agriculture

MDPI

Article

Honeybee (*Apis* spp.) (Hymenoptera: Apidae) Colony Monitoring Using Acoustic Signals from the Beehive: An Assessment by Global Experts and Our Feedback

Muhammad Zahid Sharif [1,2,*], Nayan Di [1,2] and Baizhong Yu [1,2]

1 Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei 230031, China
2 Science Island, University of Science and Technology of China, Hefei 230026, China
* Correspondence: zahident@mail.ustc.edu.cn or 2011ag4010@uaf.edu.pk

Abstract: Because the sounds emitted by a managed honeybee colony embrace a wealth of information about the status within and outside the beehive, researchers are interested in developing a beehive sound-based assessment of the colony situation. However, how the global experts rank this approach is unclear. We assessed the importance of beehive sound-based colony monitoring using formal expert elicitation. Our results indicate that policy-making bodies should focus on a non-invasive acoustic approach to monitor swarming, honeybee health, pesticides, and environmental pollution at apiaries, as these were considered very important factors with high confidence by global experts. Moreover, all other factors (pests and pathogens, weather conditions, predators, food availability, and spatiotemporal patterns) are rated as important, but experts' confidence in acoustically monitoring a few of the factors differs. Because experienced forager bees emit bursting sounds during the waggle dance (particularly during the waggle-run phase) at a specific angle on a vertical comb within the hive, we propose an acoustics-based recording setup using a Raspberry Pi and a QuadMic Array to investigate how this sound can predict the spatial and temporal information of the available food sources. In this article, we highlight how the factors falling into the inconclusive category of confidence have the potential to be acoustically monitored. Besides, this paper suggests new and unexplored directions for opening a window for future research in beehive acoustics.

Keywords: beehive acoustics; colony status; factors monitoring; expert elicitation; importance and confidence; new directions; acoustics-recording setup; spatiotemporal information

check for updates

Citation: Sharif, M.Z.; Di, N.; Yu, B. Honeybee (*Apis* spp.) (Hymenoptera: Apidae) Colony Monitoring Using Acoustic Signals from the Beehive: An Assessment by Global Experts and Our Feedback. *Agriculture* **2023**, *13*, 769. https://doi.org/10.3390/agriculture13040769

Academic Editors: Bartosz Piechowicz, Anna Koziorowska and Elena Gonella

Received: 20 February 2023
Revised: 15 March 2023
Accepted: 17 March 2023
Published: 27 March 2023

1. Introduction

Pollinators are important for multiple reasons, including food diversity, biodiversity, and conservation of natural resources [1]. About more than 75% of blooming or flowering plantations successfully reproduced through animal pollination worldwide [2]. Pollination amenities subsidize billions of dollars to the world's crop productivity as well as contributing to food security [3]. Honeybees are one of the key pollinators, and about 73% of world-cultivated crops rely on a range of bees [1]. In recent times, pollinator bees have been a focused subject of environmental debate because they are facing colony losses at various rates [4]. This decline attained key consideration in 2006, when a huge number of honeybee colonies had to face a dwindling situation entitled "Colony Collapse Disorder (CCD)" [5]. Nonetheless, major changes in colony population dynamics and overall colony health may occur within two weeks (e.g., loss of the whole colony due to swarming or parasite infection, or a queenright or queen-less situation), necessitating continuous monitoring [6]. Various external factors influence honeybee colony health, including factors such as intensification of pathologies, pollution, chemicals (i.e., pesticides and herbicides), insect predators and pests, climate change, and others [7–11]. Because of the threats and losses induced by the aforementioned factors, monitoring honeybees to ensure their colonies' survival is crucial for apiarists.

In the preceding few years, researchers have been exploring non-invasive methodologies for uninterrupted monitoring and automatic health recognition of honeybee colonies. Extraordinary consideration has established the monitoring of certain physical variables, including temperature, humidity, colony acoustics, colony vibration, colony weight, and gas contents [12]. Despite numerous smart monitoring structures for honeybees as well as hives, depending on various sensors and measuring quantities, having been projected for many years, the most promising ones are centered on acoustic analysis. Honeybees use vibroacoustic information in the colony through the wax comb and waggle dance to communicate with each other [13]. Only by employing a simple microphone along with an acquisition system could one apprehend the colony's health status [14]. Monitoring the soundscape of a bee colony and analyzing multiple acoustic features offer imperative information regarding inside and outside colony conditions. Acoustic analysis, not merely in bees but also in birds, is being extensively used over the globe [15,16].

Swarming as well as invasion are both linked with significant acoustic variations. Whether bees are excited or nervous can be directly mirrored by analyzing the acoustic spectrum of bees. In contrast, relating to disease, the bees' sound slowly declines due to a weakening in the colony's strength [17]. In discussing swarming, Vancata [18] proposed that within 21 days of a primary swarm, the frequency spectrum of a honeybee colony changes from 200 to 500 Hz. Another study describes that power spectral density is also augmented at about 110 Hz; imminent to swarm, the hive's acoustics increase in amplitude as well as frequency to 300 Hz, and sometimes a prompt transformation occurs from 150 Hz to 500 Hz [19]. Furthermore, talking about the health of a colony, when bees are healthy (with a queen), the colony sound signal indicates a unique frequency pattern of about 400 Hz that is distinct from that attained by an unhealthy or queen-less colony [20]. Employing LSTM neural networks to detect this queen-less state in hives through acoustic signals exhibits highly encouraging results [21]. Apart from swarming and queen-less states, honeybee (*Apis mellifera cypria*) colonies also face invasions of insect predators like the Oriental hornet (*Vespa orientalis*), which produce a typical hissing sound with a dominant frequency of 6 kHz [22]. Moreover, antipredator pipes are produced at high rates when workers of *Vespa soror* predators are present outside the entrances of honeybee (*Apis cerana*) colonies [23].

In our previous research [24], results have shown that the occurrence of trichloromethane-laced air within the honeybee colony can be identified by investigating the acoustic signatures emitted by chemically influenced honeybees. To distinguish chemically influenced beehive acoustics, our research outcomes established soundscape indices [out of low-level signal features and Mel-frequency cepstral coefficient (MFCC)] as a very useful and effective set of features. The excessive use of pesticides and herbicides in agriculture is causing severe impacts on the environment, and researchers are considering honeybees as a biologically distributed sensor to detect the presence of pesticides in the neighborhood. Therefore, behavioral changes in bees can be monitored. Due to this fact, various investigations suggest using honeybee colony sound and its frequency spectrum (including the frequency band and frequency resolution) as a useful source to detect environmental pollution or the presence of pesticides in agricultural settings [24,25]. Cejrowski and Szymanski [17] introduced a novel impression of a bee's fingerprint for the identification of a specific bee colony. According to this new conception, the spectral entropy (SE) was employed as an additional feature owing to its strongest association with ambient temperature. On the other hand, the experimentation was piloted again for the Acoustic Complexity Index (ACI) feature, and the results or inferences obtained were very consistent. They reflected the ACI index as the most powerful and unfailing method for the description of honeybee colony acoustics.

The aforementioned paragraphs describe the importance of honeybee colony acoustics to monitor swarming, predator attack, colony health, weather conditions, environmental pollution, and the impact of chemicals, but whether honeybee colony acoustics fingerprints could be indicative of the impact of land cover, land management, spatial (directional) patterns, and level of food richness is not clear yet. Although the role of bioacoustics, including avian and animal sounds, is reported to indicate spatiotemporal patterns [26], land cover and land management [27], and level of food richness [28], in the case of bees, the role of colony soundscape or acoustics is presented by the experts in this paper.

Therefore, in our current research, we have applied a structured expert eliciting methodology and a worldwide representative group of experts working in the field of honeybee colony acoustics to evaluate the relative importance of bees' acoustics in relation to the factors that are a threat to bees or possibly causing colony collapse disorder (CCD) in bees, as well as some ecological factors. Moreover, this paper not merely presents expert opinions or comments on a particular factor influencing colony acoustics but also highlights expert-advocated new directions for exploration in this field.

An extensive study has been conducted on the process of honeybees learning, decoding, and assessing the information contained in their waggle dance language. This language is used to communicate with other honeybees. The information included in these dances, which includes the distance and direction to food sources, is a classic example of symbolic communication among bees [29,30]. Video monitoring studies of these dances have yielded positive results for their role in providing spatiotemporal information [31–33], but no proper investigation based on waggle dance acoustics (which dancers emit during the waggle-run phase) is carried out to determine the same role via recording and analyzing acoustic data. Although some studies are carried out to exhibit how the follower bees sense these acoustic signals in the dark hive for spatiotemporal information, the mechanism or any approach on how a researcher can use these acoustic data for extracting such information is lacking. Therefore, we propose an acoustic recording setup based on a Raspberry Pi and a QuadMic Array to examine how the bursting sounds emitted by experienced forager bees during the waggle dance at a specific angle on a vertical comb within the hive are recorded and analyzed to predict the spatial and temporal information of the available food sources.

