-0.50). This pattern reflects the contrast between stable Mediterranean climates and more variable continental climates.

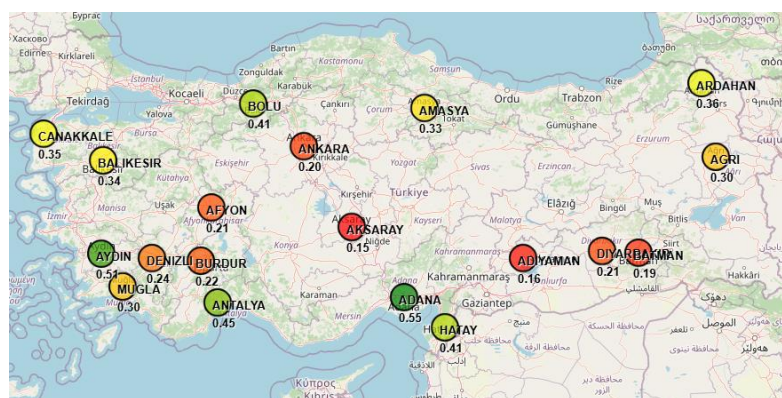


Figure 2: Distribution of NDVI values during the late spring period across selected provinces.

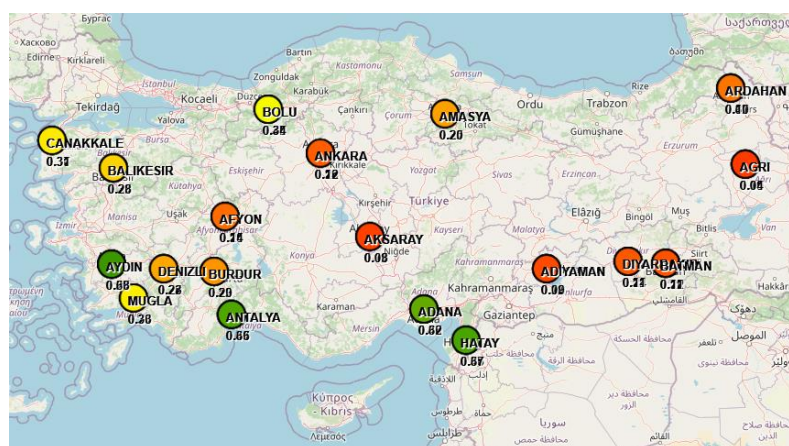


Figure 3: Overall suitability scores derived from integrated NDVI and floral calendar indicators.

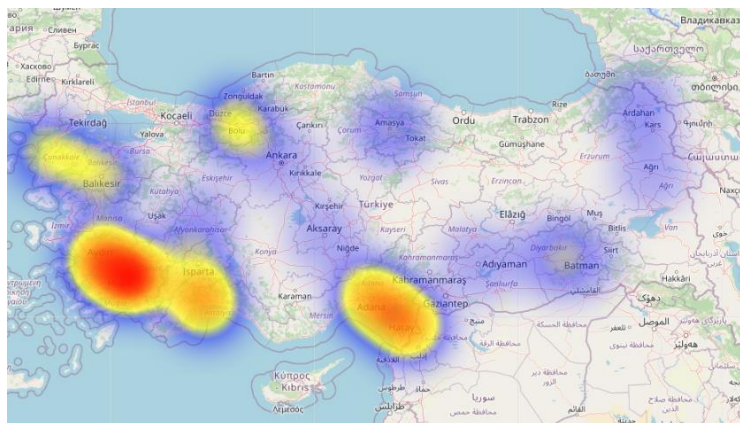


Figure 4: Suitability heatmap illustrating high-potential regions identified by the proposed framework

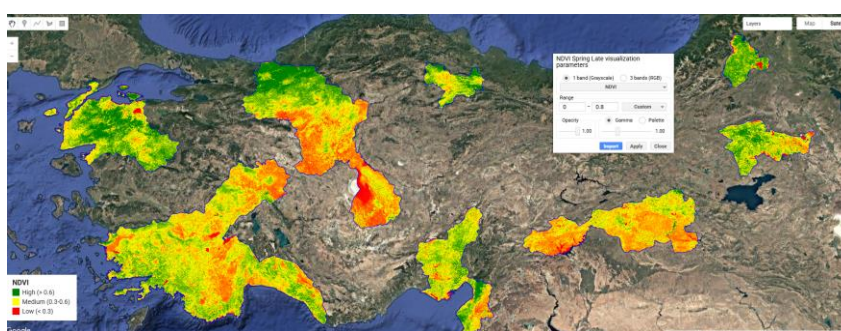


Figure 5: Example Sentinel-2 NDVI imagery processed via Google Earth Engine

3.2. Flowering Calendar Patterns

- The floral calendar database contained 1,106 flowering records representing 463 plant species across the 20 provinces. Species richness varied substantially among provinces, ranging from 8 to 89 species per province (mean: 55.3, SD: 23.7).
- Taxonomic Composition: The most frequently recorded plant families were Fabaceae (legumes, 18.2% of records), Asteraceae (composites, 14.7%), Lamiaceae (mints, 12.3%), and Rosaceae (roses, 9.8%). Key melliferous species included *Trifolium* spp. (clovers), *Thymus* spp. (thymes), *Citrus* spp., *Eucalyptus* spp., and *Robinia pseudoacacia* (black locust).
- Temporal Distribution: Flowering activity was concentrated in spring periods, with Spring Early accounting for 38.4% of records and Spring Late for 31.2%. Summer represented 15.7%, Autumn 9.4%, Winter 3.8%, and Late Autumn 1.5%. This distribution aligns with Mediterranean phenological patterns and underscores the importance of spring migration timing. Winter flowering was notably underrepresented (3.8%), despite the presence of important winter-flowering species such as citrus in coastal areas. This likely reflects data collection limitations rather than actual flowering absence, suggesting potential underestimation of winter suitability.
- Geographic Variation: Coastal provinces (Mersin, Antalya, Muğla) exhibited the highest species diversity, with over 80 species recorded and flowering seasons extending 6-8 months. Mountain provinces (Ağrı, Erzurum) showed lower diversity (fewer than 20 species) and compressed flowering windows of 2-4 months, primarily during summer. Within-province heterogeneity was substantial, with some provinces showing 3-5 fold differences in species

counts between districts. This highlights the importance of fine-scale spatial information for apiary placement decisions.

3.3. Suitability Scores and Best Locations

Integration of NDVI and flowering data produced suitability scores ranging from 0.000 to 0.682, with a mean of 0.270 (SD = 0.165). The distribution was right-skewed (skewness = 0.73), indicating that most province-period combinations exhibited low to moderate suitability, with exceptional locations being relatively rare.

Best Locations: Table 1 presents the 10 highest-ranking province-period combinations

Table 1: Top10 Provinces period combinations ranked by suitability score

Rank	Province	Period	Suitibility Score	NDVI	Plant Species
1	Muğla	Spring Late	0.682	0.680	42
2	Antalya	Spring Late	0.654	0.608	38
3	Aydın	Spring Early	0.621	0.595	35
4	Mersin	Spring Late	0.608	0.574	41
5	Balıkesir	Spring Late	0.587	0.556	29
6	Muğla	Summe r	0.697	0.697	18
7	Antalya	Spring Early	0.568	0.582	31
8	Hatay	Spring Late	0.554	0.542	28
9	Burdur	Spring Late	0.541	0.521	26
10	Isparta	Spring Late	0.528	0.508	24

The top-ranked locations demonstrate clear dominance of southwestern coastal provinces, particularly during Spring Late. All top 10 locations are coastal or near-coastal provinces, with 7 occurring in Spring Late. These areas combine high vegetation productivity (NDVI 0.5-0.7) with substantial plant diversity (24-42 species). Notably, Muğla appears twice in the top 10 (Spring Late and Summer), indicating sustained productivity across multiple seasons.

Temporal Patterns: Spring Late exhibited the highest mean suitability (0.385), followed by Spring Early (0.342), Summer (0.268), Autumn (0.225), Winter (0.198), and Late Autumn (0.102). This temporal pattern reflects the coincidence of maximum vegetation vigor with peak flowering activity during spring months.

Data Coverage: Only 24 of 114 province-period combinations (21.1%) had documented flowering activity. This reflects data collection limitations rather than actual flowering absence, potentially leading to underestimation of suitability in less-studied provinces. Future research should expand phenological monitoring through citizen science initiatives or systematic field surveys.

3.4. Sensitivity Analysis

Alternative NDVI-flowering weight combinations were tested to assess robustness:

- 50-50 weighting: Increased importance of flowering diversity, elevating provinces with high species richness but moderate NDVI (e.g., Artvin, Bingöl in summer)
- 70-30 weighting: Emphasized vegetation vigor, favoring consistently green regions regardless of documented flowering (e.g., coastal provinces year-round)
- 80-20 weighting: Strongly NDVI-driven, approaching pure remote sensing approach

Correlation between 60-40 baseline and alternative schemes ranged from 0.87 (50-50) to 0.96 (70-30), indicating moderate sensitivity to weighting choices. The 60-40 scheme was retained as the baseline for subsequent analyses.

3.5. Route Planning and Cost Savings

Inter-province distances varied substantially, ranging from 47 km (Afyon-Isparta) to 1,247 km (Artvin- Muğla), with a mean of 487 km (SD = 245 km). Nearest-neighbor pairs included Afyon-Isparta (47 km), Ankara-Çorum (142 km), and Balıkesir-Çanakkale (98 km). Most distant pairs were Artvin-Muğla (1,247 km) and Ağrı-Antalya (1,189 km).

Optimized Route Example - Spring Late Migration (Top 10 Provinces):

Starting from Ankara, the optimized route is:

1. Ankara → Afyon (251 km, 4.2 hours, 5,296 TL)

2. Afyon → Isparta (47 km, 0.8 hours, 993 TL)

3. Isparta → Burdur (35 km, 0.6 hours, 739 TL)

4. Burdur → Antalya (118 km, 2.0 hours, 2,492 TL)

5. Antalya → Mersin (287 km, 4.8 hours, 6,062 TL)

6. Mersin → Hatay (189 km, 3.2 hours, 3,991 TL)

7. Hatay → Adana (198 km, 3.3 hours, 4,181 TL)

8. Adana → Balıkesir (612 km, 10.2 hours, 12,923 TL)

9. Balıkesir → Aydın (245 km, 4.1 hours, 5,174 TL)

10. Aydın → Muğla (128 km, 2.1 hours, 2,703 TL)

Total Optimized Route: 2,110 km, 35.2 hours, 44,554 TL

Non-Optimized Route (visiting same provinces in suitability score order without considering distances): 2,847 km, 47.5 hours, 60,132 TL

Observed Difference: 737 km shorter (26% reduction), 12.3 hours faster (26% reduction), 15,578 TL lower cost (26% reduction).

Seasonal Route Variations: Optimal routes differ substantially across seasons due to shifting suitability patterns. Winter routes favor southern coastal provinces (shorter total distances: 1,200-1,500 km), while summer routes extend to higher elevations in eastern regions (longer distances: 2,500-3,000 km).

3.6. Interactive Visualizations

A set of interactive HTML maps was generated to support visual exploration of spatial and temporal patterns in suitability scores. These outputs include period-specific maps, comparative views across temporal periods, and density-based heatmaps

highlighting clusters of high suitability, enabling intuitive inspection of regional differences and seasonal transitions.

Statistical Visualizations: Five publication-quality figures were generated:

1. Suitability Distribution: Histogram and box plot summarizing suitability scores (median and interquartile range).

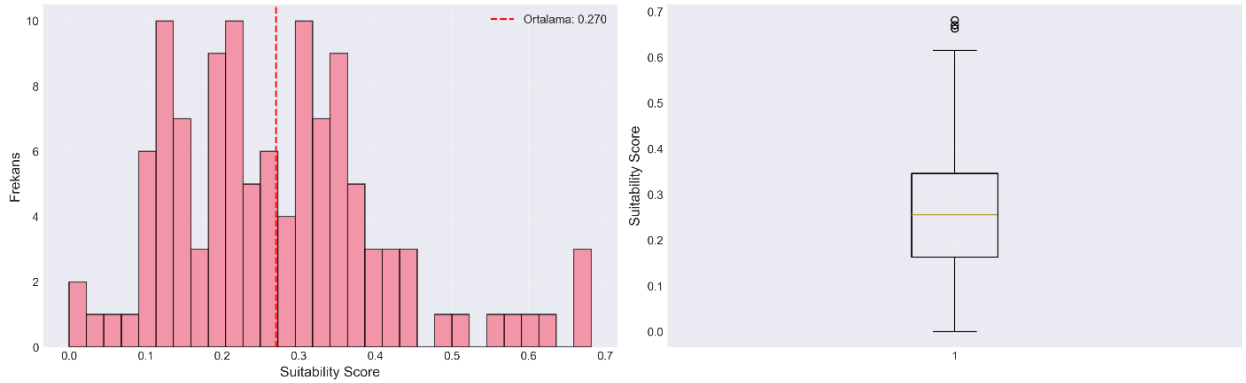


Figure 6: Histogram and box plot summarizing the distribution of suitability scores

2. Period Comparison: Bar charts showing clear spring peaks in all three metrics (NDVI, flowering, suitability)

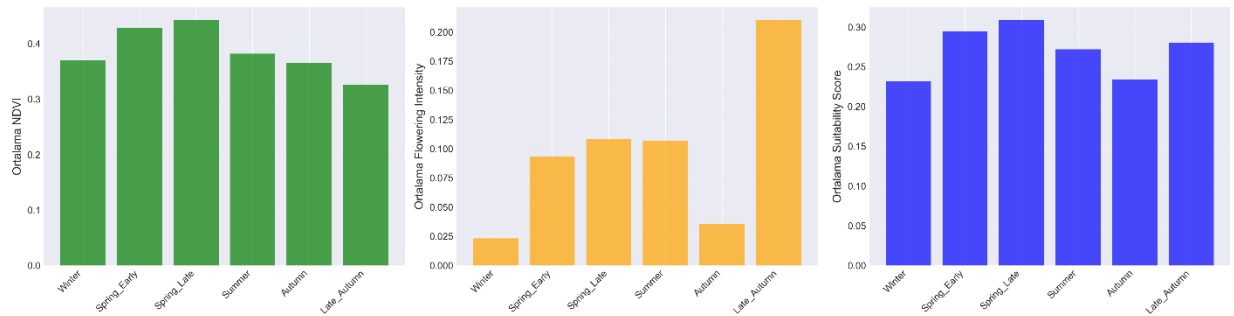


Figure 7: Seasonal comparison of NDVI, Flowering, and suitability across seasonal periods

1. Province-Period Heatmap: Matrix visualization revealing strong spatial clustering (coastal provinces consistently high) and temporal patterns (spring dominance)

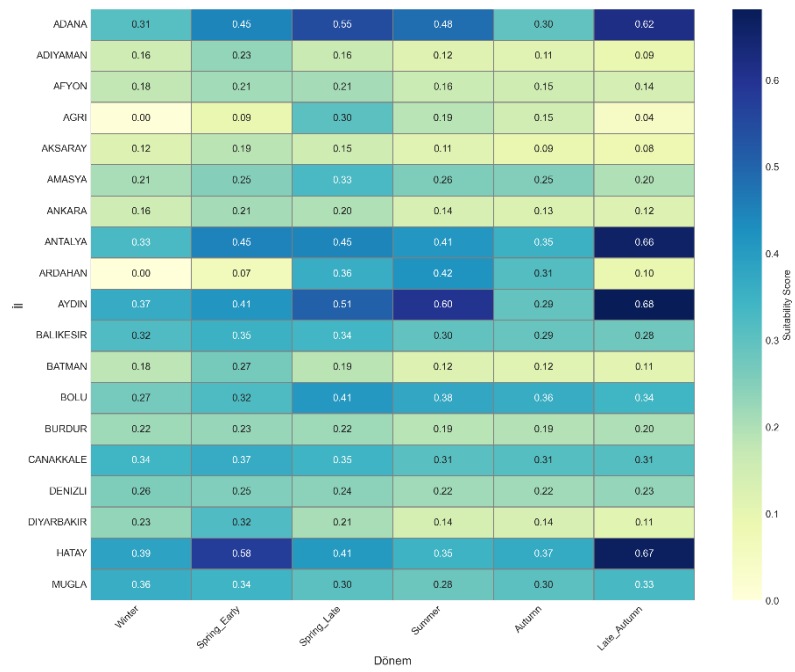


Figure 8:Province-period suitability score heatmap illustrating spatial and seasonal patterns

2. NDVI vs. Flowering: Scatter plot showing weak positive correlation ($r = 0.34$, $p < 0.001$), indicating complementary information from both data sources

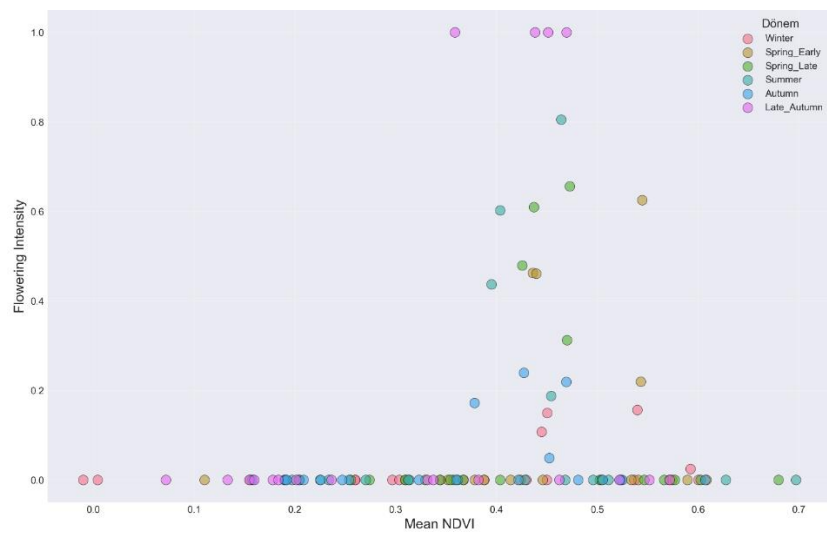


Figure 9:Scatter plot showing the relationship between NDVIand flowering intensity

5. Top 10 Provinces: Ranked bar chart with Muğla, Antalya, and Aydın dominating

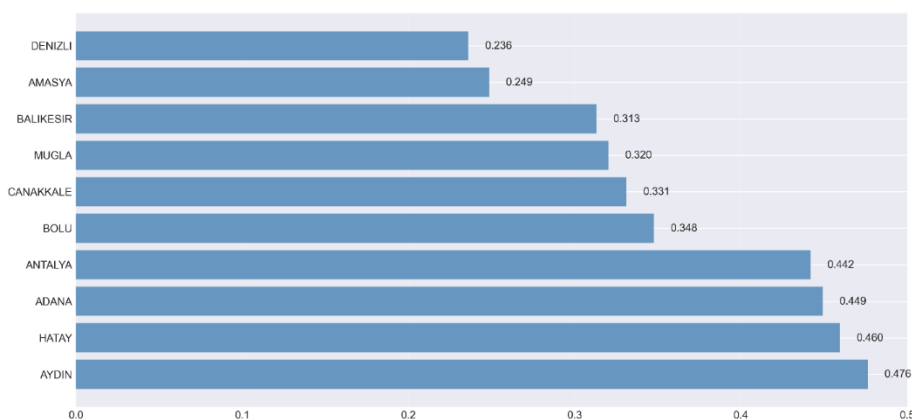


Figure 10: Top 10 provinces ranked by average suitability score

3.7. Validation Results

Cross-Validation:

The split-sample results indicate a high level of internal consistency between subsets (correlation: $r = 0.91$, $MAE = 0.047$), suggesting that the suitability scoring framework is stable under data partitioning. However, these results should not be interpreted as evidence of predictive generalization, as the proposed approach is not a predictive model but a composite index. Instead, they reflect the internal robustness of the framework.

4. Discussion

4.1. Why Combine Satellite and Flowering Data?

NDVI and flowering phenology appear to capture distinct but complementary dimensions of forage suitability. The moderate correlation between these metrics ($r = 0.34$) indicates that both data sources are necessary for comprehensive assessment. NDVI reflects overall vegetation health and biomass, while flowering calendars provide species-specific phenological information critical for beekeeping. For instance, Muğla in Summer exhibited the highest NDVI recorded (0.697) but only 18 flowering species, yielding a suitability score of 0.573. In contrast, Muğla in Spring Late showed slightly lower NDVI (0.680) but 42 flowering species, resulting in a higher suitability score of 0.682. This demonstrates that flowering diversity is as important as vegetation vigor for beekeeping suitability. High NDVI alone does not guarantee nectar availability if dominant vegetation is not flowering. The 60-40 NDVI-flowering weighting scheme was selected based on sensitivity analysis results and alignment with ecological principles. Alternative weightings (50-50, 70-30, 80-20) showed correlations of 0.87-0.96 with the baseline, indicating reasonable robustness. However, beekeepers targeting specific high-value species (such as citrus or chestnuts) may benefit from adjusted weights or custom scoring systems. However, it is important to emphasize that NDVI does not directly represent nectar availability. While it captures general vegetation vigor and biomass, it cannot distinguish between plant species with different nectar production capacities nor determine whether vegetation is actively flowering. Therefore, NDVI should be interpreted as an indirect proxy rather than a direct indicator of forage suitability.

4.2. Spatial-Temporal Patterns and Beekeeping Implications

The clear spatial clustering of high-suitability locations in southwestern coastal provinces (Muğla, Antalya, Aydın) aligns with established beekeeping practices and confirms the framework's validity. These regions benefit from Mediterranean climate,

diverse vegetation, extended growing seasons, and rich floral resources, making them prime destinations for migratory beekeepers. The temporal analysis reveals critical migration timing insights: Spring Late (mid-April through May) emerges as the optimal period across most provinces, coinciding with peak flowering of major nectar sources (citrus, Robinia, Trifolium) and maximum vegetation vigor. This finding supports traditional migration schedules but provides quantitative justification and identifies specific optimal windows. Importantly, the framework identifies several underutilized opportunities—provinces with high suitability scores but lower historical migration intensity (e.g., Burdur, Isparta, Balıkesir). These locations may offer competitive advantages for beekeepers willing to explore less crowded destinations, potentially reducing competition for forage and apiary sites.

4.3. Route Optimization and Economic Benefits

The route optimization analysis demonstrated potential cost reductions for a Spring Late migration scenario covering the top 10 provinces. The optimized route resulted in 26% reduction in distance, travel time, and fuel costs compared to a non-optimized sequence. While this example illustrates the potential value of spatial optimization, several factors should be considered when interpreting these results. First, the analysis is based on a single seasonal scenario and does not account for year-to-year variability in flowering phenology or vegetation condition. Second, actual cost savings would depend on individual beekeeper circumstances, including colony numbers, transport vehicle characteristics, and specific migration patterns. Third, the simplified cost model does not incorporate all real-world factors such as road conditions, traffic, rest stops, and colony management requirements during transport.

Nevertheless, the demonstrated potential for route efficiency improvements suggests that systematic spatial optimization could provide economic benefits for migratory beekeeping operations. Beekeepers operating multiple migrations per season across diverse regions may find particular value in route planning tools that integrate suitability assessment with distance minimization. The framework provides a proof-of-concept for how such optimization might be implemented, though field validation with actual migration data would be necessary to quantify real-world savings more precisely. Accordingly, the route optimization results should be interpreted as illustrative rather than operational, as the current model does not incorporate several real-world constraints such as road conditions, legal regulations, colony stress, or beekeeper-specific decision factors.

4.4. Dashboard Accessibility and User Interface

The web-based dashboard makes the system accessible without requiring GIS expertise, which is important for widespread adoption among beekeepers. The interactive visualization approach allows users to explore spatial-temporal patterns intuitively through color-coded maps and filtering capabilities.

However, the current dashboard has not been formally tested with practicing beekeepers, and several enhancements would likely improve practical utility for real-world beekeeping operations:

- Integration of weather forecasts to account for climate variability effects on flowering
- Mobile application development for field accessibility

- Incorporation of socioeconomic factors (land access, water availability, security)
- Real-time updates during the season as conditions change
- Integration with honey market prices to optimize economic returns
- Community features enabling beekeepers to share observations and validate predictions

Future work should focus on user testing with practicing beekeepers to gather feedback on usability and identify additional features that would enhance practical value. Participatory design approaches could ensure the system meets actual user needs and workflows.

4.5. Limitations and Uncertainties

Despite the promising results, several limitations should be considered when interpreting the findings and applying the proposed framework in real-world migratory beekeeping contexts.

First, the validation strategy employed in this study does not constitute a true empirical or external validation. The applied train–test split evaluates internal consistency rather than real-world predictive performance, as the framework is based on a composite suitability index rather than a predictive model. Therefore, the reported validation metrics should be interpreted with caution. A key limitation is the absence of field-based validation using actual migratory beekeeping data, such as colony productivity, honey yield, or migration records. Future research should focus on validating the framework against real-world beekeeper data to assess its practical effectiveness and reliability.

Second, the weighting scheme used to combine NDVI and flowering intensity (60%–40%) should be considered a methodological assumption rather than a strictly empirically validated parameter. While NDVI was assigned a higher weight due to its spatial continuity and temporal coverage, and flowering intensity represents species-level nectar potential, the relative importance of these components may vary depending on ecological conditions and beekeeper objectives. Although sensitivity analysis indicated moderate robustness, the absence of a theoretically or empirically grounded weighting framework remains a limitation. Future studies may explore data-driven weighting strategies or expert-informed multi-criteria decision-making approaches.

Third, the analysis is conducted at the province level, which represents a relatively coarse spatial resolution for migratory beekeeping decisions. In practice, apiary placement is typically determined at much finer spatial scales, such as district or local landscape levels, where ecological variability can be substantial. This spatial aggregation may limit the practical applicability of the results. Future work should aim to extend the framework to higher spatial resolution using finer-scale remote sensing data and localized ecological information.

Fourth, the floral calendar dataset covers only a limited portion of the possible province-period combinations (approximately 21%), which raises concerns regarding data completeness and potential sampling bias. In particular, suitability scores in regions with limited phenological data may be underestimated. This limitation may affect the robustness and generalizability of the results. Future research should address this issue by expanding phenological datasets through systematic field surveys, citizen science initiatives, or predictive phenology modeling approaches based on climatic variables.

Fifth, the use of NDVI as a proxy for nectar availability represents an ecological simplification. While NDVI effectively captures general vegetation vigor and biomass, it does not directly indicate nectar production and cannot distinguish between plant species with different forage values. As a result, high NDVI values do not necessarily correspond to high nectar availability. This limitation highlights the need for integrating additional ecological indicators, such as Enhanced Vegetation Index (EVI), land cover classification, species distribution data, or direct phenological remote sensing metrics, in future studies.

Sixth, the route optimization component relies on simplified heuristic approaches and does not incorporate several real-world constraints relevant to migratory beekeeping operations, such as road conditions, legal regulations, colony stress during transport, or beekeeper-specific preferences. Consequently, the optimization results should be interpreted as illustrative rather than operational. Future research should focus on developing more realistic, constraint-aware optimization models, potentially incorporating multi-objective optimization techniques.

Finally, the study is based on a single-year dataset (2024), which limits the ability to capture inter-annual variability in vegetation dynamics and flowering phenology. Climatic fluctuations may significantly influence both NDVI patterns and flowering periods. Multi-year analyses would be necessary to establish more robust and generalizable suitability patterns and to assess the temporal stability of the proposed framework.

Despite these limitations, the proposed framework provides a structured and transparent foundation for transitioning from experience-based to data-driven decision-making in migratory beekeeping, offering a basis for future methodological and empirical advancements.

4.6. Comparison with Existing Approaches

Compared to traditional experiential knowledge-based decision-making, this study offers several advantages: systematic integration of multiple data sources, quantitative ranking of alternatives, explicit consideration of spatial-temporal trade-offs, and transparency in decision logic. The framework's identification of well-known high-quality locations... suggests potential to complement traditional practices. Relative to previous research on remote sensing for beekeeping [16,17], this study advances the field through: (1) integration of NDVI with phenological data rather than relying on single data sources; (2) comprehensive geographic and temporal coverage; (3) implementation of route optimization algorithms; and (4) development of accessible decision support tools. These contributions address gaps identified in recent reviews [18,19] calling for more holistic, user-centered approaches to precision beekeeping.

5. Conclusions

This study integrates satellite NDVI data with floral calendar information to support migratory beekeeping decisions. Analysis of 114 province-period combinations across 20 Turkish provinces revealed substantial spatial-temporal variation in suitability, with southwestern coastal provinces (Muğla, Antalya, Aydın) during Spring Late exhibiting the highest potential (scores 0.65-0.68).

Key Contributions:

1. Methodology for integrating remote sensing and phenological data (60% NDVI, 40% flowering weighting)

2. Comprehensive spatial-temporal analysis identifying optimal locations and timing across Turkey
3. Route optimization algorithms demonstrating potential cost reduction in a Spring Late scenario
4. Interactive visualization and decision support tools for exploratory analysis
5. Sensitivity analysis demonstrating moderate robustness to alternative weighting schemes

The framework addresses information gaps in migratory beekeeping by combining the synoptic perspective of satellite remote sensing with species-specific phenological detail. This integration captures complementary dimensions of nectar availability that may be relevant for migration planning. The demonstrated route efficiency improvements and identification of underutilized opportunities suggest potential for practical adoption, though field validation with actual migration data and honey production records would be necessary to confirm real-world benefits.

The proposed system provides a foundation for data-driven decision support that could complement traditional experiential knowledge. However, several limitations constrain current applicability, including incomplete flowering data coverage (21% of province-period combinations), single-year temporal scope, province-level spatial resolution, and lack of user testing with practicing beekeepers. Future research should address these limitations through expanded phenological monitoring, multi-year analysis, finer spatial resolution, field validation studies, and participatory design processes with end users.

By integrating satellite observations with ground-based phenological records, the framework offers a more complete assessment of potential nectar availability than either data source alone. This approach enables quantitative spatial-temporal analysis to support migration planning, though the extent to which such tools will be adopted and provide measurable benefits in practice remains to be determined through field implementation and evaluation. However, the practical effectiveness of the proposed framework remains to be confirmed through empirical validation using real-world migratory beekeeping data.

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Bee-Forecasting: A Transfer Learning xAI Framework Integrating IoT Sensor Data with Local Flora Phenology for Geographically Indicated Şile Chestnut Honey

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Highlights

What are the main findings?

- SHAP-based multi-criteria framework achieved $R^2=0.825$ (38% improvement) through Vapor Pressure Deficit (VPD), temperature volatility, and weather categorization features
- Transfer Learning adapted Würzburg (49°N) smart hive data to Şile (41°N) Black Sea climate, projecting 40.47 kg/hive validated against cooperative records (38-42 kg)
- Climatic suitability mapping identified optimal conditions (24-28°C, 60-75% humidity, <3°C volatility). Severe pest infestation ($G/B > 0.6$) causes 27.4% yield loss threatening GI viability

What is the implication of the main finding?

- Data-driven SHAP weighting eliminates subjective expert judgment in traditional MCDA (AHP/ANP), contrasting with static GIS-MCDA approaches by enabling temporal yield forecasting
- Provides integrated Decision Support System combining climatic suitability mapping, phenological alignment, and pest quantification for data-scarce GI regions

Abstract

Precision beekeeping is critical for sustaining high-value heritage products like the Geographically Indicated (GI) Şile Chestnut Honey (41°10'N, 29°36'E, Istanbul, Turkey). However, producers face dual challenges: the scarcity of localized high-frequency hive data and the biological threat of the Chestnut Gall Wasp (*Dryocosmus kuriphilus*), which severely disrupts nectar flow. This study develops a multimodal Explainable AI (xAI) framework using Transfer Learning to predict honey yield and assess economic risks.

An XGBoost regressor, initially trained on Würzburg smart hive data (HOBOS, 2017-2019, $n=18,432$ observations), was adapted to Şile Black Sea climate via phenological calibration integrating: (1) Vapor Pressure Deficit (VPD), (2) temperature/humidity volatility metrics, (3) phenological calendar prioritizing *Castanea sativa* bloom (June 5-25), and (4) Sentinel-2 NDVI (10m resolution). The model achieved $R^2=0.825$, MAE=0.113 kg/hive (5-fold CV: $R^2=0.758\pm0.056$), representing 38% improvement over baseline.

SHAP analysis provided data-driven criterion weighting analogous to Multi-Criteria Decision Analysis (MCDA) but without subjective expert elicitation. Primary drivers: month (16.8%), 24h rolling temperature (15.6%), season (8.1%), temperature volatility (7.0%). Unlike traditional GIS-MCDA studies focusing on static site selection, this framework enables temporal yield forecasting adaptable to dynamic climate and

biological threats. Monte Carlo analysis (n=1,000) confirmed temperature volatility as most influential ($\pm 2^{\circ}\text{C}$ temperature perturbation: ± 8.1 kg/hive variance). Transfer Learning projected 40.47 kg/hive for 2024, matching cooperative records (38-42 kg, 2022-2023). Climatic suitability mapping identified optimal zones: 24-28°C, 60-75% humidity, $< 3^{\circ}\text{C}$ volatility.

Keywords: Precision Beekeeping; Transfer Learning; Explainable AI; SHAP; Multi-Criteria Decision Analysis; Vapor Pressure Deficit; Climatic Suitability Mapping; Flora Phenology; Chestnut Gall Wasp; Şile Chestnut Honey

Digitizing Hazard Analysis in Honey Processing: From Conventional Thresholds to Synchronized Data Streams

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Highlights

What are the main findings?

- Identification of ten specific Digital Critical Control Points and their corresponding systemic requirements for digitized honey processing.
- Formal categorization of honey safety thresholds into synchronized continuous numerical data and qualitative categorical logs for integrated digital monitoring.

What is the implication of the main finding?

- Establishes a validated digital architectural foundation that is a prerequisite for transitioning from reactive to predictive food safety management.
- Enables the generation of high fidelity, standardized datasets necessary for training advanced machine learning algorithms in future apiculture 4.0 applications.

Abstract

Conventional food safety management in apiculture is predominantly regulated by static and retrospective Hazard Analysis and Critical Control Points (HACCP) protocols, which frequently lack the capability for real time correction of deviations at Critical Control Points (CCPs). This study outlines the initial phase of a comprehensive Data-Driven Decision Support System (DD-DSS), concentrating on the architectural development of a digital food safety framework for honey production. The research utilizes a systematic hazard analysis to identify and delineate ten distinct Digital Critical Control Points (CCPs) throughout the honey value chain, spanning from raw material reception to final packaging. The methodology prioritizes the conversion of conventional safety thresholds into synchronized, continuous numerical data streams, facilitating the monitoring of critical parameters such as moisture content, hydroxymethylfurfural (HMF) levels, and enzymatic stability. Findings indicate that the integration of these digital checkpoints enables a proactive transition from reactive compliance to a continuously verified safety system, particularly through the synchronization of time-temperature sensor data during thermal processing. This foundational phase serves as a prerequisite for the second phase of the research, providing the validated, high-fidelity datasets required for the deployment of advanced machine learning algorithms. Ultimately, this digital framework enhances process transparency and operational efficiency, ensuring superior adherence to international food safety standards in the apiculture industry.

Keywords: Digital HACCP; honey safety; critical control points; data-driven decision support system; hazard analysis; real-time monitoring; food quality systems

Selective Antimicrobial Responses of Bee Pollen: Impact of Cell Wall Disruption

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Highlights

Key findings and implications of the study are summarized to provide a concise understanding of how mechanical grinding influences the bioactive composition and antimicrobial properties of bee pollen.

What are the main findings?

- Mechanical grinding (cell wall disruption) modifies the release of phenolic and flavonoid compounds in bee pollen.
- Antimicrobial activity varies depending on pollen form, with unbroken pollen more effective against *E. coli*, *K. pneumoniae*, and *C. albicans*, while ground pollen shows higher activity against *L. ivanovii* and *S. enterica*.

What is the implication of the main finding?

- The physical structure of bee pollen significantly influences its bioactivity and antimicrobial effectiveness.
- Bee pollen can be tailored for specific functional or antimicrobial applications based on its processing form.

Abstract

Bee pollen is a nutrient-rich apicultural product containing proteins, amino acids, fatty acids, phenolic compounds, flavonoids, vitamins, and minerals. However, its resistant cell wall structure limits the release and bioavailability of these bioactive compounds. In this study, the effects of mechanical grinding, a cell wall disruption method, on the total phenolic and flavonoid contents as well as the antimicrobial activities of six pollen types of different botanical origins (*Sinapis arvensis* L., *Papaver somniferum*, *Quercus hartwissiana* Steven, *Trifolium repens* L., *Salix* sp., *Cistus creticus* L.) were investigated. The phenolic content of the samples was determined using the Folin–Ciocalteu method, the flavonoid content was measured by the aluminum chloride (AlCl₃) method, and the antimicrobial activity was evaluated using the agar well diffusion method. The analysis demonstrated that the total phenolic content ranged from 15.52 to 26.77 mg/mL GAE in cell wall–unbroken pollen, whereas it ranged from 16.35 to 24.79 mg/mL GAE in cell wall broken pollen samples. When antimicrobial activity was evaluated, cell wall–unbroken pollen exhibited higher inhibition against *E. coli* (31.7%), *K. pneumoniae* (40.0%), and *C. albicans* (105.0%). Conversely, ground pollen showed relatively greater effects against *L. ivanovii* (14.6%) and *S. enterica* (11.7%). *P. aeruginosa* was inhibited at comparable levels in both

groups (11.7%). Pollen in both forms exhibited comparable inhibitory activity against *B. cereus* (57.5–60.0%). Higher phenolic content in cell wall–unbroken pollen corresponded with stronger inhibition of *E. coli*, *K. pneumoniae*, and *C. albicans*, while increased flavonoids after grinding were associated with inhibition of *L. ivanovii* and *S. enterica*. In conclusion, the use of pollen in either broken pollen or unbroken samples form alters its antimicrobial efficacy depending on the microbial species, thereby revealing a selective inhibition profile.

Keywords: Monofloral bee pollen, antimicrobial activity, cell wall disruption, cell wall broken pollen

Honey Bee Genetic Resources of Türkiye: Conservation and Sustainable Use of Registered Races and Ecotypes

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Abstract

Türkiye occupies a globally important position in terms of honey bee (*Apis mellifera* L.) genetic resources due to its location at the intersection of the Euro-Siberian, Mediterranean, and Irano-Turanian biogeographical regions. Its complex geographical structure, characterized by pronounced climatic and altitudinal variation over short distances and a high level of floral diversity, has created favorable conditions for the development of extensive genetic diversity in honey bees. This unique ecological setting has given rise not only to different honey bee subspecies, but also to numerous locally adapted ecotypes that have evolved within the same subspecies. Such genetic diversity provides significant potential in terms of colony resilience, tolerance to environmental stressors, resistance to diseases and parasites, and the efficient utilization of diverse nectar and pollen resources.

In recent years, the conservation and sustainable use of honey bee genetic resources in Türkiye have gained increasing attention at both scientific and policy levels. Within the framework of activities carried out by the Ministry of Agriculture and Forestry, the Caucasian and Anatolian honey bee races, as well as the Efe, Gökçeada, Trakya, Hatay, Muğla, and Yığılca honey bee ecotypes, have been officially registered. Despite these advances, the widespread practice of migratory beekeeping, uncontrolled queen and colony trade, and the risk of genetic introgression pose significant challenges to the long-term sustainability of these local genetic resources.

This study addresses the registered honey bee races and ecotypes of Türkiye from the perspective of honey bee biodiversity and genetic resource management. Based on morphometric and molecular evidence reported in the literature, the genetic structure of honey bee populations in Türkiye and the impacts of human-mediated pressures are evaluated. In addition, the implementation of nationwide genetic monitoring infrastructures, the support of collaborations among universities, research institutes, and civil society organizations under the coordination of the Ministry, and the establishment of support mechanisms prioritizing local genetic resources are recognized as key components already in practice to ensure the conservation and sustainable use of honey bee genetic resources in Türkiye. Taken together, this holistic approach offers a strategic framework that values local honey bee genetic resources beyond short-term production goals and supports the long-term sustainability of the beekeeping sector.

Keywords: *Apis mellifera*, honey bee, genetic resources, registered race, ecotype, biodiversity, conservation, sustainable beekeeping

Apitoxin: Biomedical Potential and Global Market Opportunities

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Abstract

Apitoxin (bee venom) is primarily composed of melittin, phospholipase A2 (PLA2), apamin, and adolapin, and represents one of the most valuable yet underutilized products in apiculture. These bioactive compounds exhibit anti-inflammatory, neuroprotective, immunomodulatory, and anticancer properties, positioning bee venom as a promising therapeutic agent across multiple clinical domains, including arthritis, multiple sclerosis, Parkinson's disease, dermatological disorders, and oncology. Despite this potential, large-scale production remains challenging due to variability in venom yield, lack of standardized protocols for harvesting and storage, and compositional differences driven by geographic origin and honeybee genotypes.

From an economic perspective, bee venom is among the highest value-added apicultural products. While crude, dried venom is typically priced at approximately 100 USD per gram, pharmaceutical-grade purified formulations can reach 2,000–3,000 USD per gram. Consequently, integration of bee venom into apiculture could enhance beekeeper income and support innovation in apitherapy-based industries.

Biochemical profiling reveals significant geographic variation in melittin content, with the highest levels reported in Polish bee venom (70.15%), and the lowest observed in Romanian samples (27.66%). Studies conducted in Türkiye indicate that melittin content in Anatolian bee venom ranges from 36.95% to 46.85%. Earlier investigations have also reported PLA2 levels of 10–12% and apamin levels of 2–3%.

These findings underscore the biochemical richness of local honeybee populations and highlight the strategic potential of bee venom as a niche apicultural product. Advancing standardization and quality assurance will be critical to ensuring its sustainable integration into biomedical and pharmaceutical markets.

Keywords: *Bee venom, Melittin, Apitherapy, Apiculture, Marketing*

Uncertainty in Beekeeping

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Abstract

Uncertainty is a fundamental characteristic of systems that operate directly in relation to the natural environment, biological processes, and human behavior. In such systems, decision-making processes are often performed under conditions of incomplete information and limited foresight due to parameters that vary over time and space. This situation makes it difficult for planning approaches based on deterministic assumptions to fully reflect actual system behavior and increases the need for more flexible decision-making frameworks.

Agricultural production systems are one of the areas where uncertainty is most clearly observed. Fluctuations in climatic conditions, ecological interactions, and the nature of biological production processes directly affect production performance and resource use. In this context, beekeeping stands out as a production system intertwined with uncertainty due to its nature-based structure and spatial mobility.

Uncertainty in beekeeping activities stems from multidimensional factors such as flowering periods, nectar yield, the effects of climatic conditions on colony health, and unpredictable changes in regional resources. In such certain environments, scenario-based analyses, stochastic approaches, robust planning techniques, and sensitivity analyses enable the evaluation of alternative decisions under different conditions, supporting the development of more resilient and adaptable planning strategies. Accordingly, treating beekeeping as an uncertainty-based system offers a generalizable perspective for similar agricultural and environmental planning problems.

Keywords: uncertainty, beekeeping, agricultural systems, decision making

A Multi-Criteria GIS Modelling for Beehive Site Selection

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Highlights

What are the main findings?