2. Materials and Methods

2.1. Designing and Distribution of the Questionnaire

To collect data, questions were created in the online form using Google Form, a survey administration software. Three sections were structured in a form that contained multiple pieces of information or questions, (see Google Form-Questionnaire.pdf in Supplementary Materials). Section 1 highlights the title of the research, provides information regarding the purpose of the research, and assures participants about the privacy of their feedback or responses. Section 2 collects the personal data of the participants, which includes name, e-mail address, sex/gender, country/location, education, and employment. Finally, Section 3 focuses mainly on research-based questions that relate to the importance of honeybee colony acoustics associated with apiary monitoring and some ecological factors. Overall, 11 questions were asked in these sections, and different question types were used. Three multiple-choice questions were created, but only one answer was allowed to be selected. One question type was "checkboxes" where participants were allowed to select multiple options for their answers. While two questions were generated in another question type designated as a "multiple choice grid," comprising 11 questions in rows and 6 options in columns to answer each question. Moreover, three short questions and two paragraph-type questions (long questions) were generated in the form. The contents of the questionnaire are presented in Table 1, and a detailed questionnaire can be seen in Supplementary Materials (Google Form-Questionnaire.pdf).

Table 1. Contents of the questionnaire.

Sections		Detail/Questions	Questions Type
Title of the Research and a note for the participants (experts)	1	A global expert assessment on the role of honeybee colony acoustics associated with apiary monitoring and ecological factors.	-
	2	Institutions promoting this questionnaire, the objective of the questionnaire, and a description of the privacy of the data provided by participants.	
Personal Data	1	Name	(d)
	2	Email	(d)
	3	Age	(a)
	4	Sex/Gender	(a)
	5	Country/Location	(d)
	6	Education	(a)
	7	Employment	(a)
	8	Core interest in the area (s) of acoustic research	(b)
Research Questions	1	Importance of monitoring the beehive and other factors through honeybee colony acoustics.	(c)
	2	The confidence score for each factor, which can be effectively monitored via honeybee colony acoustics.	(c)
	3	Comments from experts on the importance of factors that can be monitored via colony acoustics.	(e)
	4	Experts' suggestions about new and unexplored areas where honeybee colony acoustics could be used to monitor them.	(e)

Note: Here, small letters (a–e) show a particular question type. a = multiple choice question (MCQ), b = checkboxes, c = multiple choice grid, d = short question, e = long question.

The questionnaire was distributed in the English language version and filled out by the researchers (here we call them "experts") working on honeybee colony acoustics around the globe. The link to the Google Form to fill out the questionnaire was sent via e-mail to the experts, and also shared via messages on the ResearchGate platform (https://www.researchgate.net/ (accessed on 10 March 2022)). In the present study, we want to assess the role of honeybee acoustics concerning various categories like colony health, swarming behavior, pest and pathogenic infestations, predator attack, chemical/pesticide impact, weather conditions (temperature, humidity), environmental pollution, land cover and land management, food availability, and spatiotemporal patterns. Therefore, to get a composed representation, a link to the questionnaire was sent to several experts (about 50 experts) working in each relevant category, although merely 11 experts responded to the questionnaire. Receiving limited responses is due to the fact that honeybee colony acoustics is still a fresh topic and has a dearth of experts, although this is growing now. Despite the limited number of responses we were able to collect, we are confident that this study has assisted us in identifying several promising avenues for future research into the application of bioacoustics to the study of honeybee colony behavior and the monitoring of colony status in order to detect variant factors.

2.2. Delineations of Scores

Experts were asked to choose importance scores for each factor for their monitoring through a colony acoustics probe using a five-point Likert scale as described in a questionnaire form (see questionnaire in Supplementary Materials for a detailed scoring system). Experts rated the importance of the role of colony acoustics for each factor at the current time on a 1–5 scale from "not important to the most important". Moreover, experts also rated the confidence scores for use of colony acoustics for each factor on a 1–3 scale (representing a low, medium, or high scale, respectively), facilitating experts to provide their decisions with a level of confidence based on the extent of evidence they were fully aware of and its quality. The scoring system applied for assessing the importance and confidence level of overall factors is exhibited in Table 2.

Table 2. Scoring system used during scoring, with importance and confidence level assigned for each factor being monitored through honeybee colony acoustics.

Score	**Five-Point Scale**					**Unknown**
Factors	1	2	3	4	5	
Factor x	not important	a little important	important	very important	the most important	unknown
Confidence (repeated for every factor)	low	medium	high			unknown

2.3. Compilation of Experts' Remarks through a Rigorous Procedure

Regarding two descriptive questions asked in the questionnaire (first, the perspective of experts regarding the importance of colony acoustics for each mentioned factor and second, suggestions on where honeybee colony acoustics could be used to explore novel avenues), a revised version of a formal consensus scheme designated as the Delphi technique was applied [34]. To collect reliable information, it was mentioned that each expert should comment on the role of colony acoustics for monitoring merely those factors for which they have expertise. In the first round, comments from each expert were compiled into a single document (comments were included but anonymously) and then sent for review not only to each expert who participated in this work but also to those who could not participate due to some reasons. In this round, all experts were asked to play the cynic role (to critically analyze others' opinions) and review this document and return it with their decisions on whether they agree, disagree, or are neutral with particular remarks and further comments (if applicable) to challenge the point of view of an expert. In the second round, all the reviewed information collected from experts was compiled again in a document with some new information. In the final round, top experts investigating colony acoustics (here, top experts mean most senior researchers with high impact factors in publications and quality research work) were designated based on mutual consensus among the authors. The data compiled during the second round was sent to these top experts for review and final recommendations. Based on the recommendations they made, final information in the form of summaries or points was presented by the authors in the paper (Table S1: Summary of the experts' comments compiled during round two for the questions asked in a questionnaire). The main purpose for adopting this peer review process was only to extract and present credible information in this article.

2.4. Data Analysis

Median scores were used to derive importance scores for factors as well as rate the confidence categories for all final scores. The median of all the factors from overall universal experts was calculated by using the formula: median = {(n + 1)/2}th, where "n" represents the number of scores of importance in the set and "th" denotes the (n)th number.

In the process of assigning confidence categories, two things, such as the quantity and quality of the evidence, were created based on the experts' assigned confidence scores for each factor. The confidence score is the percentage of the maximum promising score, denoted by the median confidence scores, with the median added for the factors.

While the interquartile ranges (IQR) for importance and confidence were computed through the difference between the third and first quartiles or cut-off points, as mentioned below.

$$\mathrm{IQR} = \mathrm{Q3} - \mathrm{Q1} \quad (1)$$

Through descriptive analysis, mean scoring and IQR for importance and confidence highlighting confidence categories of each factor for being monitored via honeybee colony acoustics were discussed. Additionally, the confidence level was also analyzed following the four-box model for qualitative communication of confidence (Figure 1).

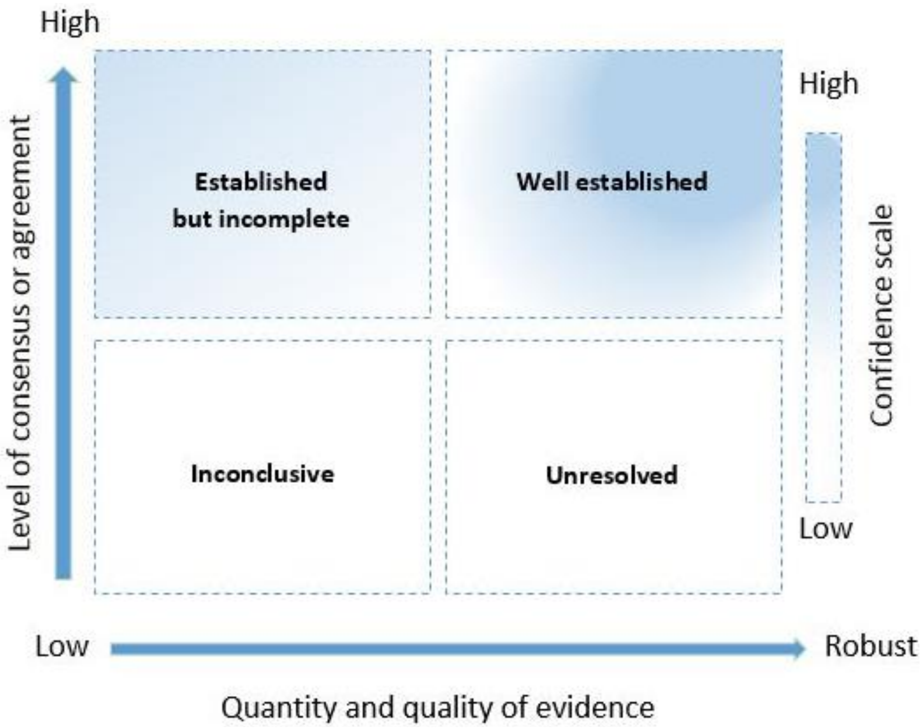

Figure 1. Confidence rises toward the top-right corner, as suggested by the growing strength of shading.

To test whether or not there is a relationship between the level of importance and level of confidence for the factors (or to check that there is a statistical difference or not between the factors in how experts answer the questions), we used a chi-square test as inferential statistics, where measurements of Phi and Cramer's V gauged the strength of this relationship (Table S3: Cross-tabulation of the experts' rating on importance and confidence regarding monitoring of multiple factors through beehive colony acoustics; Table S4: Chi-Square coefficient; Table S5: Symmetric measures for the strength of a relationship).

Figures were drawn in this paper by employing the ggplot2 package in R v.3.5.3, and we used the "maps" package in R to create a map to represent the number of participating experts from various regions around the globe. Furthermore, the statistical test (chi-square) was run using the SPSS (version 21.0) software.

3. Results

3.1. Description of Personal Information of Experts

Concerning the section "personal data" in the questionnaire, important information can be retrieved from Figures S1–S4 in Supplementary Materials, which show that all the participants from around the globe (Figure 2) were mature and experts in the field of honeybee colony acoustics.

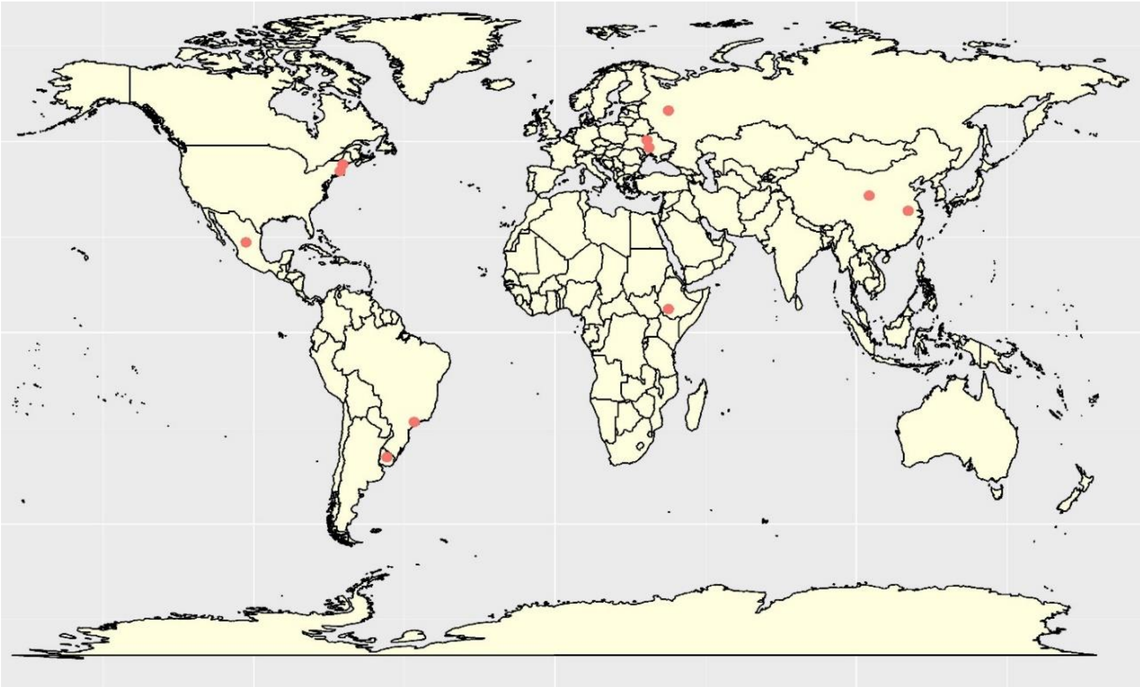

Figure 2. Map showing the experts who participated to respond to the questionnaire from around the globe.

Moreover, the results (Figure 3) exhibit that the experts who participated in responding to the questionnaire have expertise in acoustic monitoring of honeybee colonies for multiple factors (discussed in this paper) except pests and pathogens, land cover, and land management. Why did any participant not have the expertise to acoustically monitor these factors via colony sound? After thoroughly searching the literature, we found that we lacked the expertise to monitor these factors because we had not carved out the potential in these areas yet.

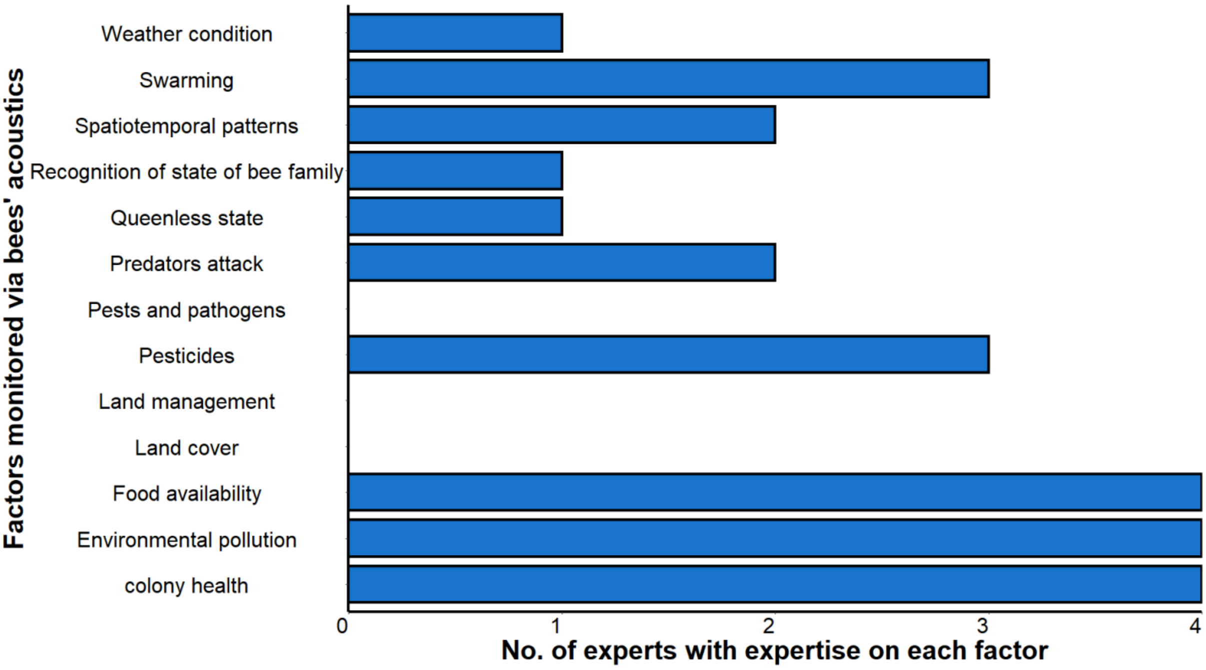

Figure 3. This figure represents the number of participating experts who have volunteered their expertise to acoustically monitor honeybee colonies for particular factors.

3.2. Description of Research-Related Questions

3.2.1. Importance and Confidence to Monitor Different Factors via Honeybee Colony Acoustics

Experts' scores for the importance of colony acoustics to monitor various factors are presented in Figure 4 and Table 3. Median scores for the importance of factors show that swarming, honeybee colony health, pesticides, and environmental pollution are 'very important' to be monitored through honeybee colonies' or hives' acoustics (Table 3). Moreover, confidence scores indicate that swarming, honeybee health, environmental pollution, and pesticides, with 'high' confidence (Figure 5) and robust evidence, are categorized as 'well established' (Tables 3 and 4), and can be acoustically monitored. Results indicate that global experts are highly confident in the acoustic monitoring of these factors (see Table S2 for information on the percent of experts exhibiting their confidence for the acoustic monitoring of various factors at different levels of confidence). These conclusions are reinforced by substantial evidence in several publications [20,24,25].

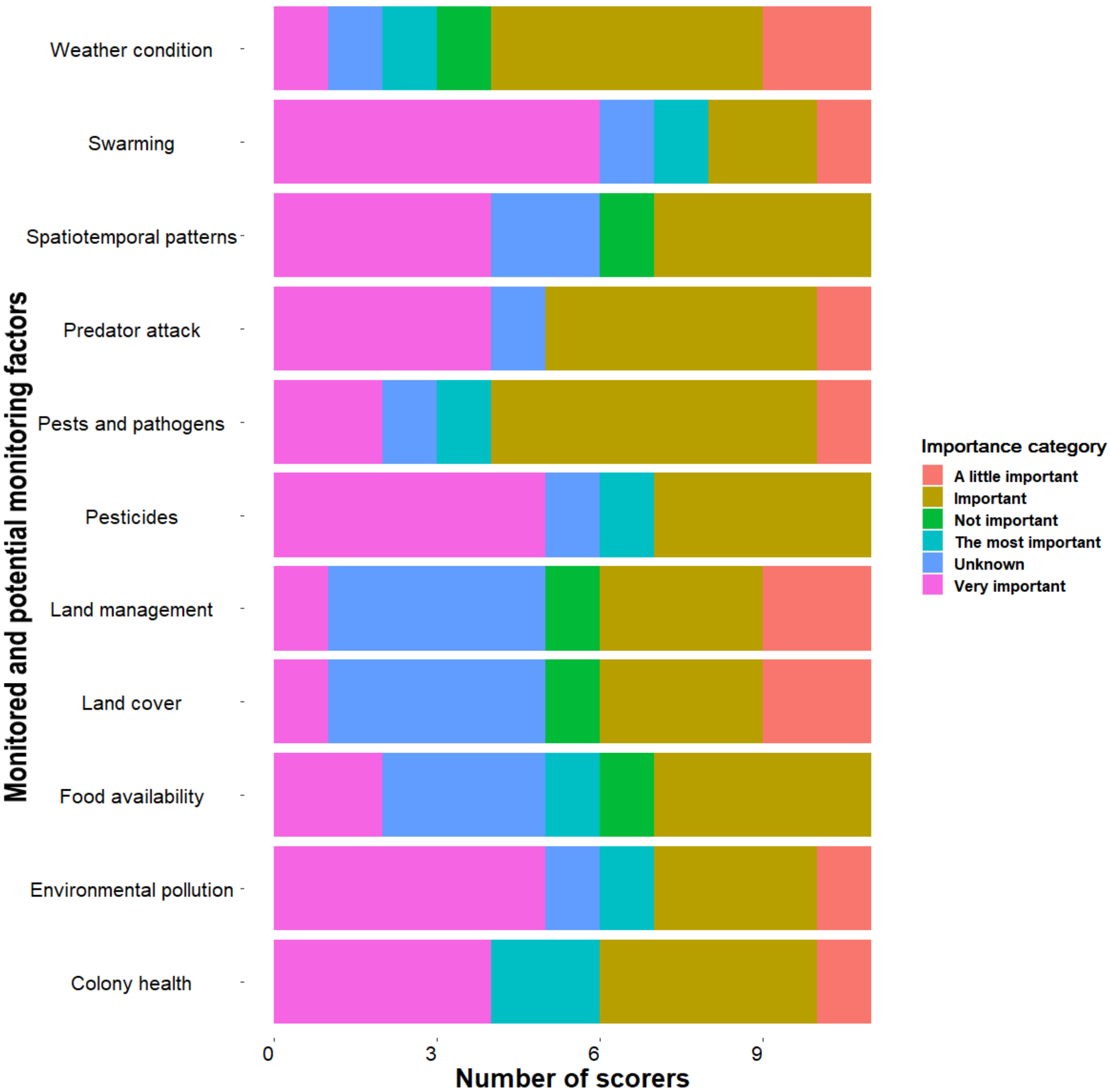

Figure 4. Final breakdown of importance level scoring for each factor for their potential monitoring via honeybee colony acoustics.