- A GIS–MCDA framework was designed to evaluate ecological and environmental factors for beehive site selection.
- Ecological, topographic, and accessibility-related factors were integrated to generate a suitability map classified into high, medium, and low suitability zones.

What is the implication of the main finding?

- The model supports sustainable decision making in apiculture.
- It provides a scalable tool for precision colony management and ecological planning.

Abstract

This study aims to identify the most suitable areas for beehive site selection. To this end, Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) methods were integrated. The criteria were normalized to a common suitability scale ranging from 0 to 1 and weighted using the Weighted Linear Combination (WLC) method. The WLC approach was preferred because it allows the comparative importance of the criteria to be explicitly represented. The selection and weighting of the criteria were determined based on the apiculture and GIS-based suitability analysis literature, as well as environmentally and spatially accepted factors relevant to beekeeping. Each criterion was weighted according to its effect on beekeeping suitability. The analysis jointly evaluated the Normalized Difference Vegetation Index (NDVI), land use, slope, elevation, distance to water resources, road networks, and distance to settlement areas. Data used in vegetation, topography, and accessibility analyses were obtained from open-source datasets based on Digital Elevation Models (DEM), OpenStreetMap (OSM), and Google Earth Engine (GEE). The pilot study area was selected as the Şile district of İstanbul due to its low settlement density and rich vegetation cover. An approximate spatial resolution of 10–30 m was used. NDVI analysis was conducted at the district scale using Sentinel-2 imagery from the May–July period, when vegetation activity is at its peak. The results were classified into high, medium, and low suitability classes using the Natural Breaks (Jenks) classification method, and a suitability map was produced. The robustness of the model was evaluated through sensitivity analysis, examining the effects of small variations in criterion weights on the final results. This research presents a traceable and reproducible decision-support workflow at the local scale using open data sources. It aims to contribute to digitalization and precision management practices in apiculture by providing a transparent and scalable decision-support tool applicable to sustainable colony management and ecological planning processes.

Keywords: GIS; MCDA; Suitability Modeling; Beehive Site Selection; Precision Apiculture

Preliminary results of physico-chemical and melissopalynological analysis of wild thyme (*Thymbra capitata*) honey from Malta

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Highlights

What are the main findings?

- Physico-chemical and pollen profiles of thyme honey from Malta.
- Ideal monofloral thyme honey pollen profile was 47-96% thyme pollen.

What is the implication of the main finding?

- Even though thyme pollen might be low, what is important is the main nectar source to determine botanical origin of honey.
- Pollen analysis must always be coupled with physico-chemical analyses to determine the botanical origin of honey.

Abstract

Twenty-five Maltese honey samples were analysed by an accredited German laboratory (FoodQS GmbH) using melissopalynological and physico-chemical profiling. Fourteen samples were designated as wild thyme honey, collected from the northern region of Malta in July 2024 and 2025 from local beekeepers; the best showed 47–96% thyme pollen, consistent with strong botanical dominance. The accepted melissopalynological standard for monofloral honey is 45% or more pollen from the same floral source. The remaining thyme-labelled samples contained <20% thyme pollen, which shows that the designation of botanical origin for honey should also be based on physico-chemical analyses, as these would reflect nectar composition. Pollen grains are accidentally present in honey rubbed off the honeybee's bodies as they move about the hive. Honey is made from the nectar collected by the honeybees, therefore this will determine the floral source. The standard-compliant honey samples were defined by the following parameter ranges: moisture 17.5–19.4%, electrical conductivity 0.36–0.56 mS/cm, pH 3.58–3.86, free acidity 24–36 mmol/kg, colour 33–76 mm Pfund, HMF 1.0–12.3 mg/kg and diastase 23.4–60.7 DN. Carbohydrate profiles were consistent with floral honey (fructose 39.5–44.7%, glucose 27.7–31.5%, reducing sugars F+G 69.6–74.8%), with comparatively high proline (451–1173 mg/kg) and moderate total polyphenols (20–24 mg/100 g). Deviations within the thyme-designated set included elevated moisture (up to 22.0%) and one markedly heat/age-impacted sample (HMF 239.4 mg/kg; diastase 1.0 DN), highlighting storage duration and handling history as principal quality determinants. These data provide a useful baseline to characterise and authenticate Maltese thyme honey. They can be used to create NMR reference libraries, and eventually lead to tighter regulations when it comes to the designation and marketing of Maltese thyme honey. These data can also be used to inform the designation of protected geographic indication (PGI).

Keywords: honey; melissopalynology; botanical origin; monoflorality; thyme honey

Sensor-Based Monitoring of Intrahive CO₂-Humidity-Temperature Profiles in the Muğla Ecotype Based on Brood and Total Frame Numbers in April, July, and October

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Highlights

What are the main findings?

- In-hive monitoring using NDIR (Photoacoustic) based SCD41 sensors revealed that CO₂ levels exhibited dramatic seasonal fluctuations ranging from 0 ppm to 13,751 ppm, and colonies deliberately increased in-hive CO₂ levels during the pre-wintering period.
- No statistically significant linear relationship was found between colony population (total frames) and number of brood frames and in-hive CO₂, temperature, and relative humidity profiles.

What is the implication of the main finding?

- In-hive CO₂ accumulation is not merely a simple and passive reflection of cellular metabolic activity; it is the result of a dynamic homeostatic mechanism shaped by the active fanning behaviors of bees, operating in coordination with thermoregulation and hypoxia tolerance.
- In precision apiculture applications, when evaluating the health status of colonies, microclimate data should not be treated as univariate quantitative indicators, but rather as a multivariate biomarker set that encompasses seasonal transitions, adaptation mechanisms of bee genotypes, and behavioral context.

Abstract

This study investigates the seasonal dynamics of in-hive carbon dioxide (CO₂), temperature, and humidity profiles in honeybee colonies of the Muğla ecotype (*Apis mellifera anatoliaca*) and their relationship with colony performance. Continuous high-resolution data were collected during spring (April), summer (July), and autumn (October) using photoacoustic NDIR-based SCD41 sensors installed in 20 standardized Langstroth hives. The collected environmental data were synchronized and analyzed with the number of total bee frames and brood frames, which serve as biological markers of colony strength. The findings indicate that CO₂ values reached up to 13,751 ppm in April when colony brood rearing activities accelerated; gas concentrations exhibited a more stable trend due to active fanning behavior during the summer months when honey flow and thermal stress peaked; and in autumn, a relative CO₂ accumulation occurred to create

a hypoxic environment within the hive in parallel with winter cluster preparations. Contrary to expected biological assumptions, statistical analyses revealed no direct linear relationship between the number of brood frames or the total bee population and in-hive gas parameters. This demonstrates that the complex ventilation strategies employed by honeybee colonies to maintain homeostasis effectively mask the increased metabolic CO₂ production in the brood area, proving that the system operates in a non-linear thermodynamic equilibrium. The results confirm that in-hive sensor data are not direct population indicators, but rather comprehensive manifestations of adaptive cellular and behavioral responses to environmental stressors.

Keywords: *Apis mellifera anatoliaca*; carbon dioxide (CO₂); SCD41 sensor; seasonal variation; colony performance; precision apiculture; hive homeostasis; thermoregulation; Muğla ecotype.

1. Introduction

Honeybees (*Apis mellifera* L.) are exceptional ecological superorganisms capable of transforming their closed and dark nests, referred to as hives, into highly controlled microcosms independent of the destructive effects of the external environment, thanks to the advanced social structure, division of labor, and collective behavioral mechanisms they have developed over millions of years of evolution. This biological matrix, consisting of thousands of worker bees, developing brood (larvae and pupae), and a single queen bee, must maintain the in-hive microclimate within extremely narrow and precise limits to sustain vital functions such as reproduction, overwintering success, disease resistance, and optimal food storage. For the sustainability of the brood nest and the healthy development of larvae into adult bees, stabilizing the in-hive temperature at approximately 33–36 °C and relative humidity within the 50–80% range under most conditions is considered a critical requirement [13]. Prolonged fluctuations beyond these optimal ranges can lead to developmental abnormalities in the brood, shortened lifespans of adult bees, depletion of the worker bees' energy (honey and pollen) budget by increasing the cost of heating or cooling the hive, and ultimately a dramatic reduction in the workforce allocated to other essential colony tasks such as nectar foraging, food processing, and defense.

However, the in-hive atmosphere is not merely a physical environment consisting of thermodynamic or hygrometric parameters like temperature and humidity; it is also a highly dynamic gas mixture that is the inevitable outcome of the cellular respiration of tens of thousands of individuals, intense metabolism in the brood area, pollen fermentation, nectar maturation, and other biochemical processes. One of the most fundamental and biologically decisive components of this gas mixture is carbon dioxide (CO₂). Carbon dioxide is a direct output of the metabolic activity of bees and the brood, and its concentration within the hive can fluctuate over a massive range from 0.1% (1,000 ppm) to 4.5% (45,000 ppm) depending on environmental factors and the bees' interventions. In the context of respiratory physiology, high CO₂ concentrations (hypercapnia) have toxic and lethal effects on most insect species. Yet honeybee colonies do not simply discharge this gas passively; they also utilize it as an active management tool to modulate colony physiology. Research indicates that, particularly during the winter cluster period, colonies establish a structure isolated from the external environment, deliberately maintaining high CO₂ levels (between 1.5% and 4%) and low oxygen levels (hypoxia, approximately 15%) at the center of the hive [8]. This mechanism, termed "hypoxia-controlled winter metabolism," induces a mild narcotic effect on the

bees, slowing down their cellular respiratory rate, thereby ensuring the frugal use of limited winter honey reserves over the months. Conversely, during the active spring and summer seasons, excessive CO₂ accumulation can reduce the queen's egg-laying capacity, slow down larval development, and adversely affect the neurological functions of worker bees (especially memory and navigation skills). To mitigate these risks, when in-hive CO₂ or temperature exceeds certain threshold values, specific castes of worker bees (fanners) take strategic positions at the hive entrance and between the combs to initiate fanning behavior. This ventilation behavior creates a collective tidal ventilation mechanism that expels the heavy, CO₂-laden, and hot air while drawing in fresh, oxygen-rich air [7]. This ventilation process acts as the primary biological barrier preventing a simple, linear relationship between CO₂ levels and colony population; as the population increases, metabolic CO₂ production rises, but simultaneously, the number of fanning bees also increases, enabling rapid evacuation of the CO₂.

In traditional beekeeping practices, monitoring the health and developmental status of a colony relies on physically opening the hives and visually inspecting individual frames. However, environmental stressors brought about by the modern era, such as climate change, pesticide pressure, and habitat loss, increasingly strain the homeostatic balance of honeybees, turning traditional interventions themselves into a major source of stress for the colonies. Opening a hive instantaneously destroys the optimized gas, humidity, and temperature balance inside, forcing the bees to expend additional energy for days to re-establish this equilibrium [7,10]. This critical issue has led to the emergence of a new-generation agricultural discipline called Precision Apiculture, which utilizes Internet of Things (IoT) based micro-sensor networks over the last decade [1,9]. Advanced sensor technologies enable the continuous, real-time, and high-temporal-resolution monitoring of hive weight, internal and external temperatures, relative humidity, acoustic fanning frequencies, and in-hive gas compositions without opening the hive. Regarding CO₂ measurement in particular, the development of Non-Dispersive Infrared (NDIR) detectors is revolutionary. Unlike traditional electrochemical or metal oxide (MOx) sensors, NDIR technology specifically targets the infrared wavelengths absorbed by CO₂ molecules, rendering it immune to other volatile organic compounds (VOCs) and complex odors within the hive. Next-generation NDIR sensors, such as the Sensirion SCD41, operate on the photoacoustic principle, making them highly miniaturized (easily deployable inside the hive) while achieving high accuracy (± 40 ppm) across a broad measurement range up to 40,000 ppm.

The Anatolian geography possesses an ancient history of beekeeping and is an immense center of biodiversity, harboring approximately 20% of the global honeybee gene pool. Evolving through natural selection over thousands of years in these lands, the Anatolian honeybee (*Apis mellifera anatoliaca*) has developed extraordinary cellular and behavioral adaptation capabilities against extreme climate events, harsh winters, and dry summers. The province of Muğla, located in southwestern Turkey at the heart of the Mediterranean climate zone, hosts the "Muğla Ecotype," one of the most critical representatives of this genetic wealth. The Muğla ecotype is a highly specialized subspecies that produces world-renowned pine honey by collecting the honeydew secreted by the insect *Marchalina hellenica*, which lives in the local Turkish pine (*Pinus brutia*) forests. In comparative studies with other geographical races (e.g., the Italian bee *A. m. ligustica* or the Caucasian bee *A. m. caucasica*), the Muğla ecotype has demonstrated superior performance, particularly regarding tolerance to drought and heat stress, exhibiting a high overwintering success rate of 63.91%, and adapting much more rapidly to local environmental conditions compared to Caucasian or Italian bees. Analyses conducted at the physiological level show that under thermal stress, the Muğla ecotype optimizes Heat Shock Protein 70 (Hsp70) expression to prevent cellular protein

denaturation, thereby maintaining uninterrupted in-hive activities even in summer temperatures exceeding 40 °C. Nevertheless, irregular temperature surges, shortened nectar flow periods, and emerging pathogenic pressures caused by global climate change are testing the homeostatic limits of even this highly resilient ecotype.

A review of the existing academic literature reveals that studies investigating in-hive CO₂ dynamics generally focus on European and North American races in temperate climate zones. Research utilizing high-resolution IoT sensors to examine the in-hive atmosphere management of specific ecotypes adapted to the extreme heat and drought conditions of the Mediterranean basin (such as the Muğla bee) across long-term seasonal transitions (spring, summer, autumn) through multiple variables remains quite limited. How this specific genotype modulates the in-hive microclimate in relation to population dynamics and brood area size represents a significant gap in precision apiculture literature.

The primary objective of this study is to quantitatively monitor the seasonal dynamics of in-hive CO₂, temperature, and humidity profiles in honey bee colonies of the Muğla ecotype (*A. m. anatoliaca*) using next-generation NDIR-based SCD41 sensors during three critical phases of the colony's annual life cycle (April: spring development; July: summer drought and honey flow; October: autumn pre-wintering). By correlating the high-dimensional atmospheric data collected from the hive with concrete biological markers of colony performance ("total hive population" and "number of brood frames"), this study aims to determine whether in-hive gas and microclimate profiles serve as a linear metric directly reflecting colony strength, or whether they constitute a non-linear, multivariate biomarker set jointly determined by seasonal conditions and the genotypic ventilation behaviors of the bees.

2. Materials and Methods

2.1. Research Area, Climatic Conditions, and Biological Material

The study was conducted in the Menteşe district of Muğla province (Muğla Sıtkı Koçman University Kötekli Campus Apiary Station), situated at the intersection of the Aegean and Mediterranean regions in southwestern Turkey. The research site is located at an altitude of approximately 660 meters above sea level. Its topography, characterized by Turkish pine (*Pinus brutia*) forests, rich maquis vegetation, and a flora hosting a wide variety of deadnettle (*Lamiaceae*) species, offers high-quality potential for beekeeping activities. According to the 2024 climate data from the General Directorate of Meteorology (MGM) and the long-term averages for the region, a typical Mediterranean climate (Köppen climate classification: Csa) prevails in the research area [14]. Summers are intensely hot and dry, while winters are mild and highly rainy. The annual average temperature is around 15 °C; however, air temperatures can reach the 35-40 °C range, particularly in July and August, posing acute thermal stress and dehydration risks for the colonies. The data collection windows for the study—April, July, and October—were strategically selected to represent spring population surge, summer drought/main nectar flow, and autumn nectar dearth/pre-winter cluster preparation periods, respectively.

The biological material utilized in this research consisted of the Muğla ecotype of the Anatolian honeybee (*Apis mellifera anatoliaca*), which has integrated into the region's harsh climatic and floristic conditions over thousands of years and is known for its high adaptation to pine honey production, resistance to heat stress, and superior overwintering ability. At the beginning of the project (August), from the large colony population present at the apiary station, 20 healthy colonies were selected based on phenotypic examinations. These colonies exhibited low *Varroa destructor* infestation levels, showed no clinical pathological signs of diseases such as *Nosema* sp. or American Foulbrood (*Paenibacillus*

larvae), and possessed homogeneous physiological characteristics. To minimize statistical deviations arising from genetic variation and queen bee performance, all selected hives were equipped with 2-year-old sister queens produced from the same breeder. By September, final pre-wintering checks were conducted, and all hives were subjected to a strict standardization protocol regarding population strength, brood volume, and food stores to ensure uniformity. In accordance with this equalization protocol, each colony included in the study was housed in standard Langstroth-type wooden hives, and exactly 7 populated frames were established in each hive, consisting of 2 frames of open/capped brood, 4 frames of honey/pollen, and 1 frame of pure honey.

2.2. Sensor Technology and Data Acquisition System (IoT Infrastructure)

A Data Acquisition System (DAQ) equipped with Internet of Things (IoT) based multi-sensor integration, specially designed for continuous and high-precision monitoring of the in-hive atmosphere and microclimate without disturbing the honeybees (non-invasive), was utilized. At the heart of the hardware architecture is the ESP32-S3 microcontroller board, chosen for its advantages of low power consumption and high processing capacity, supporting I²C (Inter-Integrated Circuit) communication protocols that allow for extensive sensor integration. For the measurement of the fundamental in-hive gas and microclimate parameters (Carbon dioxide, Temperature, Relative Humidity), the industry-standard SCD41 miniature sensor module, manufactured by Sensirion AG, was selected [4].

The SCD41 sensor employs a technology based on the innovative photoacoustic sensing principle, which overcomes the size and calibration disadvantages of traditional transmissive NDIR (Non-Dispersive Infrared) sensors. This technology relies on the principle that carbon dioxide molecules entering the measurement cell specifically absorb infrared radiation at a wavelength of 4.26 μm , causing them to expand and generate a periodic acoustic wave (pressure change). A MEMS (Micro-Electro-Mechanical Systems) microphone inside the sensor detects this acoustic wave to calculate the CO₂ concentration. This mechanism allows the SCD41 sensor to be miniaturized to an extremely small size of 10.1 x 10.1 x 6.5 mm, while enabling high-accuracy (± 40 ppm) CO₂ measurements across a very broad range of 400 to 40,000 ppm. Being NDIR-based guarantees that the sensor is immune to fermentation gases or other volatile organic compounds (VOCs) inside the hive, ensuring the detection of only true CO₂ levels. The SCD41 module also simultaneously measures in-hive temperature with an accuracy of ± 1.5 °C and relative humidity with an accuracy of $\pm 9\%$ (within the 0-95% RH range) using sensors housed in the same physical casing.

Physically placing sensors inside the hive necessitates managing the risk of propolization (the bees' behavior of coating foreign objects with propolis and beeswax), which is one of the major problems in precision apiculture research. Propolis can quickly render the device completely non-functional by blocking the sensor's air inlet holes. To overcome this issue, each SCD41 sensor unit was enclosed in specially designed fine-mesh protective wire cages and mounted just below the hive cover, on top of the turbo feeder module. This topological placement aims not only to protect the sensors from direct physical contact by the bees but also to comprehensively measure the ultimate ventilation exhaust profile created at the apex of the hive by the colony's metabolic respiration and active fanning efforts. System power was supplied by high-capacity portable power banks to ensure uninterrupted operation in the field. Data were logged to microSD cards on a per-second basis, tagged with a Real-Time Clock (RTC) integrated into the microcontroller. To calibrate the influence of environmental factors on the in-hive data, an independent reference sensor unit was also installed at the apiary site to record ambient temperature, humidity, and ambient CO₂ levels.

2.3. Data Analysis and Statistical Methods

The statistical and analytical design of the research was structured to quantitatively reveal the interaction between seasonal climatic transitions and colony population size (hive population and number of brood frames) on the in-hive CO₂, temperature, and humidity profiles. The raw data collected from the sensors were first subjected to data cleaning and filtering processes to eliminate microcontroller-based noise, deviations during the initial warm-up times required when sensors are first activated, and momentary electrical misreadings. Anomalies recorded as 0.00 ppm in the hives were masked to be excluded from statistical analyses.

For each of the months of April, July, and October 20-minute high-frequency measurement datasets were selected and analyzed from time windows where the bees' flight traffic, nectar foraging activities, and in-hive brood care metabolism were most intense. During these periods, each hive was also opened to independently observe colony activity, and biological performance metrics were generated by manually recording the "total number of frames with bees" (hive population) and the "number of brood frames" containing developing brood.

Descriptive statistics tables presenting the arithmetic mean, minimum, and maximum values of CO₂ (ppm), temperature (°C), and relative humidity (%) were generated for each month and each hive. To determine the strength and direction of potential mathematical relationships between in-hive atmospheric parameters and colony strength indicators (hive population and brood frames), Pearson correlation analysis was applied between variables. Scatter plots were produced to visualize analysis results and data distributions, and to detect potential non-linear trends. The coefficients (τ) obtained from the correlation analysis were evaluated according to literature norms to determine whether there was a direct linear relationship between the variables. Generative Artificial Intelligence (GenAI) tools were utilized for superficial text editing purposes during the text redaction, grammar correction, and formulation processes of the study; however, no artificial intelligence algorithms were used in the processes of data analysis, generation of statistical results, or interpretation.

3. Results

The data obtained from the system designed to monitor the in-hive microclimate parameters of colonies of the Muğla ecotype were analyzed across three different seasonal periods spanning April, July, and October. Following the completion of filtering and cleaning processes (outlier detection) for all months, the obtained average values were presented in tabular formats, and their relationships with colony strength (hive population and number of brood frames) were tested through correlation analyses.