Table 3. Final factor scores summarized: The median scores for importance (1–5) as well as confidence (1–3) are exhibited here according to the described scale. Moreover, interquartile ranges (IQRs), for importance and confidence, are presented in the brackets. The total number of scorers plus "% unknown" scoring is displayed, along with the confidence category for each factor.

Factors	Importance (IQR)	Confidence Score (IQR)	No. of Scorers	% Unknown	Confidence Category
Colony health	4 (1)	3 (0.75)	11	9	Well established
Swarming	4 (0.75)	3 (0)	11	9	Well established
Pests and pathogens	3 (0)	3 (1)	11	27	Well established
Predators attack	3 (1)	3 (0.75)	11	9	Well established
Pesticides	4 (1)	2.5 (1)	11	27	Well established
Weather condition	3 (0.75)	2 (0.5)	11	36	Established but incomplete
Environmental pollution	4 (1)	3 (1)	11	18	Well established
Land cover	3 (1)	1.5 (1)	11	63	Inconclusive
Land management	3 (1)	1.5 (1)	11	63	Inconclusive
Food availability	3 (1)	2 (1)	11	27	Established but incomplete
Spatiotemporal patterns	3 (1)	2 (1)	11	36	Established but incomplete

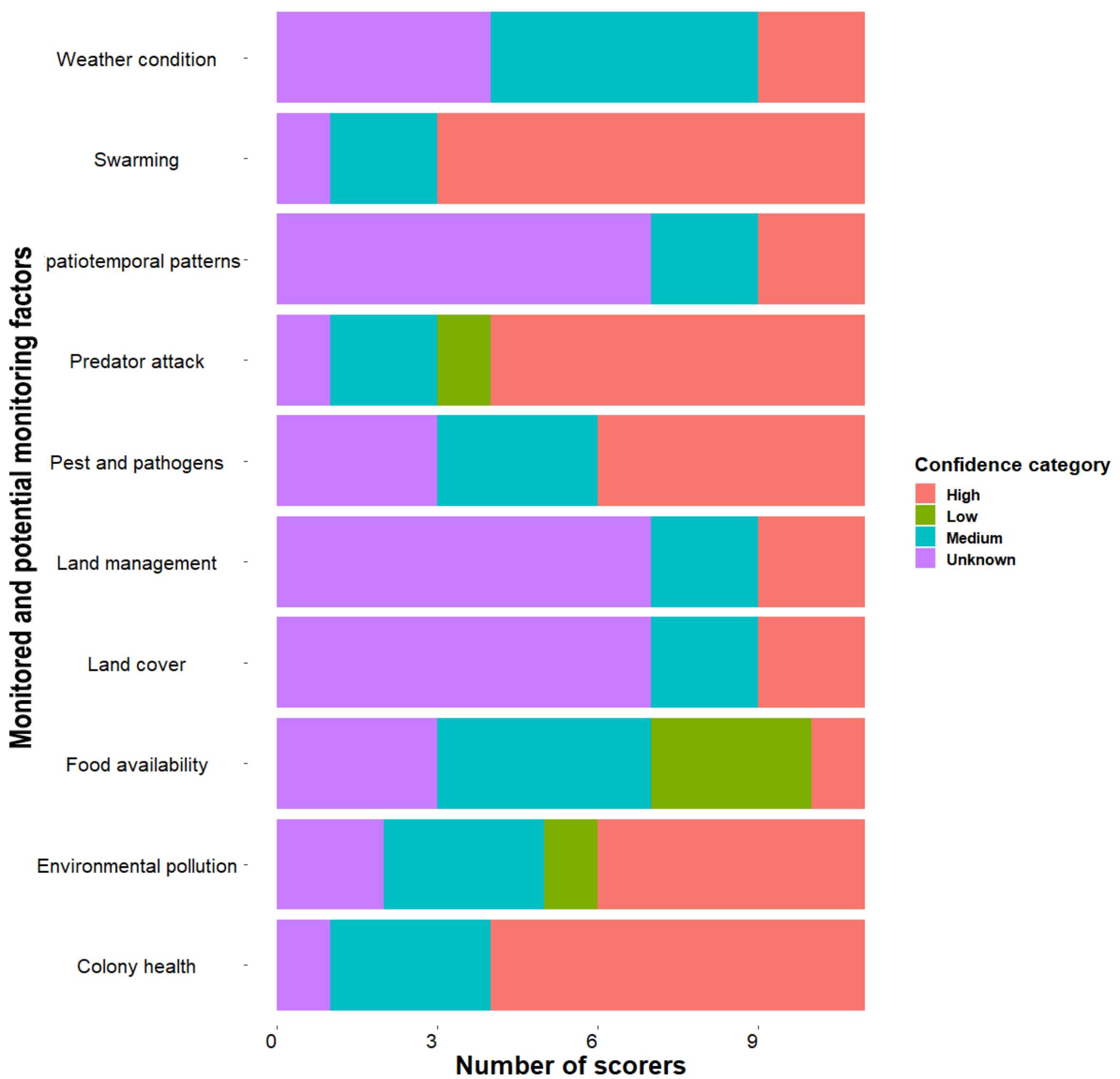

Figure 5. Final breakdown of confidence level scoring for each factor for their potential monitoring via honeybee colony acoustics.

Table 4. Communication on the gradation of confidence.

Confidence Category	Definition	Threshold, Based on Scores of Confidence, % Unknown, and Consensus Indicator (IQR)
Well established	Robust evidence High agreement or a high level of consensus	Confidence score ≤ 66.7% or the proportion of unknowns is <40% IQR ≤ 1
Established but incomplete	Low-quality evidence High agreement or a high level of consensus	Confidence score < 66.7% and the proportion of unknowns is ≥40% IQR ≤ 1
Unresolved	Robust evidence Low agreement or low level of consensus	Confidence score ≥ 66.7% or the proportion of unknowns is <40% IQR > 1
Inconclusive	Low-quality or no evidence Low agreement or low level of consensus	Confidence score < 66.7% or the proportion of unknown responses is <40% IQR > 1

We act in accordance with the four-box model for the qualitative communication of confidence (Figure 1). The level or gradation of confidence in each outcome is established based on the quantity and quality of evidence revealed by confidence scores (Methods) plus a level of agreement among global scorers or experts, interpreted by a consensus indicator or the interquartile ranges (IQRs) of expert scores for each factor.

For acoustic monitoring, all other factors, including pests and pathogens, predator attacks, weather conditions, land cover and land management, food availability, and spatiotemporal patterns, are scored as 'important' (Table 3 and Figure 4). However, experts' scores present variation in the confidence level of acoustic monitoring of these factors like weather condition, food availability, and spatiotemporal patterns, which show 'medium' confidence, while land cover and land management show 'low' confidence (Table 3, Figure 5). The aforementioned factors with medium confidence contain low-quality or limited available evidence, thus being categorized as 'established but incomplete,' while low-confidence factors are least important relative to other factors and contain very limited, unconvincing, and low-quality evidence, thus being categorized as 'inconclusive' (Table 3).

The interquartile ranges (IQRs), a consensus indicator, assessed the factors for the level of agreement or consensus among the experts (definitions for IQRs are provided in Table 4) for each acoustically monitored factor. The IQRs of importance and confidence score exhibit that experts have reached a high level of consensus or agreement that all factors are important and can be monitored through the honeybee colony's acoustic impressions. Anyhow, we also have noted variations in IQR values among certain factors, like swarming (IQR = 0), predator attack (IQR = 0.75), colony health (IQR = 0.75), and weather condition (IQR = 0.5), which display smaller values while all other factors display a bit larger values (IQRs = 1). Former factors with smaller IQR values show a relatively premier level of consensus than the latter factors; the reason might be that they have sufficient evidence or publications and are thus placed in the 'well established' confidence category (Tables 3 and 4).

Apart from this, certain factors (land cover, land management, spatiotemporal patterns, and weather conditions) have been collectively scored as 'important' and experts have also reached a high level of agreement, but the exception is that a considerable number of experts scored these factors as "unknown," which were 63% for land cover and land management, 36% and 27% for weather conditions and spatiotemporal patterns, plus food availability, respectively (Table 3, Figures 4 and 5). To understand how experts rated their percent confidence for sound-based monitoring of each factor at different levels of confidence (i.e., high, medium, and low), please see the Supplementary Table S2 (Information on the percent number of experts exhibiting their confidence for acoustical monitoring of various factors at different levels of confidence).

As inferential statistics, Chi-Square test values (chi-square coefficient of 8.590, $p = 0.043$) indicate that there is a statistically significant and positive association between experts' ratings of importance and confidence regarding all the factors. To put it another way, as the importance of acoustically monitoring various factors increases in experts' opinions, their level of confidence in monitoring these factors also increases (Table S3: Cross-tabulation of the experts' ratings on importance and confidence regarding monitoring multiple factors through beehive colony acoustics; and Table S4: Chi-Square Coefficient). Moreover, for detailed results of the chi-square test, including symmetry measures (Phi and Cramer's V) to find the association between variables, please see the Supplementary Materials (aforementioned Tables S3–S5: Symmetric measures for the strength of a relationship).

3.2.2. Experts' Comments on the Importance and New Directions of Colony Acoustics

After a couple of rounds, peer-reviewed information from the global experts is gathered. This information tells us about the importance of colony acoustics and suggests new and unexplored areas where the use of honeybee colony acoustics could be central. Compilated peer review information on the importance of acoustically monitoring various factors is conferred in the Supplementary Materials (see Table S1: Summary of the experts' comments compiled during round two for the question asked in a questionnaire). Furthermore, experts have also pinpointed new directions that could help researchers advance apiary monitoring via acoustic investigations of bee colonies (see Table 5 for the new suggested directions).

Table 5. A compilation of the experts' feedback on a question asked in a questionnaire: "What do you suggest are the new areas where honeybee colony acoustics could be used to monitor them?" during the second round of the peer review process.

New Directions to Acoustically Monitoring Honeybee Colonies	Level of Agreement among the Experts (%) for Given Comments		
	Agree	*Disagree*	*Neutral*
It can be predicted that environmental stressors (pollution, climate warming, and pesticides) may be monitored indirectly through the foragers' sounds. It can also be guesstimated that forager sounds and recruitment success change when the bees are exposed to stressful events, since sound production [35] and information use [36] are modulated by neuropeptides, such as octopamine, which, in turn, are modulated by stressors [37].	70	0	30
Researchers have yet to fully realize the potential of using bees sound to probe colony infestation with parasitic mites (Varroa destructor and other varroa mite species), and pests.	100	0	0
When a highly threatening predator (for instance, *Vespa soror*) comes close to the hive, colony workers start shrieking and generating various strong vibroacoustic signals at a frenzied speed and in parallel. Experts say that these vibroacoustic signals fuse or merge with Nasonov and venom gland volatiles generated by terrified colony mates and hornet-generated alarm signals that eavesdropping honeybees use to control their retaliation [23,38,39]. More investigations should be conducted to study the interaction between the level of threat and the above-mentioned gland volatiles (produced by the vibroacoustics of terrified colony workers) in those honeybee species that have not yet been checked for this particular phenomenon. In addition, explore some other frenetic predators that could be detected via the colony's acoustic signals. Experts believe that if acoustic signatures or patterns of bee colonies are collected for all frenetic predators, it would be promising to generate a database as well as an efficient system to identify the presence or attack of a predator on a beehive.	80	0	20

Table 5. *Cont.*

New Directions to Acoustically Monitoring Honeybee Colonies	Level of Agreement among the Experts (%) for Given Comments		
	Agree	*Disagree*	*Neutral*
Various soundscape indices, including the Acoustic Diversity Index (ADI), the Acoustic Evenness Index (AEI), the Bioacoustic Index (BI), and the Acoustic Entropy (H), are reported as important indices to determine richness or acoustic diversity as well as abundance in avian species [40–43]. So, it is likely that these indices can also be used to determine the diversity and abundance of honeybees buzzing in the environment at different spatiotemporal scales. When it comes to vocalizing animals, birds, or amphibians, it is true that soundscapes can reveal diversity. However, this is because soundscapes are described using metrics (based on spatiotemporal variations in frequency patterns, which are richer in cases of higher diversity of vocalizing species in the environment). The reviewers grasped and agreed on a critical point about how the soundscape is supposed to be measured for diversity within the environment of the hive, where the hive monitoring algorithm does not work very effectively. Researchers need to consolidate their efforts to examine if there is another way to localize genetic diversity within this noisy environment of the hive because intra- and interspecific differentiation by acoustic signaling plays an important role in the case of sympatric speciation [44]. Although honeybees flying in the environment/agriculture can be acoustically measured for diversity.	90	0	10
Acoustic properties of colony soundscapes can examine population size; this could assist researchers in digging deep into determining whether bees are surviving or collapsing (CCD) during a particular temporal scale.	80	0	20
Experienced forager bees may use sound to signal their nestmates for nectar quality, but more research is needed in this area.	100	0	0

3.3. Waggling Dance in a Colony and Its Effective Monitoring through Our Proposed Acoustics Recording Setup

Automation of bee colony evaluation utilizing specialized gear for distinguishing different behaviors taking place within the noisy beehive presents a big challenge to precision apiculture researchers. Raspberry Pi computers (RSPi) are one low-cost hardware option that are used for data preprocessing as well as model training and testing [45]. Voice recognition, voice control, and security systems are just a few audio-based applications made possible by the ability of the RSPi to record audio. The RSPi may be connected to a microphone in three ways: via USB, an external sound card, or Bluetooth. The first two ways are more reliable and provide the best audio quality. USB microphones are largely plug-and-play, requiring no extra hardware or software to function. In the latter case, the microphone jack is utilized on an external sound card, such as the Audio Injector Sound Card, to attach a microphone. Standard RCA connections can be used to connect the microphone to the sound card. On the other hand, Bluetooth microphones are the most frictionless approach to installing a microphone since no physical connection is required. However, compatibility concerns and erratic audio quality are disadvantages of Bluetooth mics; therefore, they are not ideal for honeybee colony acoustic recordings.

However, how is it possible to record audio from hives with multiple microphones simultaneously? The QuadMic Array is the best option to handle this situation. This is not mounted inside the hive because of its size and operational condition; instead, it may be fitted on the lid of the hive using a protective enclosure to keep these components secure. While microphones are placed inside the hive to make the collected sound a more realistic reflection of the condition of a beehive. The QuadMic Array is a four-microphone array based on the AC108 quad-channel analogue-to-digital converter (ADC) with Inter-IC Sound (I^2S) audio output that is compatible with the RSPi 4. The RSPi is used to take advantage of the faster processor (1.5 GHz Quad-Core Cortex-A72 (ARM v8) 64-bit SoC—Broadcom BCM2711). The sound data is stored in 32 G SD memory (Sandisk Ultra Micro SDHC Card, Edinburgh) and uploaded to the FTP cloud server via Wi-Fi.

The QuadMic array can be used for speech detection and identification applications, acoustic localization, noise control, and other audio and acoustic analysis applications. The array attached to the RSPi header can be used to simultaneously capture audio data from all four microphones attached in different directions. As part of an acoustic investigation using the four microphones, signal processing methods should be developed. The introduction of algorithms that mimic acoustic source directivity may aid in comprehending and characterizing spatial geometries, temporal information, and other features of acoustic systems. As building various signal processing methods and the introduction of algorithms can possibly mimic acoustic directivity or the spatial geometry of the acoustic data collected through our proposed technique (using a QuadMic array with a Raspberry Pi), if this role is somehow established, then we can hypothesize that it can be used to know about the waggle dances in honeybee colonies because through dances, dancer bees can tell their nestmates about the direction and distance of the food sources [29,31,46,47].

We anticipate that our suggested acoustics recording system (Figures 6 and 7) can successfully capture many acoustics-based waggle dance performances at various positions inside honeybee hives since four microphones are mounted to each corner of the frame. This might help decipher the polar coordinates or spatial information from dances to some degree and the temporal information more efficiently (the distance between the hive and the valuable food source) because the duration of the waggle run (a phase of waggle dance when the dancer waggles her abdomen and vibrates its wings, thereby producing a surge of acoustic activity) is positively correlated with the time duration bees need to travel to reach their destinations [29,31,46,47]. One report says that waggling for a second indicates that a food supply is located around a kilometer from the colony. Researchers at the University of Sussex's School of Life Sciences' Laboratory of Apiculture & Social Insects (LASI) stated that they had discovered that one second of the waggling (waggle-run phase) by foragers of *Apis melllifera* translates to around 750 m of distance to the food patch, according to The Guardian (https://www.theguardian.com/environment/2014/apr/03/honeybees-fly-further-in-summer-to-find-food-study-shows (accessed on 14 March 2023)). In contrast, recent research by Hu, et al. [48] shows that *Apis cerana* dancers need to engage in a waggle-run phase lasting longer than 1 s in order to travel the one kilometer to a food source. According to Kohl et al. [47], *Apis florea*, and *Apis cerana* need to perform a waggle-run phase for more than 1.5 s to travel the distance of 500 m while *Apis dorsata* need to perform this phase for less than 1 s to travel to the same distance. They conclude that dance dialects across the species constitute adaptations and thus affect the duration of waggle-run performances. Since the waggle-run phase is an audible phenomenon, we believe it is possible to utilize audio recordings of this phase to predict how far away the food patches are from the hive. Some audio files of merely waggle-run phase and others of entire colony (that were trained to distance of 300 m and 60 m) can be seen online from the Zenodo website (https://doi.org/10.5281/zenodo.7678084 (accessed on 14 March 2023); https://doi.org/10.5281/zenodo.7684255 (accessed on 13 March 2023)).