3.1. Spring Population Development Period Analysis (April)

April represents a dynamic period where colonies fully emerge from the winter cluster, rapidly escalating their brood rearing activities in parallel with the spring nectar and pollen flow, and the population begins to grow exponentially. The cleaned average microclimate and frame population data obtained from 20 hives during this period are detailed in Table 1.

Table 1. Average in-hive microclimate and colony performance values for April.

Hive No	CO ₂ (ppm)	Temperature (°C)	Humidity (%)	Hive population (frames)	Brood frames (frames)
1	587.45	6.20	49.56	6.00	4.14
2	3917.28	35.09	62.20	6.71	4.71
3	2888.47	30.31	57.68	5.29	3.86
4	3368.61	33.57	45.54	8.14	5.86
5	0.00*	33.41	64.73	6.29	3.86
6	11576.68	33.87	63.26	4.71	3.00
7	12579.04	38.28	60.34	9.14	7.86
8	3911.74	35.22	63.13	6.71	4.71
9	0.00*	32.01	74.72	4.71	3.00
10	1806.41	33.19	57.36	8.43	5.57
11	13751.52	39.60	65.47	3.00	1.86
12	9291.36	36.23	74.09	4.57	3.00
13	0.00*	36.03	59.44	4.00	2.14
14	1459.64	15.35	23.71	3.14	2.00
15	6207.48	36.81	75.03	6.29	4.29
16	5390.19	28.45	64.97	7.14	5.14
17	0.00*	35.94	59.06	4.43	2.14
18	5200.29	33.97	70.76	3.00	1.14
19	6819.00	35.61	68.83	5.71	4.00
20	4270.84	38.10	61.64	5.71	4.00

¹ Note: The values appearing as "0.00" in the CO₂ column in the table (e.g., Hive 5, 9, 13, 17) represent filtered readings resulting from momentary sensor resets experienced during the data collection process or outlier removal algorithms, and do not imply that CO₂ was completely depleted inside the hive.

An examination of Table 1 reveals that inter-colony microclimate variation during the spring period is massive. During the 20-minute intense activity windows measured, in-hive CO₂ levels were found to fluctuate between 587.45 ppm (Hive 1), slightly above atmospheric norms, and 13,751.52 ppm (Hive 11), indicating suffocating levels within the hive. Temperature profiles varied between 6.20 °C (a potential measurement reflection of early morning hours) and 39.60 °C, which significantly exceeds the brood optimum (33-36 °C). Humidity levels also spanned a wide range from 23.71% to 75.03%. The most striking finding of this period is the profile exhibited by Hive 11. Although Hive 11 had the highest recorded CO₂ (13,751.52 ppm) and the highest temperature (39.60 °C) values, it possessed a very weak population, with only a 3.00 hive frame count and 1.86 brood frames. In a starkly contrasting scenario, the strongest colony in terms of population, hive 7 (9.14 frame count, 7.86 brood frames), also reached a high CO₂ level (12,579.04 ppm). Furthermore, hive 18, despite having the lowest frame count (3.00) and brood frames (1.14), managed to maintain homeostasis near ideal limits in the brood area with 5200.29 ppm CO₂, 33.97 °C temperature, and 70.76% humidity. These findings demonstrate that population size is not the sole determinant of the in-hive atmosphere.

3.2. Summer Thermal Stress and Honey Flow Period Analysis (July)

July is a period in the Menteşe ecology where extreme ambient temperatures (generally >35 °C) and drought induce thermal stress on the colonies, prompting bees to engage in intense cooling and nectar processing activities.

Table 2. Average in-hive microclimate and colony performance values for July.

Hive No	CO ₂ (ppm)	Temperature (°C)	Humidity (%)	Hive population (frames)	Brood frames (frames)
1	580.26	34.31	60.89	7.00	6.00
2	4959.74	36.51	54.35	8.00	7.00
3	1222.69	37.72	44.00	4.00	3.20
4	618.14	35.84	44.90	8.00	7.00
5	5380.42	36.27	59.88	6.00	5.00
6	6706.17	37.03	52.32	7.00	6.00
7	2269.53	35.39	62.19	7.00	6.00
8	7988.81	37.03	50.63	4.00	3.00
9	818.20	35.40	44.71	7.00	6.00
10	7695.58	34.07	54.65	7.00	6.00
11	1423.70	37.91	46.28	5.00	3.00
12	5496.46	35.65	57.17	7.00	5.00
13	4400.04	35.29	51.89	5.00	4.00
14	1632.86	37.26	69.09	5.00	4.00
15	1792.71	39.51	65.65	7.00	6.00
16	908.34	34.99	53.53	4.00	3.00
17	2753.11	35.12	56.97	8.20	7.20
18	3677.21	35.62	45.62	4.00	3.00
19	1972.81	34.51	47.47	6.00	5.00
20	4073.09	37.11	47.42	6.00	5.00

July results (Table 2) indicate that despite extreme external thermal conditions, colonies managed to maintain their in-hive temperatures more stably and within a narrower band (34.07 °C to 39.51 °C) compared to spring. Due to the summer drought, humidity ratios were compressed into the 44.00% to 69.09% range, while CO₂ concentrations, in contrast to the extreme peaks in April, remained within the boundaries of 580.26 ppm and 7988.81 pp. In terms of population metrics, Hive 17 stands out as the strongest colony (8.20 frame count, 7.20 brood frames), and this hive's CO₂ level was managed at a highly moderate level of 2753.11 ppm. Conversely, in a contrast similar to the situation in April, when comparing Hive 8 and Hive 16, which have the lowest frame count and brood frame averages; Hive 8 possesses the highest measured CO₂ level (7988.81 ppm), whereas Hive 16 has a quite low value (908.34 ppm). This finding proves that weak colonies do not exhibit a consistent trend with one another regarding in-hive gas management.

3.3. Autumn Pre-Wintering Period Analysis (October)

October is a transitional phase in the Muğla ecology where air temperatures retreat towards the thresholds of brood rearing, nectar flow diminishes, and colonies begin preparations for forming the winter cluster by reducing the brood area.

Table 3. Average in-hive microclimate and colony performance values for October.

Hive No	CO ₂ (ppm)	Temperature (°C)	Humidity (%)	Hive population (frames)	Brood frames (frames)
1	5030.00	31.52	55.32	5.00	3.00
2	1717.92	32.33	56.02	7.71	5.43
3	4512.28	28.91	53.55	4.00	3.00

4	548.83	27.22	59.24	7.00	6.00
5	7956.91	30.33	57.96	5.00	4.00
6	3946.89	31.86	58.64	4.29	2.57
7	7324.61	33.28	48.92	7.00	6.00
8	5913.91	30.81	59.30	4.00	3.00
9	3737.15	29.34	60.07	5.29	2.57
10	2761.57	31.32	53.40	6.00	4.00
11	6656.45	28.11	59.89	5.00	3.00
12	4516.72	33.16	68.76	7.00	5.00
13	4977.51	32.20	54.27	5.00	4.00
14	4969.78	33.34	58.69	5.00	4.00
15	5610.81	32.13	55.95	6.00	5.00
16	7853.18	30.43	52.14	4.00	3.00
17	3103.83	35.98	53.76	6.71	5.43
18	6188.66	33.11	53.18	4.00	3.00
19	7357.10	32.62	58.56	6.00	5.00
20	8401.04	33.23	67.23	6.00	5.00

The findings obtained during the October period (Table 3) indicate that general temperature averages retreated to the 27.22 °C to 35.98 °C band. While humidity values were observed between 48.92% and 68.76%, it was determined that in-hive CO₂ averages ranged from 548.83 to 8401.04 ppm. As a characteristic reflection of autumn, despite the drop in external temperatures, CO₂ levels were recorded to remain high in units such as Hive 20 (8401.04 ppm), Hive 5 (7956.91 ppm), and Hive 16 (7853.18 ppm). During this period, the highest hive frame count average was observed in Hive 2 (7.71), and the highest brood frame average was in Hive 7 (6.00). While Hive 7 had a high CO₂ average (7324.61 ppm) in parallel with its high population, it is noteworthy that in Hive 4, which had similar brood activity, the CO₂ level dropped to the lowest measured value of 548.83 ppm.

3.4. Statistical Relationships and Correlation Among Variables

One of the most critical statistical findings of the research emerged from the Pearson correlation analysis conducted between the frame data representing the colony's physical size (total number of bees) and metabolic load (brood area), and the microclimate parameters (CO₂, temperature, and humidity) measured by the sensors.

The average CO₂ values in the hives ranged from 548.83 to 8401.04, average temperatures from 27.22 to 35.98, average humidity from 48.92 to 68.76, average hive population from 4 to 7.71, and finally, average brood frames from 2.57 to 6. Figure 1 shows the dot plot and correlation between hive population and other variables when data for all months are combined, while Figure 2 shows the dot plot and correlation between brood frames and other variables.

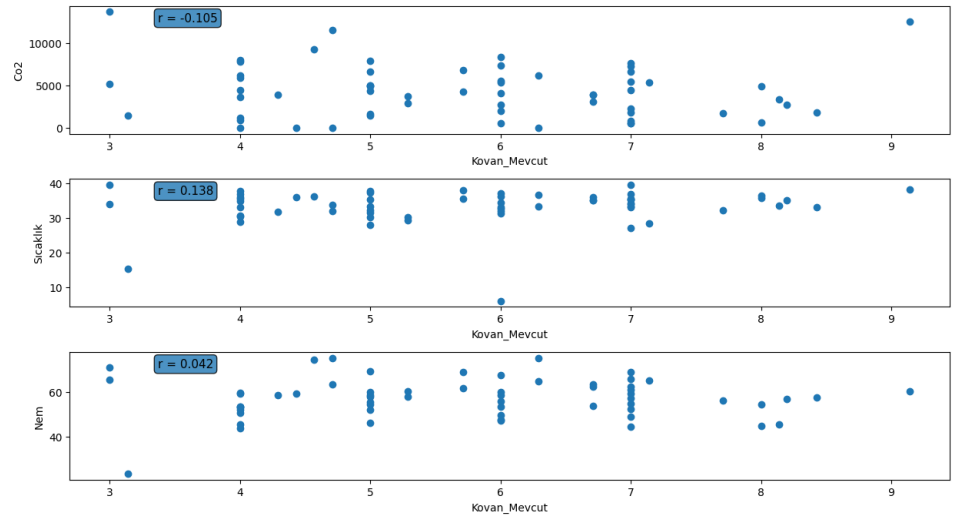


Figure 1. Dot plot between hive size and other variables.

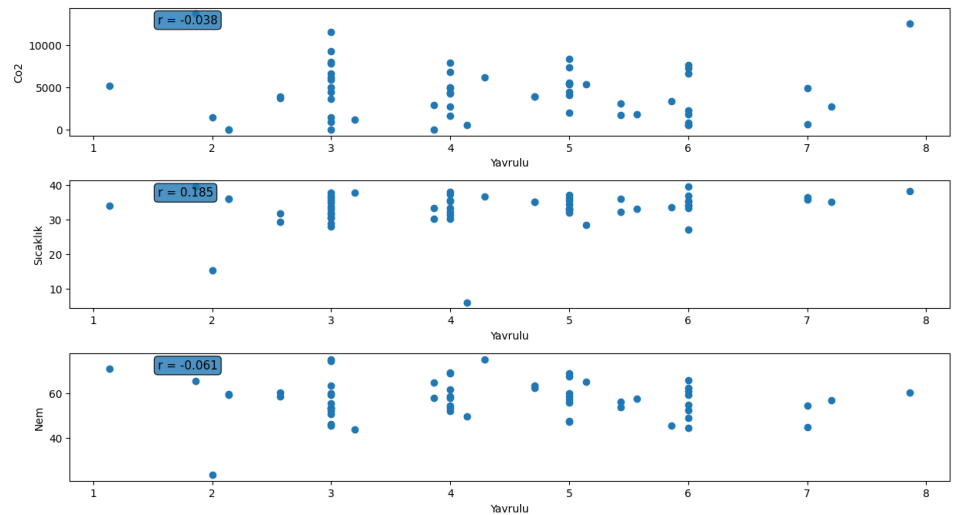


Figure 2. Dot plot between the offspring frame and other variables.

As a result of scatter plots and correlation tests performed on the datasets created by combining the data from April, July, and October, not statistically significant, strong, or moderate linear relationship could be detected between the hive population or brood frame count and the CO₂, temperature, or humidity averages. The statistical coefficient indicates that the relationship between the variables is at the level of $|\tau| \leq 0.19$ (extremely weak or coincidental). This result explicitly rejects the simple deterministic expectation that as the number of bees or the brood area in the colony increases, the amount of CO₂, in-hive temperature, or humidity will increase in a linear fashion.

4. Discussion

The regulation of the in-hive atmosphere and thermodynamic structure is one of the most sophisticated collective engineering achievements that honeybees have acquired through their social evolutionary processes. This homeostatic balance is not merely a passive thermal reaction to external climate conditions; it is an active feedback loop recalibrated second by second according to the cellular respiration needs of the colony, the

developmental tolerances of the brood, and overwintering strategies [11]. This research, conducted on the Muğla ecotype (*Apis mellifera anatoliaca*) across three different seasons using next-generation NDIR-based sensor networks, questions the traditional linear expectations between colony population and in-hive microclimate profiles (especially CO₂) on biological and physical grounds.

4.1. Behavioral and Biophysical Foundations of the Non-Linear Relationship Between Population and CO₂

Classical biological models and some early precision apiculture studies posit that as the number of individuals and the actively metabolizing brood area in the colony increase, in-hive CO₂ accumulation will increase as a direct function of cellular respiration, and this change will appear as a clear correlation in sensor data. For instance, Bencsik et al. (2023) established a relationship between daily changes in hive mass (flight of forager bees) and CO₂ variations, suggesting that colony population could be estimated via CO₂ [1]. However, the analyses conducted in our study definitively proved that hive population and the number of brood frames are not univariate indicators capable of solely explaining the CO₂, temperature, or humidity profile, yielding a statistically insignificant correlation coefficient such as $|\tau| \leq 0.19$.

This paradoxical outcome can be explained by a complex behavioral mechanism that may be conceptualized as "Active Homeostatic Masking." It is inevitable biophysically that the total amount of CO₂ and heat produced increases when the hive population and brood area grow. However, this growth simultaneously expands logarithmically the labor pool of "fanner" worker bees operating at the hive entrance and in inner layers, which constitutes the colony's ventilation capacity. Honeybee colonies operate on the principle of a "task threshold model"; worker bees with different genetic variations possess different response thresholds to microscopic increases in temperature and CO₂ levels. When the CO₂ concentration exceeds a certain tolerance limit, fanning bees engage in fanning behavior by operating their flight muscles without initiating flight, at a low and specific frequency (approximately 174 Hz) that differs from the normal flight frequency (approximately 227 Hz). This synchronized wing-beating action creates a mechanical vacuum effect that rapidly exhausts intense CO₂ accumulation and hot air outside. Consequently, even in colonies like Hive 7, where the population reaches massive proportions, the increased production capacity is instantly neutralized by the increased exhaust capacity; this compensation mechanism masks and eradicates the linear correlation in the sensor data.

4.2. Anomalies and Ventilation Vulnerabilities in Spring Development

When the April data are examined, how this theoretical foundation manifests in the field becomes much clearer. In our dataset, hive 11 is an extremely weak colony with only a 3.00 frame count and 1.86 brood frames, despite having the highest measured CO₂ (13,751.52 ppm) and highest temperature (39.60 °C) values. This situation, which appears to be an anomaly at first glance, is actually a classic indicator of "ventilation failure" in weak colonies. When a colony is weak, the bees focus their available energy and limited population solely on heating and feeding a very small brood area in the center. In this confined space, because there are not enough "fanner" bees to expel the carbon dioxide emitted from the bees' bodies and larval respiration [15], the gas inventory within the closed volume rapidly reaches dangerous levels. CO₂ exceeding the 13,000 ppm level is a toxic threshold that reduces oxygen availability, slowing brood development and even causing temporary damage (narcosis) to the neuromotor functions of the bees. On the other hand, there are some hive records (Hive 5, Hive 9, etc.) within the same month where CO₂ averages were calculated as "0.00" following data cleaning processes. This

situation does not imply that the bees completely abandoned the hive; rather, it is a statistical data loss resulting from the filtering algorithms (outlier removal) eliminating instantaneous errors that fall outside the hardware reading range of the SCD41 sensor. The placement of the sensors in the upper part of the hive (under the cover) causes the readings to reflect the diffusion in the exhaust profile where rising gases hit the hive cover, rather than the micro-balance at the brood center. This topographic placement choice is another physical factor creating weak correlations; since CO₂ is a heavier gas than air, it normally sinks to the bottom, but the bees' wing circulation forces this gas to the top of the hive, allowing it to reach the sensor.

4.3. Summer Thermal Stress, Environmental Adaptation, and Resilience of the Muğla Ecotype

The July data perfectly reflect the evolutionary endowment of the Muğla ecotype (*A. m. anatoliaca*) and the resilience it has developed against harsh Mediterranean summers. During this period, when the ambient temperature in the research area reached the 35-40 °C band and severe drought occurred, the colonies managed to keep their in-hive temperatures within a relatively narrow survival window of 34.07 °C to 39.51 °C.

Thermoregulation is achieved through the bees carrying water, placing water droplets on the combs, and evaporating this water by fanning their wings (evaporative cooling) when the temperature needs to be lowered [6]. Subspecies adapted to regions with long, hot, and dry summers, like the Muğla ecotype, genetically manage water loss better than other races (e.g., Italian or Caucasian bees) and optimize Heat Shock Protein 70 (Hsp70) production at the cellular level during thermal stress to prevent protein denaturation and cell deaths. Physiological research has reported that, thanks to the high Hsp70 expression in queens and workers of the Muğla ecotype, survival and brood rearing rates remain at top levels even under shock temperatures of 40 °C. In our study, the ability of strong colonies like Hive 17 (8.20 frame count) to keep CO₂ levels at an ideal and fresh level of 2753.11 ppm in July is a direct proof of the biophysical and behavioral cooling/ventilation efficiency possessed by the Muğla bee.

However, as indicated in current research conducted by Kutby et al. (2024) on Langstroth and Warré type hive designs, the spacious and synthetic structure of modern Langstroth hives makes it difficult for bees to insulate the hive akin to natural log nests, which increases daily humidity and temperature fluctuations, thereby imposing an extra biological cost on colony homeostasis [2,12]. In the standard Langstroth hives used in our study, the fact that Hive 8's CO₂ level reached one of the highest measured values (7988.81 ppm) in July despite a low population (4.00) demonstrates how weak colonies fail to control the hive volume, leading to a breakdown in their evaporative cooling and gas exhaust mechanisms (ventilation breakdown). Because weak colonies cannot find enough worker bees to carry and evaporate water, they cannot lower the internal heat, and the rise in temperature accelerates the cellular respiratory rate, triggering CO₂ production; this creates a vicious cycle of suffocation and overheating.

4.4. Autumn Transition, Hypoxia-Controlled Winter Metabolism, and the Future of Sensor Data

The findings obtained in October provide significant physiological clues regarding the survival strategies of colonies during the winter months. With the downward trend in external temperatures in October, it was observed that CO₂ values in hives such as Hive 5, Hive 16, and Hive 20 approached the 8000-ppm boundary. This accumulation (7324.61 ppm) was also clearly detected in the heavily populated Hive 7. These findings indicate that the honeybee colonies are not experiencing a malfunction or vulnerability; on the contrary, they are transitioning into a biologically programmed regime of "hypoxia" (low

oxygen) and "hypercapnia" (high carbon dioxide) specific to the pre-wintering preparation period.

According to the "hypoxia-controlled winter metabolism" theory introduced to the literature by Van Nerum and Buelens (1997) [5] and confirmed in winter monitoring studies by Newton et al. (2024) [3]; when honeybees form the winter cluster, they deliberately block the inflow of fresh and cold air from the outside to prevent heat loss. While the oxygen level drops to as low as 15% in the center of the hive, the CO₂ concentration rapidly rises. This CO₂ accumulation creates a mild narcotic effect on the bees' nervous systems, lowering their metabolic rates (MR). The slowing of metabolism enables the bees, which will remain inactive inside the hive for months, to minimize their honey consumption. Therefore, the high CO₂ rates recorded by our sensors in October should actually be interpreted as an indication that the colonies are making successful physiological and behavioral preparations for the cold seasons. Conversely, an unexpected drop in the CO₂ level to atmospheric norms (around 400 ppm) during the winter period is considered a definitive failure indicator that the cluster has broken or the colony has died, as seen in the study by Newton et al. (2024) [3].

The results of this study confirm the superior performance of NDIR photoacoustic sensors, such as the Sensirion SCD41, in monitoring the in-hive environment, while also emphasizing the need for new analytical perspectives in the use of such IoT devices. Although the wire meshes (mesh cages) used to prevent the sensors from being coated with propolis offer a physical solution, reading the data in a unidimensional manner can lead to incorrect interventions. For instance, a beekeeper looking purely at sensor data might interpret a CO₂ level reaching 8000 ppm in summer as a sign of an excellent population; whereas our findings have proven that this hive could be a weak colony that has lost its ventilation capability. Therefore, in-hive atmospheric data must be analyzed in conjunction with other IoT sensor data—such as temperature, humidity, in-hive vibration (acoustic fanning frequency), and seasonal temperature normals—and integrated into multivariate decision support systems backed by artificial intelligence or machine learning models.

5. Conclusions

This research has detailed the multi-layered relationship between the in-hive carbon dioxide (CO₂), temperature, and humidity dynamics and the physiological status of the colony through high-resolution sensor monitoring studies conducted on the Muğla ecotype (*Apis mellifera anatoliaca*), which is adapted to Mediterranean flora and climate. The most striking and transformative result of the study is that it statistically proved that the assumed simple and linear relationship between the total hive population or brood area size and the atmospheric gas profiles measured by sensors does not exist in the field. Honeybee colonies are extraordinary masters of thermodynamic equilibrium, dampening increased metabolic CO₂ production and heat with an equally increased workforce of "fanning bees" (Active Homeostatic Masking), thereby invalidating straightforward correlations in sensor outputs [16].

While the extreme CO₂ fluctuations observed in spring and gas crises in weak hives are signs of insufficient ventilation capacity; the maintenance of internal heat despite extreme ambient temperatures in the summer months reflects the Muğla ecotype's Hsp70-mediated heat tolerance and intense evaporative cooling efforts. The high CO₂ profiles recorded during the autumn transition are not a sign of deterioration, but rather the biological proof of the shift to "hypoxia-controlled winter metabolism," energy conservation, and winter cluster insulation.

These results obtained for Precision Apiculture applications serve as a major warning. Data flowing from IoT sensors should not be used as univariate population

estimation indicators in beekeeping. In-hive health status must be deciphered through complex bio-informatics algorithms that blend temperature, humidity, mass, and acoustic vibration data, considering the seasonal context, local adaptations of honeybee genotypes, and circadian ventilation rhythms. The resilient homeostatic profile exhibited by the Muğla ecotype in this research provides an invaluable genetic and behavioral reference model for developing adaptation strategies in the beekeeping sector against global climate change and increasingly frequent extreme heat events.

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Abbreviations

The following abbreviations are used in this manuscript:

CO ₂	Carbon dioxide
NDIR	Non-Dispersive Infrared gas sensor technology
IoT	Internet of Things
Hsp70	Heat Shock Protein 70
RTC	Real-Time Clock
I ² C	Inter-Integrated Circuit Protocol
ppm	Parts Per Million
DAQ	Data Acquisition
Csa	Mediterranean Climate (Köppen climate classification coding)
MEMS	Micro-Electro-Mechanical Systems

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Increasing The Use of Bumble Bee (*Bombus terrestris*) In Greenhouse Cultivation in DOKAP Provinces

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Highlights

What are the main findings?

Significant improvements ($P < 0.05$) with bumble bee pollination:

- F ruit length increased (60.55 mm vs 46.74 mm)
- Fruit width increased (75.03 mm vs 58.25 mm)
- Color score improved (4.16 vs 3.25)
- Weight per fruit nearly doubled (227.61 g vs 117.11 g)

No significant differences:

- pH and °Brix

What is the implication of the main finding?

- Bumble bees improved physical fruit quality traits, but not chemical quality parameters.
- Results were consistent across different climatic conditions.

Abstract

In greenhouse cultivation, the inability to ensure adequate and high-quality pollination leads to problems such as reduced fruit set, fruit deformities, and yield losses. Under greenhouse conditions, particularly in tomato production, limited air movement and low temperatures substantially restrict natural pollination in tomato plants. For this reason, the use of biological pollinators in protected agriculture has gained increasing importance in recent years.

In Türkiye, the use of *Bombus* bees for pollination has become widespread in the Mediterranean and Aegean Regions, where greenhouse cultivation is intensive. The primary aim of this study was to promote the use of *Bombus terrestris* in other regions and to determine its effects. Within this scope, the study was conducted by the

Apiculture Research Institute, affiliated with the General Directorate of Agricultural Research and Policies, with support from the Ministry of Industry and Technology of the Republic of Türkiye and the Eastern Black Sea Project Regional Development Administration (DOKAP). The study was carried out in the provinces of Artvin, Bayburt, Gümüşhane, Trabzon, Giresun, Ordu, Samsun, Tokat, Amasya, and Çorum, where the use of bumble bees is limited. Field applications were implemented in a total of 47 tomato-producing enterprises, and 100 bumble bee colonies were used. In the study, bee-free plots were established by isolating the areas in a way that prevented bee entry, and the growth status of tomato seedlings under both environmental conditions was recorded. For harvested tomatoes, fruit length and width, color, weight per fruit, pH, and °Brix values were measured. The results showed that, in nearly all provinces, there were statistically significant differences in length, width, color, and weight per fruit in the with bees plots ($P < 0.05$). In contrast, no significant differences were detected in pH and °Brix values ($P > 0.05$). Overall, the findings indicated that the use of bumble bees improved certain quality traits in tomatoes, while it did not produce a marked change in some chemical characteristics.

Keywords: *Bombus terrestris*; pollination; tomato; greenhouse; fruit

1. Introduction

Greenhouse cultivation has become an important component of modern agriculture because it enables production that is partially independent of climatic conditions, allows production to be distributed throughout the year, and provides higher yields per unit area. In Türkiye, protected agriculture has made notable progress in recent years, particularly in vegetable production, and its areas of use have increased substantially. Tomato holds a significant share within protected vegetable production due to its wide range of uses, both for fresh consumption and as an industrial raw material. As an important export commodity, tomato ranks first among protected-cultivation crops in Türkiye in terms of cultivated area (Anonim, 2025).

Although tomato is a self-pollinating species, under greenhouse conditions this process often does not occur at a sufficient level. In greenhouses, reduced natural vibration of flowers due to limited air circulation, together with unfavorable temperature–humidity conditions, hinders the transfer of pollen onto the stigma. This can lead to decreased fruit set, fruit deformities, and quality losses (Gürel et al., 1999).

In the past, mechanical vibration devices and plant growth regulators were used to overcome these undesirable outcomes. However, these approaches are not considered sustainable solutions due to factors such as high labor costs and practical difficulties in implementation. In addition, increasing consumer sensitivity regarding uncontrolled chemical use has brought environmentally friendly alternatives to the forefront (Gösterit, 2016).

Bumble bees (*Bombus* spp.), particularly *Bombus terrestris* colonies, are widely used as biological pollinators in greenhouse cultivation. Through their buzz pollination behavior and regular flower visits, these bees provide effective pollination in tomato flowers and can remain active even at low temperatures (Velthuis & van Doorn, 2006;

Spangler & Moffett, 1977). These characteristics have made bumble bees an ideal pollinator for greenhouse tomato production (Gürel & Gösterit, 2007).

The DOKAP region (Artvin, Bayburt, Gümüşhane, Trabzon, Giresun, Ordu, Samsun, Tokat, Amasya, and Çorum) does not present a homogeneous structure in terms of greenhouse cultivation due to its climatic conditions and topographical characteristics. In particular, in inland provinces or high altitude areas such as Tokat, Amasya, and Çorum, low greenhouse temperatures make pollination problems more pronounced and limit greenhouse cultivation to small locations that benefit from microclimatic effects. In this context, this project supported by DOKAP contributed to expanding the use of bumble bees in protected tomato production in the region and to raising producers' awareness about addressing their pollination needs through biological methods.

In this study, in addition to the scientific data obtained through field applications conducted in the DOKAP provinces, the effects of using *Bombus terrestris* colonies on tomato growth characteristics were determined, and the resulting findings were aimed to be evaluated in terms of regional production.

2. Materials and Methods

Production and Preparation of Bumble Bee Colonies

The founder queens of the *Bombus terrestris* colonies used in the study were reared under controlled conditions in an in vitro environment, and a standard production protocol was applied until they reached an optimum (marketable) pollination level (Gösterit & Gürel, 2016). The colonies were fed ad libitum with 50 °Brix sugar syrup and freshly frozen pollen. During feeding, no restrictions that could negatively affect colony development were imposed, and all colonies were maintained under the same environmental and feeding conditions (Gürel et al., 2012).

Study Area and Field Applications

Within the scope of the study, a total of 47 agricultural enterprises engaged in greenhouse tomato production were identified in the provinces of Artvin, Bayburt, Gümüşhane, Trabzon, Giresun, Ordu, Samsun, Tokat, Amasya, and Çorum, and a total of 100 bumble bee colonies were used. This study was conducted under the coordination of the Apiculture Research Institute (Ordu, Türkiye), affiliated with the General Directorate of Agricultural Research and Policies (TAGEM), and implemented through field applications in participating enterprises across the DOKAP provinces. The distribution of bumble bee colonies across provinces was calculated as a weighted allocation based on the number of enterprises. To reduce losses of pollinating bees and improve performance, colonies were fixed in elevated, easily visible locations (Doorn, 2006). Colony placement was carried out at the onset of flowering in tomato plants. In each enterprise, two separate plots were established: one with bumble bees and one without. In the bee-free plot, bee-exclusion nets were installed to prevent *Bombus* bees from accessing the tomato seedlings. The nets were arranged solely to block bee entry, without altering environmental factors such as temperature or sunlight inside the plot. Practices including irrigation, fertilization, and

pruning (sucker removal) were conducted in the same manner in both with bees and bee-free plots. Seedling growth was monitored at regular intervals, and tomatoes harvested at the end of the first flowering period were analyzed on the same day.

Traits Evaluated

In the study, the following tomato traits were evaluated: fruit length (mm), fruit width (mm), color (1–5), weight per fruit (g), pH, and °Brix (%).

Statistical Analysis

Fruit quality parameters obtained from plots with bumblebee pollination (“With bees”) and plots where bee access was prevented (“Without bees”) were compared both at the provincial level and across all provinces combined. Data for each variable were expressed as mean \pm standard error (SE). Differences between the two independent groups were evaluated using an independent samples t-test. Statistical significance was determined at $P < 0.05$. In the tables, means followed by different letters (a, b) indicate statistically significant differences, whereas means sharing the same letter do not differ significantly.

3. Results

The findings obtained from the study were evaluated both on a provincial basis, and across all provinces overall.

According to the data obtained from with and without bees plots in Amasya, statistically significant differences were found for all traits except pH and °Brix ($P > 0.05$) ($P < 0.05$, Table 1).

Table 1. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Amasya province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	P<0,05	30	62,60	$\pm 1,429$
	Without bees		37	47,35	$\pm 1,345$
Fruit Width	With bees	P<0,05	30	76,76	$\pm 1,539$
	Without bees		37	57,73	$\pm 1,663$
Color	With bees	P<0,05	30	4,16	$\pm 0,069$
	Without bees		37	3,13	$\pm 0,150$
Weight (per fruit)	With bees	P<0,05	3	220,31	$\pm 31,092$
	Without bees		3	110,41	$\pm 13,608$
pH	With bees	P>0,05	3	4,31	$\pm 0,081$
	Without bees		3	4,16	$\pm 0,103$
Brix	With bees	P>0,05	3	4,64	$\pm 0,598$
	Without bees		3	4,53	$\pm 0,368$

For the same trait, means indicated with different lowercase letters differ significantly ($P < 0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P > 0.05$).

In the findings for Çorum province, a statistically significant difference between the with and without bees groups was observed only for fruit length, fruit width, color, and weight per fruit ($P < 0.05$, Table 2).

Table 2. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Çorum province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	$P < 0,05$	37	62,38	$\pm 0,952$
	Without bees		46	48,31	$\pm 1,398$
Fruit Width	With bees	$P < 0,05$	37	78,46	$\pm 1,191$
	Without bees		46	58,99	$\pm 1,880$
Color	With bees	$P < 0,05$	37	4,29	$\pm 0,076$
	Without bees		46	3,60	$\pm 0,129$
Weight (per fruit)	With bees	$P < 0,05$	5	257,43	$\pm 28,171$
	Without bees		5	125,04	$\pm 21,893$
pH	With bees	$P > 0,05$	5	4,36	$\pm 0,052$
	Without bees		5	4,33	$\pm 0,064$
Brix	With bees	$P > 0,05$	5	4,25	$\pm 0,264$
	Without bees		5	4,17	$\pm 0,197$

For the same trait, means indicated with different lowercase letters differ significantly ($P < 0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P > 0.05$).

In the findings for Tokat province, unlike many other provinces, a significant difference between the means was observed for pH ($P < 0.05$). Considering all traits, the differences were significant for all characteristics except °Brix ($P < 0.05$, Table 3).

Table 3. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Tokat province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	$P < 0,05$	73	62,73	$\pm 0,597$
	Without bees		88	45,91	$\pm 1,007$
Fruit Width	With bees	$P < 0,05$	73	74,89	$\pm 0,738$
	Without bees		88	57,71	$\pm 1,211$
Color	With bees	$P < 0,05$	73	4,32	$\pm 0,058$
	Without bees		88	3,62	$\pm 0,096$
Weight (per fruit)	With bees	$P < 0,05$	8	216,33	$\pm 5,659$
	Without bees		8	108,04	$\pm 10,031$
pH	With bees	$P < 0,05$	8	4,66	$\pm 0,091$
	Without bees		8	4,361	$\pm 0,065$
Brix	With bees	$P > 0,05$	8	4,308	$\pm 0,119$
	Without bees		8	4,423	$\pm 0,143$

For the same trait, means indicated with different lowercase letters differ significantly ($P < 0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P > 0.05$).

According to the findings for Samsun province, a statistically significant difference was found only for fruit length, fruit width, color, and weight per fruit ($P < 0.05$, Table 4).

Table 4. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Samsun province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	$P < 0,05$	31	67,30	$\pm 1,766$
	Without bees		45	50,23	$\pm 1,685$
Fruit Width	With bees	$P < 0,05$	31	79,23	$\pm 1,952$
	Without bees		45	59,19	$\pm 1,835$
Color	With bees	$P < 0,05$	31	4,22	$\pm 0,100$
	Without bees		45	3,44	$\pm 0,160$
Weight (per fruit)	With bees	$P < 0,05$	6	265,38	$\pm 27,308$
	Without bees		6	123,54	$\pm 17,202$
pH	With bees	$P > 0,05$	6	4,28	$\pm 0,062$
	Without bees		6	4,33	$\pm 0,057$
Brix	With bees	$P > 0,05$	6	4,70	$\pm 0,256$
	Without bees		6	4,62	$\pm 0,261$

For the same trait, means indicated with different lowercase letters differ significantly ($P < 0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P > 0.05$).

In the studies conducted in Ordu province, statistically significant differences between the groups were identified in terms of fruit length, fruit width, color, and weight per fruit ($P < 0.05$). No differences were found for the other traits ($^{\circ}$ Brix and pH) ($P > 0.05$, Table 5).

Table 5. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Ordu province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	$P < 0,05$	45	58,33	$\pm 1,282$
	Without bees		35	48,51	$\pm 1,279$
Fruit Width	With bees	$P < 0,05$	45	74,85	$\pm 1,774$
	Without bees		35	61,09	$\pm 1,927$
Color	With bees	$P < 0,05$	45	4,60	$\pm 0,086$
	Without bees		35	3,74	$\pm 0,243$
Weight (per fruit)	With bees	$P < 0,05$	7	230,54	$\pm 26,798$
	Without bees		7	129,88	$\pm 17,774$
pH	With bees	$P > 0,05$	7	4,40	$\pm 0,173$
	Without bees		7	4,24	$\pm 0,041$
Brix	With bees	$P > 0,05$	7	4,79	$\pm 0,150$
	Without bees		7	4,70	$\pm 0,278$

For the same trait, means indicated with different lowercase letters differ significantly ($P < 0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P>0.05$).

The findings obtained from comparing the mean values of the experimental groups in Giresun province are consistent with those for Ordu. Among the traits evaluated, no significant differences were observed only for pH and °Brix ($P>0.05$, Table 6).

Table 6. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Giresun province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	P<0,05	18	59,55	± 1,779
	Without bees		15	44,38	± 3,206
Fruit Width	With bees	P<0,05	18	79,77	± 2,542
	Without bees		15	55,61	± 3,296
Color	With bees	P<0,05	18	3,72	± 0,157
	Without bees		15	2,33	± 0,410
Weight (per fruit)	With bees	P<0,05	2	242,70	± 63,424
	Without bees		2	103,69	± 16,721
pH	With bees	P>0,05	2	4,12	± 0,045
	Without bees		2	4,26	± 0,060
Brix	With bees	P>0,05	2	4,04	± 0,325
	Without bees		2	4,11	± 0,160

For the same trait, means indicated with different lowercase letters differ significantly ($P<0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P>0.05$).

Similarly, in the findings for Trabzon province, consistent with many other provinces, a statistically significant difference between the with and without bees groups was found only for fruit length, fruit width, color, and weight per fruit ($P<0.05$, Table 7).

Table 7. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Trabzon province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	P<0,05	57	60,02	± 0,980
	Without bees		44	47,28	± 1,442
Fruit Width	With bees	P<0,05	57	70,38	± 1,575
	Without bees		44	57,05	± 1,645
Color	With bees	P<0,05	57	4,14	± 0,088
	Without bees		44	2,86	± 0,185
Weight (per fruit)	With bees	P<0,05	7	212,20	± 21,036
	Without bees		7	113,56	± 14,071
pH	With bees	P>0,05	7	4,28	± 0,097
	Without bees		7	4,24	± 0,055
	With bees	P>0,05	7	5,12	± 0,202

Brix	Without bees	7	4,91	± 0,222
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For the same trait, means indicated with different lowercase letters differ significantly ($P < 0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P > 0.05$).

Bayburt and Gümüşhane provinces, where a harsh continental climate prevails, differed from the other provinces with respect to the findings for the “weight per fruit” trait. In both provinces, no significant differences were observed not only for pH and °Brix but also for weight per fruit ($P > 0.05$, Tables 8 and 9). Because greenhouse cultivation is not widespread in Bayburt and Gümüşhane, the number of enterprises included in the study was limited. It was noted that this limitation may also have influenced the analysis results.

Table 8. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Bayburt province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	P<0,05	16	49,16	± 1,385
	Without bees		13	40,91	± 2,371
Fruit Width	With bees	P<0,05	16	64,35	± 2,925
	Without bees		13	47,69	± 3,038
Color	With bees	P<0,05	16	3,12	± 0,426
	Without bees		13	1,46	± 0,243
Weight (per fruit)	With bees	P>0,05	2	130,93	± 10,337
	Without bees		2	85,48	± 40,340
pH	With bees	P>0,05	2	4,27	± 0,120
	Without bees		2	4,37	± 0,310
Brix	With bees	P>0,05	2	4,96	± 0,085
	Without bees		2	4,60	± 0,205

For the same trait, means indicated with different lowercase letters differ significantly ($P < 0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P > 0.05$).

Table 9. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Gümüşhane province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	P<0,05	27	52,20	± 1,678
	Without bees		29	44,51	± 1,457
Fruit Width	With bees	P<0,05	27	71,27	± 2,377
	Without bees		29	66,66	± 2,651
Color	With bees	P<0,05	27	3,33	± 0,324
	Without bees		29	2,48	± 0,296
Weight (per fruit)	With bees	P>0,05	4	173,62	± 12,902
	Without bees		4	146,81	± 22,781

pH	With bees	P>0,05	4	4,17	± 0,075
	Without bees		4	4,18	± 0,085
Brix	With bees	P>0,05	4	4,68	± 0,199
	Without bees		4	4,24	± 0,240

For the same trait, means indicated with different lowercase letters differ significantly ($P<0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P>0.05$).

Based on the findings obtained by installing bumble bee colonies in enterprises clustered in specific areas within the Yusufeli and Ardanuç districts of Artvin province, restricted to enterprises that did not practice mixed cropping, a statistically significant difference between the groups was found for fruit length, fruit width, color, and weight per fruit ($P<0.05$, Table 10). In contrast, no statistically significant differences were observed for pH and °Brix ($P>0.05$, Table 10).

Table 10. Effect of *Bombus terrestris* on greenhouse tomato growth traits in Artvin province

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	P<0,05	24	62,94	± 2,054
	Without bees		24	42,88	± 1,785
Fruit Width	With bees	P<0,05	24	81,83	± 2,270
	Without bees		24	53,09	± 2,148
Color	With bees	P<0,05	24	4,58	± 0,102
	Without bees		24	3,50	± 0,340
Weight (per fruit)	With bees	P<0,05	3	295,33	± 45,296
	Without bees		3	90,92	± 9,181
pH	With bees	P>0,05	3	4,56	± 0,360
	Without bees		3	4,22	± 0,026
Brix	With bees	P>0,05	3	5,73	± 0,420
	Without bees		3	5,82	± 0,508

For the same trait, means indicated with different lowercase letters differ significantly ($P<0.05$).

For the same trait, means indicated with the same lowercase letter do not differ significantly ($P>0.05$).

In the analyses in which all provinces were considered together for the evaluated traits, findings consistent with the overall trend were obtained. In the overall assessment, a statistically significant difference between the with and without bees groups was found only for fruit length, fruit width, color, and weight per fruit ($P<0.05$, Table 11).

Table 11. Effect of *Bombus terrestris* on greenhouse tomato growth traits across all provinces

Traits	With bees/Without bees	P	N	Means	SE
Fruit Length	With bees	P<0,05	358	60,55	± 0,452
	Without bees		376	46,74	± 0,492

Fruit Width	With bees	P<0,05	358	75,03	± 0,569
	Without bees		376	58,25	± 0,625
Color	With bees	P<0,05	358	4,16	± 0,045
	Without bees		376	3,25	± 0,065
Weight (per fruit)	With bees	P<0,05	47	227,61	± 9,064
	Without bees		47	117,11	± 5,603
pH	With bees	P>0,05	47	4,38	± 0,045
	Without bees		47	4,28	± 0,023
Brix	With bees	P>0,05	47	4,69	± 0,091
	Without bees		47	4,60	± 0,095

For the same trait, means indicated with different lowercase letters differ significantly (P<0.05).

For the same trait, means indicated with the same lowercase letter do not differ significantly (P>0.05).

4. Discussion and Conclusion

The findings of the study indicate that the use of bumble bee colonies positively affects crop development in greenhouse tomato production. The increases observed in fruit length, width, and weight per fruit are considered to result from bumble bees' ability to perform buzz pollination, their regular flower visits, and their capacity to remain active at low temperatures, as also reported by Velthuis and van Doorn (2006) and Gürel and Gösterit (2017). The consistency of results obtained from provinces with differing climatic conditions suggests that bumble bees have a broad environmental tolerance (Gösterit, 2016).