There is a limitation that other activities, such as hive cooling, cause wing vibrations that emanate sounds with a frequency comparable to dancing sounds [49,50], and some other phenomena, such as queen tooting and quacking (a communication system at the level of the colony that assists the worker population in the organized coordination of the release of queens), also produce several bursts of sound (as it happens in the case of the waggle run phase) with a fundamental frequency ranging from 200–550 Hz [51,52]. Therefore, a key question arises: how will we acoustically differentiate between the sound emitted via the waggle run phase and all other activities (hive cooling, queen tooting, and quacking) if they emit sounds of the same frequency range and/or are audibly comparable? To understand these distinctions, we will have to take support from the temporal structures of all these sounds associated with a particular behavior that occurs in the honeybee colony. These temporal structures can be obtained through spectrographic analysis in the domain of frequency and amplitude. Although temporal structures for queen piping (tooting and quacking) have been described in various publications, these structures for the waggle run phase of the bee waggle dance and hive cooling behavior have yet to be clearly investigated. So, once we have correctly recognized the acoustic signatures or structures of the waggle run phase, we will certainly be able to consider the duration of this acoustic phase as a measurement tool for detecting the duration (temporal information) the bees needed to travel to their food sources.

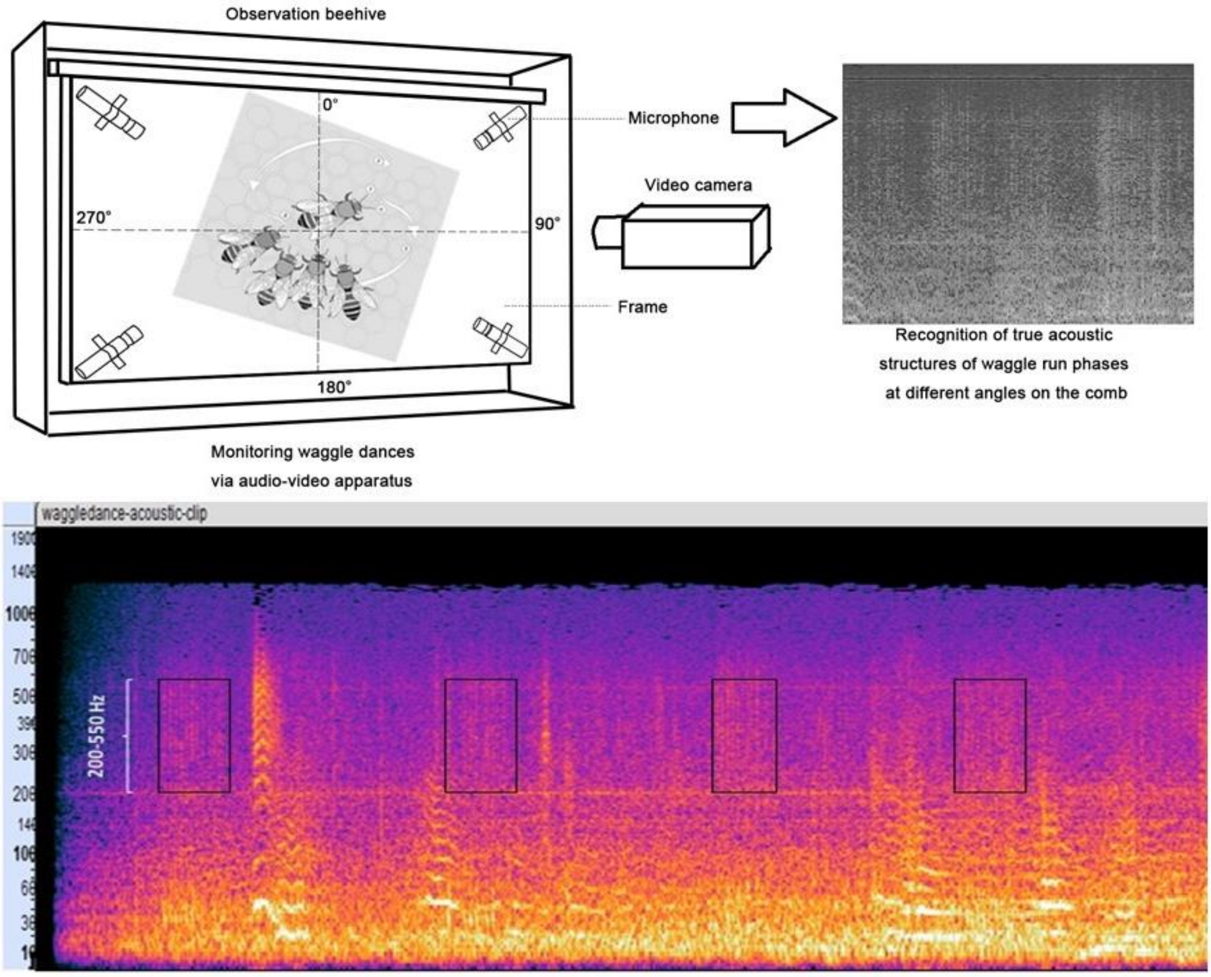

Figure 6. Our proposed setup is where waggle dancers are recorded in an observation beehive through audio-video monitoring for the bursting sound they produce during the waggle-run phase and their dancing angels on the comb relative to the position of the microphone (**left**), plus recognition of the true acoustic structures produced from these dances (**right**). Below is a view of the acoustic structure of the waggle-run phase of a dancing bee (from the *Apis mellifera* colony) in the form of a spectrogram (see the spectral composition of the waggle-run phase in the black-colored vertical boxes, which display frequencies between 200 and 550 Hz).

To communicate spatial or directional information with follower nest-mates, waggle dancers make an angle between the upward and waggle run directions on the vertical comb, which encodes the direction to a food source from the hive relative to the sun's azimuth (Figure 7), and while they are doing so, they generate a sound that falls within a specified frequency range of 250–300 Hz, peaking at 1 m/s, triggering a sound pressure of 1 Pa/mm at the wings, which is noticed running dorsoventrally (perpendicular to the plane of the wings) [47,53]. Because their wings act as an asymmetrical dipole emitter, dancer bees generate acoustic near fields when they flutter their wings. Furthermore, dancer bees generate an enormous flow of air particles by side-to-side shaking of their abdomens. The pressure gradients are low enough in radial directions away from the dancer bees, and they decrease quickly as they move away from the wings. When a bee shakes its body from side to side, the pressure of the "sound" that a stationary probe on one side of the bee picks up strongly at 12–13 Hz shifts. However, more importantly, we will need to look at various angles of dancer bees (during the waggle run phase) towards any microphone and notice what acoustic signatures or structures are formed at each angle (Figures 6 and 7). There are various signal processing methods, including beamforming, time-frequency analysis (i.e., short-time Fourier transform [STFT], wavelet transform, or constant-Q transform [CQT]), spectral analysis (for instance, Fourier analysis or cepstral analysis), and pattern recognition techniques (such as machine learning algorithms). Regarding spatial information, we believe that beamforming is the best approach because it uses the directional information captured by the quadmic array to extract the sound from a particular direction while suppressing noise from other directions. This technique can be used to detect the direction of the dancing sound and ignore bees noise from other directions, thus providing directional information about the food resources. Although this approach will help us to clearly capture the dance sound from a particular direction of the microphone within the hive, even then we need to know what is the angle or position of the dancing bee relative to the microphone and the sun's azimuth. To notice what acoustic patterns are formed at each angle, we can utilize pattern recognition techniques such as machine learning algorithms. We are positive that the use of both of the aforementioned approaches will greatly contribute to extracting spatial or directional information. While time-frequency analysis can provide information about the temporal evolution of the sound, meaning that it can tell us about the distance toward lucrative food sources.