It was determined that, in the regions included in the study, the extent of greenhouse cultivation areas remained low, except in Amasya province, and that the awareness level of enterprise owners was extremely limited. It was concluded that the primary reason Amasya stands out among protected-cultivation growers is that the vast majority of producers consider greenhouse farming as their main source of livelihood. To reduce this disparity, it is necessary to increase farmers' awareness levels, alongside factors such as investment and cooperative development, as observed in the Amasya example.

Another notable issue identified in the study was that, in Samsun province, the physical conditions of greenhouses and the overall level of awareness were highly inadequate, except for a few enterprises engaged in strawberry production. This situation is considered to stem not so much from financial constraints as from the fact that a substantial proportion of farmers operating under difficult conditions view greenhouse cultivation as a secondary activity. Considering that Samsun has the highest population among the provinces included in the study and factors such as market potential and relatively earlier soil warming, it was concluded that Samsun's potential for greenhouse tomato production remains far below its capacity.

The development of tomato production, one of the major components of greenhouse cultivation, which ranks among the priority sectors for development, also in regions beyond the Mediterranean and Aegean is important for price stability. Through this study, bumble bee colonies, which are regarded as essential and are used extensively in nearly all greenhouses producing tomatoes in the Mediterranean and Aegean Regions, were introduced to the target audience, enabling them to observe the added value these colonies

provide in pollination directly on their own products. It is considered that the yield increase observed in the products of the selected producers included in the study being recognized by other producers, or by entrepreneurs with the potential to become producers, has made a significant contribution to the wider adoption of bumble bee use, which is the project's primary objective.

Within this scope, it is recommended to promote the use of bumble bees in greenhouse cultivation across the region, to organize province-based practical training programs, and to support the development of high-quality greenhouse infrastructure.

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Stress Factors in Honeybee Colonies and Prevention Possibilities

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Highlights

What are the main findings?

- Colony stress in honeybees primarily arises from disruptions in energy flow caused by environmental limitations, management practices, climatic extremes, and inadequate nutrition.
- Proper apiary management, including queen quality, location selection, feeding strategies, and climate control, plays a decisive role in maintaining colony strength and productivity

What is the implication of the main finding?

- Minimizing stress through genotype–environment matching and informed management practices directly enhances colony survival, disease resistance, and honey production.
- Stress-oriented colony management provides a practical framework for sustainable beekeeping and long-term productivity under changing environmental conditions.

Abstract

As with all livestock planning, the goal in beekeeping is to achieve maximum yield. Beekeeping, being one of the livestock branches most affected by environmental conditions, also experiences stress factors that reduce production performance, negatively impacting the targeted yield. Stress leads to a decrease in population strength and a shortened lifespan of adult bees in honeybee colonies. Incorrect management practices cause stress in honeybee colonies. The main factors leading to high levels of stress in the bee colony, reduced survival and production performance, include: not using a genetically unsuitable queen bee breed and/or ecotype; an old queen bee in the hive; unsuitable apiary location; insufficient access to nectar and pollen sources; exposure of hives to excessive heat and inadequate ventilation and poor wintering practices. Failure to adhere to necessary technical rules, particularly during the transportation of honeybees to nectar sources, can lead to bee deaths due to increased temperatures inside the hive, or cause stress to the colony by resulting in the loss of the queen bee during transport. Furthermore, stress caused by adverse conditions such as high humidity inside the hive, bad weather, and insufficient nectar and pollen weakens the bees' immune system, leading to the emergence of various adult and brood diseases. The medications used to combat bee diseases and pests also constitute a separate source of stress for the bees. By correctly applying hive management techniques and prevents causing stress can be eliminated, resulting in increased bee productivity.

Keywords: Honeybee, stress factors, colony performance, production, prevention

1. Introduction

In a bee colony, nectar, pollen, and water, which form the fundamental source of vital functions, are used within the colony and transformed into bee products such as honey, beeswax, bee bread, royal jelly, and bee venom. The sustainable supply of these basic nutrients considered the “energy source” of the colony, plays a major role in ensuring the healthy survival of the bee family. However, certain factors and/or practices that disrupt this balance and thus cause stress to the colony are also a significant problem in beekeeping. Anything that reduces the energy flow of the hive is called “stress” [1]. Many factors trigger stress in bees and cause a cumulative process that can lead to the loss of the colony [2]. Stress in bees is caused by insufficient environmental food and water resources, changes in climatic conditions, the aging of the queen bee, the negative effects of genetic factors, unsuitable wintering conditions, problems in spring development, colony division, bee swarming, problems encountered when moving bees from one place to another, hive inspections, and certain procedures such as honey harvesting. The main signs of stress are unexplained lethargy and weakness in the colony, physical abnormalities, aggressive and rapid behavior, decreased grooming behavior, and decreased flight activity. This situation shortens the lifespan of worker bees, reduces the bee population in the hive, and increases the colony’s risk of disease and pests [3]. Stress also shortens the lifespan of adult bees, thereby negatively affecting the size of the colony population [4]. As a result, it leads to a decrease in honey production and causes colonies to enter winter with a weakened population. Since the basic principle of beekeeping is to make the most of this energy conversion, beekeepers also become part of the stress accumulated on the colony [1]. As well as other living creatures, honeybees can develop in some environments but fail to thrive in others. The management system implemented is defined as the environment for the bees when compared to other factors. Management practices are generally used to help bees recover from various diseases, but their primary purpose is to prevent bees from becoming stressed and diseased [5].

2. Genetic Factors and Queen Bee

In beekeeping, the genotype of the bee is of great importance in terms of production goals. Therefore, the bee race used should be selected from a locally adapted subspecies (ecotype). In other words, in beekeeping terminology, the selection of bee race and subspecies is considered queen bee selection. Having a high-quality queen bee in the colony will help eliminate most potential stress factors. Colonies struggle to accept queen bees that are not raised at the appropriate time because their performance is inadequate. Replacing these queen bees shortly after they are raised causes stress in the colony [4].

3. Selection of Apiary Location

Choosing a location for a beehive is one of the most important decisions in beekeeping. The better the location, the more productive the bees will be. The location of the hives should have a dry surface, receive plenty of sunlight throughout the day, protected from winter winds, have a slight slope for adequate air drainage, have access to roads, protected from theft, and have plants that provide nectar and pollen for most of the season. Wet, swampy, and muddy areas, flood-prone areas, hills that are too windy to allow bees to fly in summer and require more effort to warm up in winter, areas close to residential areas, and areas where bees may be exposed to pesticides should be avoided [2,6,7]. While a suitable apiary location meets most of the desired criteria, it may also have some disadvantages. A location that is highly productive for the honey production season may

not be suitable for successfully overwintering. If transporting bees presents no problem, two separate apiary locations can be used, each for honey production and overwintering, respectively. Additionally, multiple hive locations may be necessary to monitor nectar flow at different times and places throughout the summer season. Potential locations should be evaluated before making a final decision on where to transport the bees [4].

4. Placement of Colonies

Colonies should be placed on stands 4 to 8 cm above the ground. This prevents the bees from being affected by soil moisture and maintains the temperature inside the hive. It also prevents weeds from blocking the hive entrance and the materials used from being affected by moisture [4]. Locations between south and southeast are suitable for placing bee colonies. Hives on the south side benefit most from the sun, which helps the bees warm up, especially in the morning. Wind can negatively affect honeybee populations in winter, making the choice of hive location even more important during the cold months. The sound wind hitting the hives causes the colony to become very stressed, rapidly consume their stored honey and increases the risk of diseases such as nosema [8]. In addition, to prevent rainwater from accumulating on the bottom board of the hives, the hives should be placed at a 5-degree angle forward in the apiary. Another point to consider is the swarming of bees into another hive due to disorientation. This weakens some colonies in the apiary and consequently reduces the honey yield from these hives. Furthermore, disorientation can cause the spread of disease-causing mites between hives in the apiary. Orientation disorder can be minimized by placing hives in a staggered arrangement or using colored markers [4].

5. Nectar and Pollen Sources

It is important to have a thorough understanding of nectar flow patterns in the areas where bees will be relocated. This information enables the assessment of nectar flow each year. If the nectar flow for the current year is determined to be below average, hives can be relocated to other areas or supplemental feeding can be provided [9]. Nectar flow generally shows regional trends, but in some years it may be below average in one region and above average in another. Some apiaries can accommodate a large number of colonies in a year with sufficient nectar flow. However, in some years, the number of colonies that can be placed is limited. If a hive exceeds its capacity, the average yield per colony can decrease significantly. This also leads to a decline in colony population. As a result, colonies cannot take full advantage of the nectar flow throughout the year, causing bees to enter winter in a very weak state. Production records carefully kept in the hives where colonies are moved and the experience gained over the years are the best way to ensure that hives are used effectively in their current locations. It should be remembered that a steady supply of nectar and pollen is crucial for the well-being of bee colonies [10,11].

6. Hive Microclimate

Honey bee colonies function as a superorganism that must keep their brood nest within tight temperature and humidity limits to grow, stay healthy, and survive winter and heat waves. In this context, hive microclimate—particularly internal temperature and humidity—plays a pivotal role in brood development, adult physiology, disease susceptibility, and overall energy balance. Beehives located in extremely hot regions are therefore subject to significant thermal stress. Painting hives white or in other light colors can help reduce heat absorption and mitigate these effects. For this purpose, it is

recommended that the outer surfaces of hives be painted in light colors. Especially in very hot regions, hives should be placed in locations that are not exposed to the midday heat. In addition, a separate flight hole that can be opened in the honey chamber during the summer months allows air to pass through the hive, enabling the bees to regulate the temperature inside the hive and allowing the nectar to dry quickly. Bees are exposed to excessive heat when transported from one place to another in hot weather if there is insufficient ventilation inside the hive. During transport, piles of dead bees on the bottom board of the hive or worker bees rapidly flapping their wings indicate that the hive is exposed to excessive heat. Bees confined in the hive during transport should be secured with wire-mesh hive covers that provide adequate ventilation. Insufficient ventilation conditions inside the hive can also be considered a significant stress factor for honey bees. It is important that the hive is not directly exposed to the wind and is designed and constructed with materials that allow for indirect ventilation. High carbon dioxide accumulation inside the hive can cause stress by reducing both brood development and the living comfort of adult honeybees, therefore, it is important to be careful when choosing a hive. For both wild and managed bees, supporting a stable, appropriate microclimate is central to colony health and resilience.

7. Outside Climatic Conditions

Weather conditions are another major cause of colony stress. Extreme weather conditions can reduce or completely halt the flow of nectar and pollen to the colony. In early spring and early summer, large amounts of energy or food are required for brood production in the hive. Factors such as rainy weather or bees being closed in during transport can cause a sudden interruption in the flow of nectar to the hive, which can cause serious stress if it continues for a long time. In order to overcome this stress, bees reduce brood production and population development, which in turn reduces their energy requirements. During this stressful period, additional nutrition should be provided to the bees through management practices [1,12]. Irregular fluctuations in air temperature also cause stress. Maintaining a constant temperature in the brood chamber is very important for proper brood development. Anything that prevents this temperature from being maintained (such as placing colonies in cold or humid locations) requires more energy to produce heat and forces bees to work harder to collect pollen and nectar. The presence of dead larvae in honeycomb cells is an indicator of stress in the colony. Having more brood than the current bee population can support causes the death of larvae outside the brood chamber. This situation requires more energy to produce new individuals to replace them and to remove dead larvae and pupae from the cells [1].

8. Water Source

Water availability is also a critical factor in the emergence of stress. During periods of drought, bees have to make countless flights over long distances to reach water, which requires more energy. Bees need water to cool the hive and raise their brood. Water makes up about 66% of brood feeding and is necessary to maintain humidity in the brood chamber of the hive. Nurse bees need water to produce royal jelly and dilute honey. In extreme hot weather, when water is unavailable, the honeycomb may melt despite the bees' efforts to cool themselves. If there is no clean water source nearby, water should be provided to the bees in the hive. A 5-liter bucket can be used for this purpose. This source should be placed near the hive and changed weekly. Additionally, floating branches should be added to the water to prevent the bees from drowning. Creating a water source for the bees during dry periods when water is unavailable can reduce this stress [1].

9. Feeding Honey Bees

Inadequate nutrition is a serious stress factor for all living beings. During periods of nectar scarcity, colonies reduce brood production and begin to consume their stored nectar. This situation can weaken colonies and ultimately result in bees entering winter or the main nectar flow with a very small population. A colony with 10 frames of bees and less than 3 frames of stored honey is at risk of starvation. In this case, supplemental feeding with syrup should be provided at the end of summer, before winter begins [3]. Colonies may experience pollen scarcity in addition to nectar scarcity. Pollen is extremely necessary for brood production. During periods of pollen scarcity, bees eat their existing brood. When brood is observed being eaten in the hive, it is noticed that there is no stored pollen, and if there are not enough forager bees returning to the hive with pollen, colonies should be supplemented with a pollen source or another pollen substitute. Another solution is to move the bees to areas with sufficient pollen sources [4]. Bees require different amounts of protein depending on the severity of the stress they experience. Knowing the stress levels of bees allows beekeepers to take better precautions regarding feeding techniques. Bee colonies are under stress when brood rearing is intense and when the air temperature is below 20°C or above 35°C. In this case, one of the most beneficial practices is to supplement the bees with an additive [9].

10. Transportation of Honeybees

Although it is necessary to transport bees to take benefit of nectar flow, this process can be risky for bees if not done properly. During transport, bees may die or lose their queen due to excessive heat caused by the increase in temperature inside the hive. This is especially the case for strong hives that are kept closed for more than a few hours during transport. If bees are to be transported in hot weather, wire mesh covers should be used to ensure ventilation. Also, when loading hives onto the vehicle, care should be taken to place the combs parallel to the road. This placement prevents the bees from hitting each other and prevents collisions that may occur during transport and during takeoff or stopping. Hives should be transported at night or on cool days when there is no flight activity. If they are transported in good weather when the bees can fly, the forager bees in the hives will be lost. When transporting bees, the rule of "less than one meter, more than a few kilometers" should be followed. If hives are moved one meter away from their previous location but within the bees' flight range, foraging bees will return to their previous location and get lost. In this way, the colonies' foraging bee power is also lost. As a result of the decrease in the foraging bee force, worker bees cannot find food to use for brood production, which creates significant stress for the bees. However, if the hives are moved far away, the bees quickly adapt to their new, unfamiliar location [4].

11. Synthetic Chemicals

Chemicals are commonly used to fight bee diseases and pests such as American foulbrood and Varroa mites. It is crucial that these chemicals are used at the right time, in the right dosage, and with the right method. Some unlicensed drugs used for Varroa control are toxic to bees. Furthermore, these chemicals increase the risk of residues in bee products. Unlicensed drugs should never be used to treat diseases in bee colonies. Recently, there has been great interest in essential oils used for Varroa control due to their natural properties and lack of residue risk in the hive. When essential oils are used for Varroa mite control, they can sometimes pose a risk to bee health. Some essential oils are as toxic to bees as they are to mites [13]. Although widespread bee deaths do not occur, bees may

be exposed to indirect effects. These effects are generally not noticeable during daily hive inspections. It should be remembered that anything that shortens the lifespan of bees will reduce the hive's honey production capacity and overwintering ability [12].

12. Queen Renewal

A colony should always have a young and strong queen bee. An insufficient queen bee will severely weaken the colony, resulting in reduced honey production and wintering capacity. Colonies must absolutely enter winter with young and strong queens [4].

13. Wintering

A successful production season begins with strong and healthy colonies in the spring. This requires good planning during the previous summer and fall to ensure colonies enter winter with healthy bees and sufficient honey and pollen stores. One of the biggest mistakes is entering winter with weak colonies. Weak colonies should be monitored throughout the fall to assess their condition. One month before fall, colonies that are heavily infested with varroa mites or carrying other diseases should be removed. This is because treating colonies at that time may solve the problem, but there is not enough time to ensure that the colonies enter winter with a healthy and strong population. Furthermore, since the bees in these hives will be weak and powerless, such colonies will do more damage than good. Queenless colonies and colonies weakened by nectar or pollen deficiency should be combined with stronger colonies at the beginning of the season [2]. Colonies must have sufficient and high-quality food reserves as they enter winter. However, colonies without sufficient food reserves must be fed before winter. The best winter food is sealed honeycomb obtained from healthy and disease-free hives, but it is important to ensure that the honey does not crystallize. Sugar syrup prepared with two parts of powdered sugar and one part of hot water is also a suitable winter food for bees [4]. Additionally, colonies must have sufficient pollen reserves in the fall to support brood production starting at the end of winter and to use during spring development when fresh pollen sources are unavailable in early spring. Colonies entering winter without sufficient pollen reserves cannot develop adequately in spring. The amount of pollen required depends on how long the bees will be unable to access natural pollen sources. Before wintering, the hive entrance should be narrowed to limit the amount of cold air entering the hive and to prevent infestation by mice and other pests. This practice also reduces the risk of theft and allows the bees to best prepare their hives for winter. Furthermore, light ventilation is essential to remove moist air from hives during winter. To achieve this, the back of the hive's top cover should be slightly raised [14,15].

14. Early Inspections

At the end of winter, colonies should be checked to determine whether the bees are alive and have sufficient food reserves to last until they can access natural nectar and pollen sources. However, the winter cluster should not be disturbed during this inspection. Empty combs can be removed, and sealed honey frames can be placed next to the cluster. To prevent the larvae from freezing due to low temperatures, brood combs should not be removed, and hives should never be opened in rainy or windy weather [4].

15. Other Factors

Other important factors that negatively affect or hinder productivity within the hive are the number of adult bees, the ratio of adult bees to young bees, and the queen bee's egg-laying rate. These are all related to determining the energy required for the colony to function. Since young bees are fed during the larval stage, the hive must have a young bee population relative to the number of larvae that need to be fed. Bee swarming and pesticide toxicity are two conditions that alter the population balance within the hive. Practices carried out by beekeepers, such as splitting and combining hives, are other factors that disrupt the balance within the hive and cause stress in the bees [1]. Stress weakens colonies and creates a breeding ground for diseases [1]. Brood-rearing colonies are constantly under stress, but this stress intensifies when nectar flow is not at the expected level, leading to many undesirable consequences [16]. One of the significant brood diseases caused by stress factors is chalkbrood disease. However, this is not the only disease associated with stress in beekeeping. Nosema is another example of an adult bee disease caused by a stress factor. If there is an increase in both nosema and chalkbrood disease during a stressful period, their effects on the colony can be devastating. European foulbrood also increases depending on the amount of stress the colony is exposed to. Working with a honeybee breed with high hygienic behavior ensures that these diseases are minimized. In other words, replacing existing colonies with queens from disease-resistant bee breeds is the best way to eliminate these symptoms. The most important and general rule of stress prevention is to ensure that the colonies are always strong [8].

16. Conclusions

In conclusion, by using genotypes suitable for environmental conditions, selecting a suitable apiary location, providing sufficient food and water sources, proper colony management, and effective control of diseases and pests, the stress factors experienced by honeybees can be minimized, and significant progress can be made towards achieving optimal production performance in honeybees.

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Possible Effects of Global and Regional Temperature Changes on the Sustainability of Agriculture and Beekeeping in Türkiye

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Highlights

What are the main findings?

- Global land temperature anomaly reached 2.1 °C in 2024, confirming 2015–2024 as the warmest decade on record.
- In Türkiye, temperature anomaly increased significantly from 0.184 °C in 1961 to 2.765 °C in 2024, indicating a strong regional warming trend.
- Seasonal warming is particularly pronounced during key biological periods, with March and July temperature anomalies increasing markedly between 2015 and 2024.
- Rising temperatures affect agricultural systems by increasing crop water demand, yield variability, and shifts in sowing, flowering, and harvesting periods.
- Climate-driven changes may disrupt plant pollinator synchrony, reducing nectar and pollen availability and potentially affecting beekeeping productivity.

What is the implication of the main finding?

The observed warming trends indicate that agriculture and beekeeping systems in Türkiye are increasingly vulnerable to climate change, particularly within Mediterranean climate conditions. Rising temperatures and drought stress may reduce agricultural productivity, alter ecosystem processes, and disrupt pollination dynamics. These findings highlight the urgent need to develop climate-resilient agricultural practices, improve water-use efficiency, protect soil resources, and support ecosystem-based management strategies to sustain agricultural production and beekeeping in the region.

Abstract

Global temperature increases impose significant pressure on agricultural production, land use, and ecosystems through rising surface temperatures. This study analyzes global and Türkiye-scale temperature change trends for the period 1961–2024 using the FAOSTAT *Temperature Change on Land* dataset and evaluates their implications for agricultural sustainability and beekeeping. In 2024, the global average annual land temperature anomaly reached 2.1 °C relative to the 1951–1980 baseline, representing the highest value on record and confirming the last decade (2015–2024) as the warmest observed period. In

Türkiye, the temperature anomaly increased from 0.184 °C in 1961 to 2.765 °C in 2024, with a decadal mean of 1.744 °C during 2015–2024.

Seasonal analyses indicate marked warming during critical biological periods. March temperature anomalies, corresponding to the onset of beekeeping activities, rose from 1.371 °C in 2015 to 2.486 °C in 2024, while July anomalies, associated with summer drought stress, increased from 1.563 °C to 2.898 °C over the same period. These trends highlight Türkiye's heightened vulnerability to climate change within the Mediterranean climate zone.

Rising temperatures increase crop water demand, amplify interannual yield variability, and shift sowing, flowering, and harvest periods, while altered soil moisture regimes and more frequent extreme events intensify erosion risk and soil organic matter loss. Climate-driven disruptions also affect beekeeping and pollination by desynchronizing plant flowering with bee colony development and reducing nectar and pollen availability under heat and drought stress. Overall, the findings emphasize the urgent need to prioritize water-use efficiency, soil conservation, climate resilient production systems, and ecosystem-based management strategies to sustain agriculture and beekeeping in Türkiye.