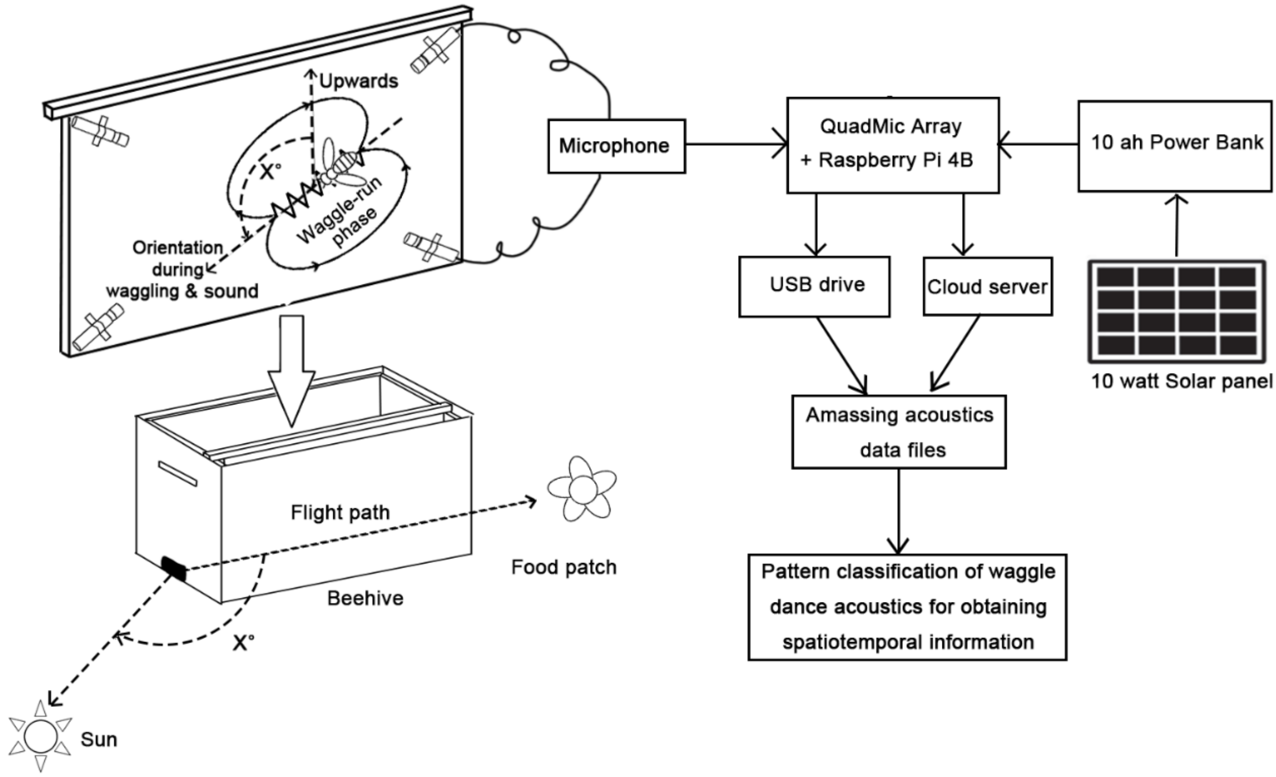

Figure 7. A proposed acoustics-recording setup installed within the hive to tape the sounds of different dancing bees (**top left**), steps to gather the massive acoustic dataset from these dances, and their analysis for pattern recognition for spatiotemporal information on the food-rich sources (**right**). In the sketch, there is shown an orientation of the dancing bee (**top left**), which represents the coordinates or spatial geometry of the food patch relative to the solar azimuth (**down left**). Temporal information (foraging distance from the hive to the food patch) is exhibited through the vibroacoustic activity of dancers during the waggle-run phase (**top left**).

While the above data gives us reason to be optimistic about finding sound-based spatial information within the hive, we still believe that there are several knowledge gaps or limitations that need further examination and integration to enhance our suggested acoustic recording setup. Limitations and/or questions include: (1) It has not yet been determined how far sound waves (with particular pressure and particle motions) travel on the vertical frame where microphones are attached. (2) If the frame with microphones mounted on it is placed in the middle of the hive, are the microphones capable of picking up sounds of bees performing waggle dances on another vertical frame(s) within the hive? (3) And will the results of picking up sound be different from the original vertical frame? Therefore, we recommend measuring the actual path length from the sound source or acoustic near field (caused by the dancer's wing flapping and reverberating abdomen) to the microphones in order to determine if this single proposed recording setup is sufficient to capture the dances of an entire hive or if additional microphones will be required. Here, we make it clear that the proposed solution is a concept, not finished research, so researchers can further check its validity and performance, as well as suggest and/or apply new ideas to further upgrade our proposed setup.

4. Discussion

In our investigation, the global ranking of various acoustically monitored factors in terms of importance and confidence showed a divergence. Swarming, colony health, pesticides, and environmental pollution are designated as "very important factors" in the level of importance (Figure 4), while showing "high confidence", in the level of confidence (Table 3, Figure 5). The majority of the global experts rate the factors mentioned above in the well-established category (low amount of disagreement) because they are highly confident in the fact that there are considerable and very comprehensive shreds of evidence for acoustically monitoring these factors. These results are reinforced by significant evidence in several publications [20,24,25,54,55]. The majority of experts with the highest confidence (Table 3, Figure 5) assessed swarming as a more important factor relative to the others mentioned above (Figure 3). Zgank [56] proposed in a paper that machine learning and IoT-based farm services can be used to classify sound for the activity of the honeybee colony swarm. According to him, these approaches can simplify and enhance apiary management significantly. Moreover, Ramsey et al. [13] describe a significant development in the recognition of pre-swarming indications through averaged vibroacoustic records or information to carefully observe the swarming events within the hives. Not merely the information provided in the papers mentioned above is the supporting proof, but also some monitoring systems, including the HiveMind system, the Hive-Tech system, the Arnia system, as well as the Buzzbox system, to acoustically monitor a colony for swarming and other events, show a strong correlation with our results and indicate that swarming is one of the "very important" factors to be monitored via sound signatures [57,58].

Other factors, including weather conditions, food availability, and spatiotemporal patterns, are scored as "important", and there is high consensus among the global experts (established but incomplete confidence category) for monitoring these factors through colony acoustics (Figures 4 and 5, Tables 3 and 4), although limited evidence is present. After a watchful surf of the literature, we found that only a couple of works done by Tlačbaba, et al. [59] and Cejrowski and Szymanski [17] described the role of colony acoustics to monitor weather conditions. For instance, former work refers to how the acoustic emission in the honeybee colony is influenced by extreme weather conditions (i.e., strong winds and hailstorms), while later work refers to how temperature variations influence the colony's acoustic fingerprint, using spectral entropy and the Acoustic complexity index (ACI). While the evidence of an acoustic check of a honeybee colony for other weather conditions, such as humidity, cloudiness, atmospheric pressure, blizzards, and droughts, is still lacking. However, recently we have found a published work by Abdollahi et al. [60] which shows that rain sounds can significantly alter the hive's multiple frequency ranges, increasing the recorded sound in some bands by as much as 10 dB and thus likely diminishing monitoring performance. The effect of precipitation on this parameter is seen in the histogram of the MFCC distribution. Rain artifacts and their effects on the discrete wavelet transform (DWT) components are also demonstrated. Through searching various platforms, we could find two publications presented by Hasegawa et al. [47] and Kawakita et al. [61] that exhibit evidence of spatiotemporal acoustic patterns persuaded by honeybee colonies. Whereas Collison [62] discussed the concept of an acoustic near field produced by honeybee waggle dancers, which could yield directional or spatial information for follower bees. Detail on the development of Hackathon in SAS® Viya® to decode the waggle dance into direction and distance is described in our previous research [58]. Moreover, merely publication by Nieh et al. [63] discusses the effect of food quality on recruitment sound in two stingless bees, *Melipona mandacaia* and *Melipona bicolor*. All the aforementioned publications are in line with our results that weather conditions, food availability, and spatiotemporal patterns are important factors, but there is a limited or small amount of evidence for their acoustics-based colony check.

Land cover and land management (the components of the landscape) fall into the 'inconclusive' category of confidence (Table 3) because no evidence was found in support of monitoring these factors through colony acoustics, and moreover, a consensus could not be built among experts. However, some experts (median score = 3) assessed land cover and land management as 'important' factors to be monitored acoustically (Table 3, Figure 4), which may be because researchers are already reporting that birds and animals' soundscapes have a connection with the landscape [64–66]. Results of the current study indicate that there is a maximum number of experts who do not know (63%) (Table 3, Figure 4) whether or not the acoustic changes in bee colonies can tell something about the landscape. These findings are due to the fact that experts working on honeybee waggle dance could not respond to our request to contribute to the process of assessing the role of colony acoustics in detecting various factors, despite the fact that the role of waggle dancers in communicating with their nestmates about landscapes with rich food sources is very important. Moreover, during waggle dance (a unique behavior of walking dancers in a figure-eight pattern), dancers emit sound in the frequency range of 250–300 Hz, peaking at 1 m/s, causing a sound pressure of 1 Pa at the wings. Pressure gradients cause oscillating air currents around the dancer's abdomen [47,53]. We believe that by studying the precise mechanism of the waggle dance, the sound pressure created, and the dancing orientation, one may recognize at least which landscapes have food supplies or in which directions experienced foragers are traveling. If researchers are able to measure the pressure of acoustics or hum produced during waggling and the orientation of the dancers' bees relative to the microphone placed inside the hive, as well as understand and apply the Directivity Index (DI) and the acoustic nearfield [53,61,67], we hope to be able to estimate spatiotemporal or landscape-related information. In light of the fact that land-use changes diminish the habitat appropriateness for maintaining managed honeybee colonies, the aforementioned are new study options for scientists to investigate [68]. Furthermore, although considering the importance of sound (emitted during waggle dancing) in landscape orientation, it seems impossible to extract acoustic characteristics from waggle dancers in such a noisy environment inside the hive, and it may only be achievable if many microphones are installed within the hive.

On the importance of factors' sound-based monitoring, all global experts commented to share their opinions or points of view. Regarding chemicals present inside or outside of the hive, experts consider inclusively that they are important and can be monitored via colony acoustics. There are mixed thoughts; some say that chemicals' presence can only be detected via sound when they are in high concentration, but another aspect is that honeybees are sensitive to chemicals, such as queen pheromones (consider them as chemical communication to signal their reproductive status, attraction, stopping others from developing ovaries, etc.). One of the experts says that if somehow pesticides are mixed with pheromones, it can disturb the sense of chemical communication, and thus honeybees could conceivably respond to beehive sounds differently. At what level of pesticide concentration are the acoustics produced by honeybees transformed? This has not been explored yet. Furthermore, one of the experts, showing a new direction, predicts that stressful events (exposure to pesticides, pollution, and climate warming) may change the foragers' sounds and recruitment success because both are modulated by neuropeptides (i.e., octopamine), which are, sequentially, modulated by stressors (see Table 5). So, by digging deep into finding interactions among stressful events, octopamine, and honeybee foragers' sounds, researchers can open a new window for future research.