Keywords: Temperature anomaly; climate change; FAOSTAT; agricultural sustainability; beekeeping; pollination; Türkiye

Mobile Beekeeping Approach for Sensitive Beekeeping Technologies

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Highlights

What are the main findings?

- Sensitive/precision and mobile beekeeping systems enable continuous, non-invasive monitoring of the colony's biological status via intra-colony temperature, humidity, weight, vibration and acoustic signals.
- Sensor-based monitoring provides early warning mechanisms and data-driven colony management, overcoming the limitations of traditional colony inspections.

What is the implication of the main finding?

- Precision beekeeping offers a decision support approach that strengthens the human experience with objective data without eliminating the decision-making role of the beekeeper.
- In countries with high levels of migratory beekeeping and rich biodiversity, such as Türkiye, the development of flexible, low-cost, and human-centered technologies is critical for sustainable beekeeping.

Abstract

Honeybees (*Apis mellifera* L.) play a vital role in the sustainability of the natural ecosystem, environmental health, and the protection of life. Their role extends beyond the production of bee products; they are fundamental to the pollination process of plants and play a key role in the reproduction of cultivated flora. For these reasons, research into solutions to protect and support the existence of honeybees is of great importance. Traditional beekeeping methods rely heavily on the beekeeper's experience and manual inspection of colonies. However, these inspections both stress the colony, disrupt the delicate thermal balance within the hive, and may be insufficient for detecting immediate problems. Especially in large-scale apiaries, physically inspecting hundreds of hives at regular intervals is quite difficult. Technological advancements offer new approaches that allow for remote and real-time monitoring of hive conditions. These systems give beekeepers the opportunity to make data-driven decisions and act proactively against potential threats. Maintaining colony health and increasing productivity are central to this technological adaptation. Today, the effects of developing technology are beginning to be seen in beekeeping; rapid advancements in temperature and sound measurement systems and information technologies have made it possible to apply precision agriculture technologies with mobile data. Using mobile data, it is possible to monitor colonies, track real-time temperature, humidity, meteorological data, and changes in bee movement. Furthermore, the use of precision beekeeping technologies allows for the evaluation of colony performance data, the development of specially designed tools for colonies,

specially designed beehives, bee product harvesting machines, the use of smartphones in marketing, and many other new technologies are becoming increasingly widespread. Precision beekeeping emerged as a response to the need to manage beekeeping in the most optimal way. In this context, the widespread decline in honeybee colonies recorded especially in recent years has led to the increasing application of precision agriculture technologies in beekeeping to identify possible causes and design countermeasures. This allows for monitoring colony activity and gathering deeper information about this phenomenon. Precision-beekeeping integrates technology aimed at managing an apiary effectively and practically through the use of mobile data, reducing the risk of situations that could lead to bee population losses. Precision beekeeping is defined as a hive management strategy based on monitoring individual bee colonies to minimize resource consumption and maximize bee productivity. However, the feasibility of widely using and implementing an economically viable system for beekeepers is still lacking. Uncertainty regarding the benefit/investment ratio, complexity in use, and the additional operating costs required for sensors and electronics are among the obstacles to the implementation of existing precision beekeeping systems. Collaboration between research teams from different disciplines such as engineering, mathematics, physics, ethology, etc., could lead to greater effectiveness in integrating mobile beekeeping into precision beekeeping technologies.

Keywords: Beekeeping, mobile beekeeping, sensitive beekeeping, technologie

1. Introduction

Honeybees (*Apis mellifera* L.) are crucial pollinators with major ecological, economic, and cultural roles. Bees (especially honeybees) pollinate crops that provide about one-third of the human diet, and roughly 5–8% of all global crop production would be lost without animal pollinators. Honeybees are the most economically valuable pollinator worldwide, supporting over 100 major crops (fruits, vegetables, nuts, coffee, cocoa, oilseeds) [1,2,3]. In natural habitats, honeybees are among the most frequent flower visitors globally. By enabling plant reproduction, honeybees and other pollinators support forest regeneration, wildflower diversity, and habitats for other animals, stabilizing ecosystems and improving resilience to environmental change. Additionally, honeybees provide high-quality food and raw materials (honey, wax, propolis, pollen, bee bread, bee venom, royal jelly, apilarnil) and are widely used in pharmaceuticals and traditional medicine. Besides, their products and bodies can act as bioindicators of pollution, helping monitor environmental health [4]. Also, honeybees hold strong symbolic and cultural value, helping connect people with nature and supporting rural livelihoods and sustainable development goals [4,5]. Unfortunately, honeybee populations, which are so important to the ecosystem and humanity, have been declining in recent years for various reasons. Honeybee colonies are declining due to multiple interacting stresses, especially parasites, pesticides, poor nutrition, and climate extremes, which cause ecological risk, economic threats, and food security concerns. As beekeeping faces multiple interacting crises, technological solutions are needed to detect problems early, guide better decisions, and keep colonies productive and alive.

2. Challenges in Traditional Beekeeping

Traditional beekeeping relies on manual, periodic inspections of each hive, often at apiaries far from the beekeeper's home [6]. Periodic colony/hive inspections can only occur in good weather and daylight, and a single beekeeper can inspect only about 10 hives per day, making large operations difficult to manage [6,7]. Conventional hive management relies heavily on beekeeper experience, and it is difficult to manage large-scale apiaries efficiently. Manual hive inspections could increase colony stress, cause thermal and structural disturbance, may trigger defensive behavior or queen loss, may increase diseases and inspections provide snapshots, not continuous data that early-stage problems often remain undetected. In traditional beekeeping, beekeepers must infer colony health from short, intrusive checks and experience-based judgment. Problems such as brood disruption, queen loss, hunger, or disease may develop unnoticed for days or weeks, increasing colony mortality risk. Besides, climate variability (early flowering, sudden cold snaps) can cause food shortages that are hard to detect in time without continuous monitoring [7,8,9]. Traditional inspections require frequent hive opening, which disturbs bees and may negatively affect colony health and productivity [6,7]. Traditional beekeeping could be challenged by infrequent, laborious, and intrusive inspections that provide poor continuous information, limit timely decisions, and become inefficient or risky as apiaries grow or climates become more variable.

3. The Need for Technological Solutions

As the colony losses increase due to climate change and environmental stressors rapidly worldwide, the need for early warning systems, continuous, non-invasive monitoring and data-driven decision-making systems becomes essential. Technical solutions in beekeeping are needed to keep colonies productive and healthy under increasing environmental and economic pressures. Technical/digital solutions are becoming necessary in beekeeping with the rising stress and mortality in bee colonies, for better management with fewer, smarter inspections and for higher productivity. Honeybee colonies face multiple simultaneous threats like climate change, habitat loss, pesticides, diseases, pests (e.g., *Varroa*), and colony collapse disorder, causing high annual losses and reduced productivity. Digital/precision systems (sensors, IoT, AI) allow early detection of disease, stress, or predation and help prevent or reduce colony losses. Sensors for weight, temperature, humidity, sound and flight activity give continuous data that cannot be obtained by occasional manual inspections. Remote monitoring cuts unnecessary hive openings and trips to the apiary, supports timely feeding, harvest, and treatment decisions and enables low-stress, "precision" management of colonies. Improved and "modern" technologies (modern hives, smart monitoring) are linked to higher honey yields, better honey quality, and easier inspection compared with traditional methods. Besides, continuous hive data help understand bee behavior, environmental impacts, and develop better health and biosecurity practices, supporting more sustainable beekeeping and agriculture.

4. Precision or Mobile Beekeeping

Precision beekeeping is data-driven, sensor-based apiary management that monitors individual colonies to minimize resource use and maximize productivity using mobile systems. Precision beekeeping (also called precision apiculture) is defined as “an apiary management strategy based on monitoring individual bee colonies to minimize resource consumption and maximize bee productivity” [7,8,10]. Precision beekeeping has three main phases as data collection (sensors on or in hives measure weight, internal temperature, humidity, sounds/vibrations, gases, bee traffic, plus external weather (wind, rain, ambient temperature)), data processing and data analysis (microcontrollers send data (often via IoT networks) to servers/cloud; algorithms or AI detect patterns (e.g., nectar flow, swarming, disease, brood issues) and compare to “normal” ranges) and application/decision support (beekeepers receive alerts and dashboards (PC, web, mobile app) and choose targeted interventions, reducing unnecessary hive openings and travel) [6,7,8,11,12,13]. Precision beekeeping systems work by turning each hive into a data source and using software to translate that data into decisions. In practice, a precision beekeeping system continuously senses hive and environment, sends data to the cloud, analyzes it with algorithms, and delivers clear information and alerts so the beekeeper can intervene earlier, visit fewer hives unnecessarily, and better protect colony health and productivity.

5. Hive Sensor Placement & Configuration

Designing a good precision beekeeping system is mostly about where and how sensors are placed, so they “see” the bees but don’t disturb them. In a smart beehive monitoring system, sensors are strategically placed in different hive zones: temperature and relative humidity sensors in the brood area (central frames); temperature, humidity, and optionally CO₂ sensors in the upper hive area beneath the inner cover; optical or infrared bee counters and motion sensors at the hive entrance; load cells, temperature, and vibration sensors on the bottom board; acoustic microphones and accelerometers along the inner hive walls; and ambient temperature, relative humidity, light intensity, and optionally wind and rainfall sensors in the external hive environment. For temperature and humidity sensors, best single-point placement is near the geometric center/brood area that gives the strongest link to colony strength; sensors near the hive center correlated better with frames of bees than edge sensors. Whole-hive weight sensors could be 3–4 load cells under hive corners or in a frame/metal support structure to cover 50–200 kg ranges or while per-frame weight (research) sensors force or capacitive sensors under each frame lug; mechanically tricky and aging-sensitive, so mainly experimental. Microphones are usually placed inside the brood box for acoustic sensors but shielded from direct contact; some systems add external mics or accelerometers for security/impact detection. Also, for air sampling, probes placed between combs near the brood give cleaner, more consistent gas readings than at the hive entrance. Modern precision beekeeping systems rely on biologically meaningful signals generated by the colony. Temperature signals could mean brood presence and brood development, queen activity, colony strength and vitality. While a stable temperature gives a clue about a healthy colony, irregular patterns could

be evaluated as an early stress indicator. Humidity signals can give information about hive ventilation efficiency, risk of fungal and microbial diseases and overwintering conditions [6,14]. Acoustic signals could be used to gather information about queen piping, swarming preparation and stress-related buzzing patterns. While vibration and movement signals provide information about collective bee activity, foraging intensity, and disturbance or agitation, hive weight data provide information about nectar flow, honey production, swarming, theft, or population loss [8,15].

6. Limitations and Challenges of Precision & Mobile Beekeeping Systems

Especially for our country, precision beekeeping must be designed around biological diversity, migratory practices, and economic realities rather than imported as a standardized technological package. The implementation and dissemination of precision beekeeping technologies in Türkiye faces difficulties due to various technical, economic and structural limitations. First, the high cost of existing monitoring and decision support systems constitutes a significant constraint, especially for small and medium-sized enterprises. In order to solve this problem, it is necessary to develop technological solutions that have a modular structure, are low-cost and can be scaled according to need. The widespread application of migratory beekeeping limits the effectiveness of systems based on fixed infrastructure and makes data continuity difficult. In this context, platforms that can be used in different locations and have mobile and offline working capacity stand out as an important solution that can increase the sustainability of data collection and monitoring processes. Türkiye's wide geographical diversity and the resulting genetic differences between bee species and ecotypes prevent standardized, uniform technological approaches from being sufficient. Therefore, it is necessary to develop customized artificial intelligence models that consider regional and species/race-based differences. Inadequacies in energy and communication infrastructure in rural areas are another important factor that restricts the continuous and effective use of precision-beekeeping technologies. In order to overcome this limitation, choosing systems with low energy consumption and supported by solar energy is considered an appropriate approach. Collecting data in a fragmented manner between different platforms and systems makes it difficult to conduct holistic analyses and create effective decision support mechanisms. To solve this problem, the development of cooperative-based and open-to-share data management models will contribute to the creation of a common data infrastructure. The limited knowledge and experience of beekeepers regarding the use of technology negatively affect the adoption and effective use of complex systems. Therefore, it is important to design interfaces that are user-friendly, simple and focus directly on the decision support process. Finally, the lack of integration between technological developments and national policies and practices constitutes a structural obstacle to the dissemination of these systems. Ensuring integration at the national level and supporting pilot applications play a critical role in adapting precision beekeeping technologies to the field and increasing their sustainability.

7. Human–Technology Interaction in Precision Beekeeping

Precision beekeeping changes the relationship between beekeepers, bees, and data. Instead of relying only on in-person inspections, beekeepers increasingly interact with colonies through sensors, apps, and decision-support systems, which creates both opportunities and risks for how humans manage and relate to bees. Beekeepers access hive weight, temperature, humidity, sound, flight activity, and environmental data and alarms to decide which hives to visit and what actions to take [6,11,16]. Large surveys showed that most beekeepers still do not use digital monitoring, and adopters are more often professional, managing many hives far from home. Perceived benefits are regarded as easier management, better colony health, reduced winter losses, time saving, and support for decisions while barriers are regarded as high cost, limited IT skills, older age, attachment to “hands-on” beekeeping, and fear of over-reliance on technology [11,17,18,19]. Precision and mobile beekeeping systems are not designed to replace traditional beekeeping knowledge or the role of the beekeeper. Instead, they function as decision-support tools that complement human observation, experience, and ecological intuition. In the precision beekeeping approach, the beekeeper is always the main decision-maker. Technological systems ensure continuous monitoring of the colony, early warning signals and objective data-driven support. However, the biological interpretation of these data and the determination of the final interventions to be applied depend on the knowledge, experience and intuition of the beekeeper. Precision beekeeping is not a structure where technology decides for the beekeeper; it is a support system that allows the beekeeper to better 'listen' to the dynamics of the colony, strengthening human judgment with data. Technology does not speak for the colony, it mediates more accurate communication between the colony and the beekeeper.

8. Conclusions

As a result, precision and mobile beekeeping approaches represent a transformation in beekeeping where technology strengthens human knowledge. Colonies can be continuously monitored due to sensors, mobile data and decision support systems that provide early warning signals and objective data to the beekeeper. However, making biological sense of this data, correctly reading the real needs of the colony, and deciding on the interventions to be applied always depends on the beekeeper's knowledge and experience. For this reason, precision beekeeping is not a system where technology makes decisions on behalf of the beekeeper; it is a support mechanism that allows the beekeeper to better understand and observe colony dynamics. Especially in countries such as Türkiye, where biodiversity, migratory beekeeping and different farming practices are common, the development of human-centered, flexible and compatible systems with biological realities is of great importance. This approach will provide a core knowledge for both protecting colony health and building a sustainable and resilient beekeeping in future.

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Analysis of Honey Production and Honey Yield per Beehive in Türkiye Using an ARIMAX Model in the Context of Climate Change

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What are the main findings?

- Changes in annual average temperature have a limited and statistically weak relationship with total honey production in Türkiye.
- Honey yield per hive responds more sensitively to temperature increases, indicating that productivity captures climate-related stress better than aggregate production figures.

What is the implication of the main finding?

- Relying solely on total honey production may mask the effects of climate change in beekeeping systems.
- Productivity-based indicators, such as honey yield per hive, provide a more informative basis for climate-adaptive beekeeping policies.

Abstract

This study examines the relationship between climate conditions and beekeeping performance in Türkiye using annual data for the 1991–2022 period. Total honey production, total number of hives, honey yield per hive, and annual average temperature are analysed within a time series framework. Stationarity is assessed using the Augmented Dickey–Fuller (ADF) unit root test, and the results indicate that all variables become stationary after first differencing. Based on information criteria, ARIMA(0,1,1) is selected for total honey production and ARIMA(2,1,0) for honey yield per hive. These baseline specifications are then extended to ARIMAX models by including annual average temperature as an exogenous variable. The findings show that temperature has a negative but weak and only marginally significant association with total honey production. In contrast, temperature has a negative and statistically significant effect on honey yield per hive, suggesting that productivity is more sensitive to climatic pressures than aggregate production levels. Overall, the results indicate that focusing solely on total production may understate climate-related impacts in beekeeping, while yield-based indicators provide a clearer signal of environmental stress.

Keywords: beekeeping; honey production; yield per hive; climate change; ARIMAX model.

1. Introduction

Beekeeping occupies a distinctive place within agricultural production systems. Beyond honey production, its contribution to crop production through pollination and its role in maintaining biodiversity make it a critical activity for ecosystem functioning. For this reason, the beekeeping sector is widely regarded as one of the agricultural areas that is highly sensitive to environmental change [1].

Rising temperatures and increasing climatic variability have become more visible drivers of change in agricultural production worldwide. Beekeeping is among the activities where these effects can be felt directly. Shifts in temperature regimes can influence flowering periods, nectar and pollen availability, colony development, and foraging behaviour, thereby shaping honey production outcomes. Despite this, the climate–beekeeping relationship has often been discussed mainly through total production figures, while productivity has received less attention [2].

Time series models, particularly ARIMA-based approaches, have been widely used in agricultural forecasting studies. In the context of Türkiye, previous studies have applied ARIMA models to forecast honey production and demonstrated that time series techniques can provide reliable projections for the beekeeping sector [3]. Similarly, ARIMA models have been used to analyse agricultural outputs such as fig production, highlighting the applicability of these methods under dynamic conditions [4]. These studies underline the relevance of ARIMA-type models for analysing production trends; however, they primarily focus on forecasting aggregate production and do not explicitly incorporate climatic variables. In this regard, the present study contributes to the literature by extending the ARIMA framework to an ARIMAX specification and by examining not only total production but also productivity indicators such as honey yield per hive in relation to climate change.

Türkiye holds an important position in global honey production due to its rich flora and ecological diversity. Over the last three decades, both honey production and the number of hives have increased markedly. However, it remains unclear to what extent this growth reflects improvements in productivity and how it relates to changes in climatic conditions [5]. Honey yield per hive provides a more direct indicator of performance and sensitivity to environmental pressures, yet it has been placed at the centre of only a limited number of empirical studies.

This study examines the time series properties of total honey production and honey yield per hive in Türkiye within the context of climate change. Annual data for the 1991–2022 period are used, covering honey production, hive numbers, and annual average temperature. Total honey production and honey yield per hive are treated as separate outcome variables, and the influence of temperature on these indicators is assessed using ARIMA models and ARIMAX specifications in which temperature enters as an exogenous variable.

By focusing on productivity alongside aggregate production, the study offers a clearer perspective on the dynamics behind Türkiye’s rising honey output. The findings provide evidence on which indicators are more informative for tracking climate-related pressures in beekeeping systems.

2. Materials and Methods

2.1. Data

This study uses annual data for the 1991–2022 period to examine the time series dynamics of honey production and honey yield per hive in Türkiye. Data on total honey production as well as the number of modern and traditional hives are compiled from official statistical sources [6]. The total number of hives is calculated as the sum of modern and traditional hives. Honey yield per hive is obtained by dividing total honey production by the total number of hives.

Annual average temperature data for Türkiye are used as the climate variable and are obtained from the Global Data Lab database (surface temperature, yearly averages) [7]. Temperature is treated as an indicator capturing the general climatic conditions that

may influence beekeeping activity. All variables are measured at annual frequency, and the dataset is constructed based on the common time span available across series.

2.2. Analytical Approach

In this study, total honey production and honey yield per hive are examined as separate time series. This choice reflects the view that aggregate production and productivity indicators may follow different dynamic patterns over time. Before moving to time series modelling, the basic characteristics of the data are explored using descriptive statistics and graphical analysis.

To ensure the suitability of the series for time series analysis, their stationarity properties are assessed using the Augmented Dickey–Fuller (ADF) unit root test. The test results indicate that all series are non-stationary in levels but become stationary after first differencing. Based on this evidence, model specifications incorporating a first-order difference are adopted in the subsequent analysis.

2.3. Time Series Modelling (ARIMA and ARIMAX)

Time series models are employed to examine the dynamic behaviour of total honey production and honey yield per hive over time. In the first stage, ARIMA models are estimated as baseline specifications that capture the internal dynamics of the series [8]. These models are intended to reflect the behaviour of honey production and productivity based solely on their past values, prior to incorporating any climate-related variables.

Alternative lag structures are considered in determining the appropriate ARIMA specifications, and model selection is guided by the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). In line with the unit root test results, all series are modelled using specifications that include a first-order difference [9].

In the second stage, annual average temperature is introduced into the ARIMA framework as an exogenous variable. The resulting ARIMAX models allow for an assessment of the role of climate conditions in shaping both total honey production and honey yield per hive. Temperature is included in levels in order to capture the broader climatic environment rather than short-term fluctuations.

Following model estimation, residual diagnostics are examined, indicating that the underlying model assumptions are generally satisfied. Within this framework, ARIMA models provide a reference structure for comparison, while ARIMAX models serve as the main analytical tool for evaluating the influence of temperature on production and productivity dynamics.

Generative artificial intelligence tools were not used in the design of the study, data collection, data analysis, model specification, or interpretation of the results. Any language-related assistance was limited to minor editing for clarity and readability, which does not affect the scientific content of the study.

3. Results

3.1. Descriptive Statistics

Descriptive statistics are computed to provide an overview of the beekeeping sector and climatic conditions in Türkiye over the 1991–2022 period. The analysis focuses on total honey production, total number of hives, honey yield per hive, and annual average temperature. The descriptive results indicate a clear upward trend in both total honey production and the number of hives during the sample period, while honey yield per hive fluctuates within a relatively narrow range. This pattern suggests that the increase in total production has largely been driven by the expansion in hive numbers, whereas improvements in productivity have remained limited. In addition, the upward movement

observed in annual average temperature highlights the relevance of examining the potential influence of climate conditions on beekeeping productivity through time series methods.

Table 1. Descriptive Statistics (1991–2022)

Variable	Mean	Std. Deviation	Min.	Max.
Total honey production (tons)	82142	19347	54655	118297
Total number of hives (Million)	5.56	1.79	3.43	8.98
Honey yield per hive (kg)	15.16	1.62	11.03	17.94
Annual average temperature (°C)	11.80	0.85	9.53	13.37

Table 1 provides a clear overview of the main variables describing beekeeping activity in Türkiye over the 1991–2022 period. Based on the sample averages, total honey production is around 82 thousand tons, while the total number of hives is close to 5.5 million. The relatively large standard deviations observed for both variables indicate that beekeeping activity expanded substantially over time and that notable fluctuations occurred across years. In particular, the increase in the number of hives stands out as the key factor explaining the rise in total production.

A different picture emerges when honey yield per hive is considered. The average yield remains close to 15 kg per hive, and the minimum–maximum range is fairly narrow. The low standard deviation of the yield variable suggests that, rather than experiencing a sharp and sustained improvement, per-hive productivity followed a fluctuating but broadly stable path. This supports the view that the growth in total honey production has been driven primarily by the expansion in hive numbers rather than by gains in productivity.

Annual average temperature displays limited variation over the sample period; however, the gap between minimum and maximum values indicates a level of climatic change that cannot be ignored. From this perspective, a micro-level performance indicator such as honey yield per hive is expected to respond more sensitively to climate conditions than aggregate production figures. The descriptive statistics reported in Table 1 therefore provide the empirical basis for a more detailed investigation of this relationship using time series models.

Figure 1 shows that total honey production in Türkiye follows an overall upward trend during the study period. The increase becomes particularly visible from the early 2000s onward, and although short-term declines occur in certain years, the long-run pattern remains positive. This trajectory suggests an expansion in production capacity and a clear quantitative growth in the sector. At the same time, the fluctuations observed in production levels point to the possibility that climatic conditions, along with other environmental or structural factors, may generate year-to-year variation in output.

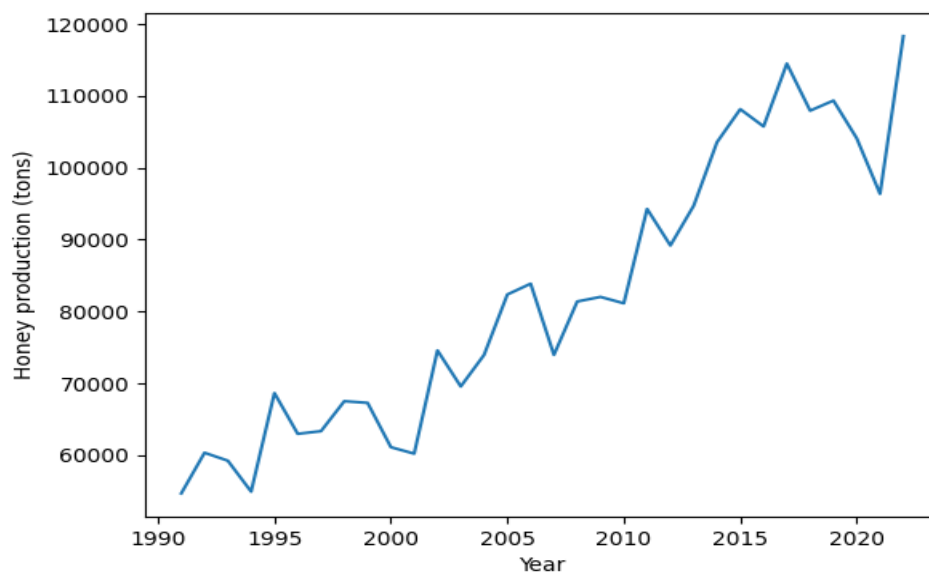


Figure 1. Total honey production in Türkiye (1991-2022).

Figure 2 presents the time series of honey yield per hive, which displays a notably different pattern compared to total honey production. Rather than following a clear upward trend over the sample period, yield levels fluctuate within an uneven trajectory. A downward tendency becomes particularly visible from the mid-2000s onward. This pattern suggests that the rise in total honey production has largely been driven by the expansion in hive numbers, while improvements in productivity have remained limited. In this sense, honey yield per hive stands out as a more sensitive indicator, reflecting structural constraints in the sector as well as environmental pressures.

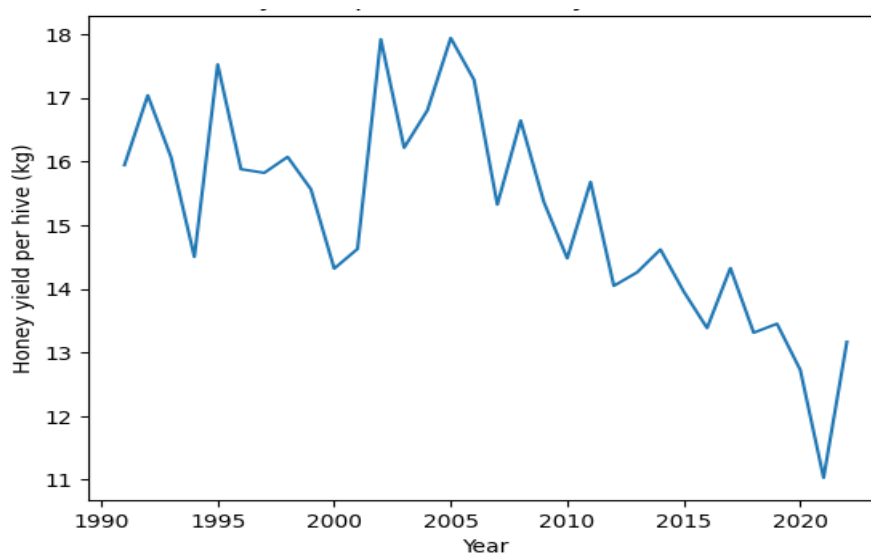


Figure 2. Honey yield per hive in Türkiye (1991-2022).

Figure 3 shows that annual average temperatures in Türkiye follow an overall upward trend over the study period. Although year-to-year fluctuations are observed, temperature levels in recent years appear noticeably higher than those recorded in earlier decades. This pattern is consistent with broader discussions on climate change and underlines the relevance of considering temperature as a potential factor influencing agricultural output and productivity.

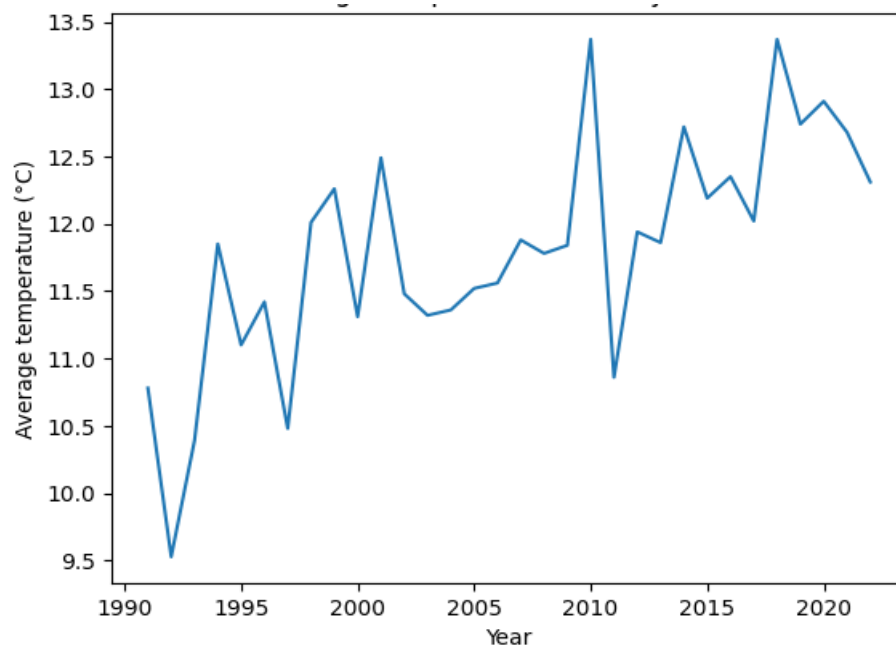


Figure 3. Annual average temperature in Türkiye (1991-2022).

3.2. Time Series Properties and Stationarity

Before estimating time series models, the stationarity properties of the variables need to be examined. For this purpose, the Augmented Dickey–Fuller (ADF) unit root test is applied to total honey production, honey yield per hive, and annual average temperature. The tests are first conducted using the series in levels, and for variables that do not satisfy stationarity, the analysis is repeated after taking first differences.

Table 2. ADF unit root test results

Variable	Level ADF	Level p-value	First-difference ADF	First-difference p-value
Total honey production	-0.261	0.9308	-6.164	0.0000
Honey yield per hive	0.018	0.9600	-7.574	0.0000
Annual average temperature	1.092	0.9951	-3.633	0.0052

The ADF unit root test results reported in Table 2 indicate that total honey production, honey yield per hive, and annual average temperature are non-stationary in levels. For all variables, the p-values in levels remain above the 5% significance threshold, pointing to the presence of a unit root. In contrast, the test results for the first-differenced series show that all variables become stationary. In particular, the p-values for the first differences of total honey production and honey yield per hive fall below the 1% significance level, suggesting that these series are integrated of order one [I(1)]. These findings imply that the differencing order should be set to $d = 1$ in the ARIMA and ARIMAX specifications.

3.3. ARIMA Model Selection (AIC/BIC)

After establishing that all series become stationary after first differencing, a set of alternative ARIMA(p,1,q) specifications is estimated for total honey production and honey yield per hive. Model selection is based on the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), and the preferred models are those that jointly minimise both criteria. Within this framework, ARIMA(0,1,1) is selected as the

most suitable specification for total honey production, while ARIMA(2,1,0) is identified as the best-performing model for honey yield per hive. These models are then used as baseline references for the ARIMAX estimations that incorporate temperature as an exogenous variable.

3.4. ARIMAX Models and Findings

This section examines the effect of annual average temperature on total honey production and honey yield per hive using ARIMAX models. Building on the ARIMA structures selected in the previous section, temperature is included as an exogenous variable in the ARIMA(0,1,1) specification for total honey production and in the ARIMA(2,1,0) specification for honey yield per hive. Temperature is entered in levels to capture the broader climatic environment and its potential influence on production and productivity.

Table 3. Temperature Coefficients in ARIMAX Models

Model	Temperature coefficient	Std. error	p-value
Total honey production	-3439.59	1994.95	0.0847
Honey yield per hive	-0.7068	0.2622	0.0070

In the ARIMAX model estimated for total honey production, the temperature coefficient is negative and shows only limited statistical significance. This suggests that rising temperatures do not act as a strong and direct driver of aggregate honey production, which appears to be shaped largely by structural factors such as the expansion in the number of hives. By contrast, in the ARIMAX model estimated for honey yield per hive, the coefficient on temperature is negative and statistically significant. The results indicate that increases in annual average temperature are associated with lower honey yield per hive. This pattern implies that productivity indicators respond more sensitively to changes in climatic conditions than aggregate production measures.

Overall, the ARIMAX findings suggest that the effects of climate change may not be fully captured when attention is limited to total production figures. Micro-level performance indicators, such as honey yield per hive, appear to reflect environmental pressures more directly. From this perspective, the results underline the importance of approaches that prioritise productivity and climate adaptation in beekeeping rather than focusing solely on increasing production volumes.

4. Discussion and Conclusions

Previous studies in Türkiye have primarily employed ARIMA models to forecast agricultural production, including honey and fig production [3, 4]. While these studies provide valuable insights into production trends, they focus mainly on aggregate output and do not explicitly consider the role of climatic variables. In addition, productivity indicators such as yield per hive have not been examined in detail within this framework. The present study extends this line of research by incorporating temperature as an exogenous variable in an ARIMAX model and by distinguishing between total production and productivity.

The results point to a clear gap between aggregate production outcomes and productivity-based indicators in Türkiye's beekeeping sector under changing climatic conditions. Total honey production increased over the study period, whereas honey yield per hive remained broadly stable and showed a downward tendency in the later years of the sample. The ARIMAX estimates reinforce this distinction. Annual average temperature has a negative coefficient in both models, but its association with total honey

production is weak and only marginally significant. In contrast, temperature has a statistically significant and negative effect on honey yield per hive, indicating that warmer conditions are linked to lower productivity at the hive level.

This pattern is consistent with evidence from broader agricultural research showing that climate variability often affects biological and performance-related measures more strongly than aggregate output [10, 11]. In pollination-dependent systems, temperature-driven shifts in phenology and forage availability have also been associated with reduced nectar flow and changes in foraging behaviour, which can translate into lower productivity even when total production remains relatively resilient [12, 13]. Overall, the findings suggest that honey yield per hive provides a more sensitive indicator of climate-related pressures in beekeeping systems than total honey production.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ADF	Augmented Dickey–Fuller
AIC	Akaike Information Criterion
ARIMA	Autoregressive Integrated Moving Average
ARIMAX	Autoregressive Integrated Moving Average with Exogenous Variables
BIC	Bayesian Information Criterion
TÜİK	Turkish Statistical Institute

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Using enzymatic analysis methods in separation of natural honey from imitated and augmented honey

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Abstract

Honey is a natural food product produced by honey bees (*Apis mellifera*) from flower nectar or secretions originating from living parts of plants and has important nutritional and therapeutic properties. Today, adulterated honey production through the feeding of bees with inexpensive sugar syrups such as sucrose, fructose, glucose, and invert sugar has become an important problem affecting both consumer health and honey quality. Current analytical techniques used for the detection of adulterated honey, including isotope ratio analysis, chromatographic, and spectroscopic methods, are generally expensive, technically demanding, and difficult to apply routinely in quality control laboratories. Therefore, there is still a need for rapid, cost-effective, and practical screening methods for distinguishing natural honey from adulterated honey. In this study, it was aimed to evaluate the potential use of enzymatic profile changes as practical biochemical markers for the discrimination of natural and feeding-induced adulterated honey. For this purpose, six experimental groups were established, including bee colonies fed with different sugar syrups (glucose, fructose, maltose, sucrose, and invert sugar) and a non-fed control group. Bee colonies were fed daily with sugar syrups adjusted to 50° Brix between May 25 and June 25, 2023. Honey samples obtained at the end of the feeding period were analyzed spectrophotometrically for diastase, amiloglucosidase, catalase, and glucose oxidase enzyme activities. Statistical analyses were performed using ANOVA, and significance was accepted at $p < 0.05$. The results demonstrated that there were no statistically significant differences among fructose, maltose, sucrose, and invert sugar syrup groups. However, significant differences were observed between the control group and syrup-fed groups in terms of amiloglucosidase, catalase, glucose oxidase, and diastase enzyme activities. The relatively different findings observed in the glucose syrup group were considered to be associated with the lower sweetness of glucose syrup and the possible continued nectar collection behavior of bees from environmental floral sources. The findings obtained in this study suggest that enzymatic activity profiles may have potential as practical and low-cost biochemical indicators for distinguishing natural honey from feeding-induced adulterated honey. However, further studies involving larger sample sizes, different geographic regions, seasonal conditions, and floral sources are required to validate the applicability and reliability of this approach under broader production conditions.

Keywords: Honey, Honey Adulteration, Enzymatic Analysis, Food Fraud, Honey Quality

Investigation of the Effect of Different Nutritional Groups on Bee Venom Production Capacity and Composition Under In Vitro Conditions

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Abstract

In recent years, supportive therapeutic approaches have increasingly complemented conventional medical treatments. Apitherapy uses bee-derived products such as honey, pollen, propolis, royal jelly, and, more recently, bee venom. Bee venom shows promising bioactivity across diverse diseases, yet clinical use is constrained by allergic reactions. Enhancing the relative abundance of disease-relevant components may improve efficacy and safety. This study evaluated whether diet alters bee venom yield and composition under in vitro conditions. Newly emerged bees (same-day birth) were allocated to five cages per group (150 bees/cage) and fed for 20 days with glucose, fructose, sucrose, invert sugar, or honey (control). On day 21, bees were frozen, venom sacs were dissected with stingers, and apamin, melittin, and phospholipase A2 were quantified by HPLC at Muğla Sıtkı Koçman University. Venom quantity increased in all feeding groups, with invert sugar producing the greatest increase. Melittin levels did not differ significantly among groups. Apamin differed significantly in the invert sugar and sucrose groups, while phospholipase A2 showed significant differences with glucose, fructose, and invert sugar. Targeted feeding may therefore enable production of bee venom with optimized therapeutic profiles.

Keywords: in vitro, apamin, melittin, Phospholipase A2, nutrition

Determination of Some Chemical Properties of Propolis Samples Provided from Ordu Province

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Abstract

Propolis is a bee product produced by honeybees and possesses various bioactive properties. The chemical and biological characteristics of propolis vary depending on the geographical features of the region where it is produced. Although research on propolis characterization continues in various countries worldwide, a consensus has yet to be reached regarding the specific criteria for its classification. This is due to the numerous environmental and genetic factors influencing propolis properties, which hinder the production of standardized propolis and complicate its characterization.

This study aims to investigate the properties of propolis samples obtained from apiaries practicing stationary beekeeping in Ordu province, Turkey, and to determine some of their key characteristics. Within this scope, propolis samples were extracted using an ultrasound-assisted extraction method to obtain ethanolic extracts. The samples were then analyzed for balsam content, wax content, Brix value, pH, electrical conductivity, total phenolic content, %DPPH radical scavenging activity, FRAP (ferric reducing antioxidant power), phenolic compound composition, and volatile compound profiles.

The analysis revealed significant variations among the samples. The fact that propolis samples produced even within the same provincial boundaries exhibited distinct properties supports previous research findings. Based on existing literature and the results of this study, it is evident that attributing generalized characteristics to propolis from a given region would be inaccurate. Therefore, target-oriented utilization of propolis is essential.

Keywords: Antioxidant, Phenolic compound, Propolis, Ultrasound, Volatile compound

Optimization of Extraction and Encapsulation Parameters of Propolis and Its Application in Functional Food Systems

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Highlights

- Optimization of extraction and encapsulation techniques enhanced the bioactivity and sensory acceptability of propolis.
- Encapsulated propolis powders successfully enriched ice cream formulations while maintaining desirable quality attributes.

What are the main findings?

- Encapsulation improved the microstructure, texture, and color stability of propolis-enriched ice cream.
- The process effectively masked the strong taste and odor of propolis, increasing consumer acceptability.

What is the implication of the main finding?

- Propolis, when processed under optimal conditions, can be incorporated into foods as a functional ingredient.
- This approach opens opportunities for developing consumer-friendly products with added health benefits.

Abstract

Propolis, produced by bees by combining plant resins with their own secretions, is a vital natural product known for its antibacterial, antiviral, and antioxidant properties, as well as its immune-modulating effects. However, raw propolis contains wax and various impurities that limit its direct application and bioavailability. This study aimed to enhance the biological activity of propolis via extraction optimization and to improve its sensory acceptability using encapsulation techniques.

In the first phase, extraction conditions were optimized using Response Surface Methodology (RSM), while lyophilization and specific coating materials were employed to boost bioavailability. In the second phase, the resulting encapsulated propolis powders were incorporated into ice cream formulations at various ratios and monitored throughout a 90-day storage period. The analysis revealed that propolis enrichment significantly increased the phenolic content of the ice cream. Moreover, encapsulation not only improved the product's microstructure and textural properties but also preserved key quality parameters like color, while effectively masking the characteristic strong taste and odor of propolis. These findings suggest that when processed under optimal conditions, propolis serves as a promising functional ingredient for food applications.

Keywords: propolis; RSM; optimization, encapsulation, functional food

Acknowledgments

This study is based on data derived from the doctoral thesis titled 'Investigation of the Effects of Propolis Extracts Encapsulated with Different Materials on the Functional Properties of Ice Cream.' Furthermore, this research was supported by the General Directorate of Agricultural Research and Policies (TAGEM) under project number "TAGEM/HSGYAD/A/22/A3/P6/5578."

The BEE-OPTIMA Workshop was built upon a shared vision of strengthening the future of sustainable apiculture through data-driven decision making, optimization, digital technologies, and multidisciplinary collaboration. Beekeeping is not only an agricultural activity, but also a vital component of biodiversity, food security, rural development, and ecosystem sustainability. However, climate change, resource limitations, habitat degradation, productivity challenges, and increasing uncertainty continue to create complex pressures on the sector.

This workshop was organized as a scientific and collaborative platform to discuss innovative approaches that can support more resilient, efficient, and sustainable beekeeping systems. At the core of BEE-OPTIMA lies the idea that modern apiculture requires integrated solutions that combine field knowledge with analytical methods, spatial intelligence, digital monitoring, decision support systems, and optimization-based planning.

The contributions included in this proceedings volume reflect this perspective. They bring together academic insights, applied research outcomes, and practical solution-oriented studies addressing different dimensions of modern beekeeping. From resource allocation and apiary site selection to digital monitoring, traceability, quality management, and sustainability-oriented decision support, these studies demonstrate the importance of connecting scientific knowledge with real field needs.

BEE-OPTIMA is more than a workshop proceedings volume; it is a collective effort to bridge research, technology, and practice for the benefit of beekeepers, researchers, institutions, and future generations. By encouraging interdisciplinary dialogue and long-term collaboration, we hope that this initiative will contribute to the digital transformation and sustainable development of apiculture.

I extend my sincere gratitude to all researchers, young scholars, project partners, invited speakers, reviewers, and members of the organizing committee whose valuable contributions made this event possible. BEE-OPTIMA represents an important step toward smarter, more sustainable, and more resilient beekeeping systems.

Dr. Şahin Aydın
Chair, BEE-OPTIMA Workshop
Founder, INTALA LAB
FMV Işık University, Türkiye

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