Regarding comments on the importance of colony health, experts are cohesive on the fact that colony health concerning the queen's presence and absence can be acoustically supervised, but still, there is a need to fill the gap by conducting further investigation to see whether there is a significant difference in sounds of bees influenced by varroosis (caused by *Varroa destructor* and other varroa mite species) [69], other pests and parasites such as *Aethina tumida*, *Galleria mellonella* L., *Achroia grisella* Fabricius, *Acherontia atropes*, *Iridomyrmax humilis* Mayr, *Apocephalus borealis*, and *Braula coeca* [70–74]. Acoustic recordings from colonies have been utilized in investigations to effectively detect the presence of queens and detect swarming. However, there are some limitations, including small sample sizes, the demand for a standardized approach to feature engineering, and the need for more generalizable models. For this reason, it is recommended to employ larger sample sizes to avoid anomalies and make conclusions more generalizable [75]. Furthermore, in the case of parasitic and pest infections in a colony, experts predict that the odor produced by these infections may trigger bees to produce acoustic cues to signal their colony mates to remove festering and infected bees (Table S1: Summary of the experts' comments compiled during round two for the question asked in a questionnaire).

In addition, experts believe that beehive sound or vibration has the potential to serve as an alternative method to assess and monitor plant nectar. If the nectar supply is of high quality, almost all foragers will dance excitedly and for a long period when they return after foraging. While the lower-quality food supplies will lead to fewer, smaller, and less intense dances, attracting fewer new foragers. Since dances are acoustic events, their intensity, length, and overall numbers may all be used as indicators of the quality of food or nectar supplies. So, given the relation between dancers' acoustics and nectar quality, the experts give the impression that food availability should possibly be monitored through the vibroacoustics of foragers, though with a more sensible microphone.

Comments show that experts are highly confident in the colony's acoustic response against frenetic predators. They describe that the colony workers exposed to frenetic predator attack produce strong antipredator signals, which lead worker bees to expose their Nasonov glands and activate venom gland volatiles to alarm the nestmates for defense (Table 5) [23,38,39]. Which undocumented honeybee species against which predator exhibit the above-mentioned behaviors? What kind of acoustic patterns do bee colonies (from unexplored honeybee species) emit against the attack of each particular frenetic predator? Experts are positive that if we could succeed in obtaining the required results, then a novel system could be developed for the well-being of bees and efficient apiary monitoring against dangerous predators (Table 5).

Diverting attention to the population size of a honeybee colony, it has been reported that colonies are facing decline or the wipeout of a large number of worker bees [76,77]. Relating this, the experts' point of view is that examining the acoustic properties of the colony soundscape may bring an emerging solution to understanding whether or not a colony population is in decline. Since the role of the soundscape in determining the abundance and richness of birds in an ecosystem is evident from Celis-Murillo et al. [78] and Morrison et al. [79], experts are confident that apiaries can also be monitored for the population status of their colonies (Table S1: Summary of the experts' comments compiled during round two for the question asked in a questionnaire). Although the sound of a beehive may be used as a proxy for a colony's size, we believe it is important to take acoustic samples from the hives in a strategic manner, since the sound produced by a certain number of bees in a small beehive may vary from the sound produced by the same number of bees in a big beehive. Researchers need to know the dimensions of the hive, the types of hives being used (i.e., the Langstroth, the Warre, the Top Bar, and the Long/Horizontal), and the number of frames in the hive prior to the sound analysis because each of these aspects has an impact on the reliability of estimates of population size in a bee colony. Recently, we released a paper [80] detailing the efficacy of using the log spectrum of the *Apis cerana* colony sound signal in conjunction with two models (MFCC and VGGish embedding) to determine the number of bees in a colony. We discovered that VGGish embedding outperforms MFCC by around 20% across all of the ML techniques we tested (with the exception of classifying the sounds of colonies with pupa and colonies with a new queen, where MFCC performed slightly better than VGGish embedding), and that UMAP is superior to t-distributed stochastic neighbor embedding (t-SNE) as a colony sound separation feature. We anticipate that the success of VGGish embedding will aid in the detection of the population dynamics/or population size of other significant honeybee species and serve as a useful indicator of the bee decline.

Publications reveal that different drivers (including almost all the factors discussed in the present paper) are more or less responsible for the bees' decline around the world [81]. To protect bees, various platforms and plan launchers are doing great work and thus can be approached to solicit cooperation for the provision of hive acoustics data. These platforms include the COLOSS honeybee research association (https://coloss.org/ (accessed on 10 March 2023)), the United States Environmental Protection Agency (EPA, https://www.epa.gov/pollinator-protection/epa-actions-protect-pollinators (accessed on 10 March 2023)), European Commission on the Protection of Bees (https://ec.europa.eu/food/plants/pesticides/protection-bees_en (accessed on 10 March 2023)), Bee Informed Partnership (BIP, https://beeinformed.org/ (accessed on 1 March 2023)), the International Bee Research Association (IBRA, https://ibra.org.uk/ (accessed on 1 March 2023)), The Bee Conservancy (https://thebeeconservancy.org/ (accessed on 1 March 2023)), and others. While various plans by the launchers include Healthy Bee Plan 2030, Pollinator Protection Strategic Plan, Managed Pollinator Protection Plan (MP3), Pollinator Protection Initiative, Idaho Pollinator Protection Plan, Delaware Managed Pollinator Protection Plan, etc. If researchers who are connected to all these platforms and have launched plans collaborate with other researchers working on honeybee acoustics, it is likely that we can see a great boom in the role of acoustics for effective monitoring of apiaries and other factors, as well as in delivering novel insights to explore further new directions in this field.

Out of all other new avenues, experts have focused our attention on one of the most crucial areas of determining honeybee diversity via soundscape at a global scale (Table 5). According to the earlier studies, acoustic or soundscape indices are strongly interconnected with the diversity, richness, or abundance of avian species [40–43]. The size of the colony will undoubtedly change as a result of the global decline in honeybee abundance for a variety of reasons, which may also affect the acoustic characteristics of the colony soundscape. Additionally, the results of the reduced representation genome sequencing of historical specimens and their comparison with the genomic data of the current populations demonstrate that there has been a loss of genetic diversity over the past century, potentially making honeybees more susceptible to current ecological (i.e., climate change, environmental contaminants, various pesticide applications, nutritional deficiency, etc.) and anthropogenic stressors [82]. Experts are confident that acoustic changes occurring due to declines in population abundance (in the environment and within the hive) and the loss of diversity in the bees (mainly those present in the environment or any landscape) can be acoustically quantified by using various acoustic indices (ADI, BI, H, and AEI) [79,83]. Increases in soundscape indices such as ADI, BI, and H and decreases in AEI reflect the increase in species richness and abundance, and vice versa [79].

According to experts, why is it difficult to identify the diversity of bees inside hives using colony acoustics in soundscape indices? They have several concerns about using soundscape indices to assess the diversity of bees housing inside the hives. One is that metrics for describing soundscapes are dependent on spatiotemporal changes in frequency patterns, yet in the busy and noisy environment of the hive, they are often captured using a single fixed microphone placed in the midst of the frames. Two, it's not impossible, but it's highly unlikely that more than one species of bee would live in the same nest. If, for instance, multiple species are present, an acoustics-based recording utilizing a single fixed microphone will not effectively help us get the audio signals of all the species we need to record. In order to get an accurate representation of the colony's acoustics, we think it's necessary to upgrade our recording equipment and place multiple microphones within the hives. After connecting microphones to the inputs of the sound recording setup, we may collect sound samples from different positions inside the hive (meaning that there will be maximum chances to have recordings of each species present in the hive). Considering the importance of the genetic diversity of bees within honeybee colonies in thwarting severe infection and supporting colony growth and defense [84,85] and the experts' reservations (as mentioned above), future studies should consider those aspects since an up-to-date recording setup could improve the quality, reliability, and significance of the results.

In our recently published article [80], we used three bee colony sound datasets (first for identifying chemical compounds, second for queen state, and third for colony size) to generate VGGish (a visual geometry group-like audio classification model) embedding as well as the Mel-frequency Cepstral Coefficient (MFCC), which we then used to train four machine learning algorithms to discern which acoustic feature works better in bee colony acoustic recognition. Based on our findings, VGGish embedding outperformed the MFCC on all three datasets. Since this is the first publication of its kind, we strongly encourage researchers in the field of honeybee colony acoustics to utilize this approach for categorizing additional sound-based characteristics of a colony.

Experts agree that there is merit in investigating colony acoustics on a temporal scale, but they are divided on whether or not the features of the colony soundscape can capture spatial scale. (Table S1: Summary of the experts' comments compiled during round two for the question asked in a questionnaire). Although it is logically impossible for an entire colony soundscape to yield spatial data, there is a possibility that we could obtain such data from the acoustic emissions of waggle dancing bees by employing our proposed acoustic recording setup (Figure 7), which consists of a QuadMic Array (based on the AC108 quad-channel ADC with Inter-IC Sound (I^2S) audio output) attached to a Raspberry Pi. Refer to Section 3.3 for further information on how our suggested arrangement for recording waggle dance acoustics may be utilized to get spatiotemporal data on food resources located outside the hive (Figures 6 and 7). In the preceding section (Section 3.3), we also highlighted the prospective constraints or limitations of our suggested setup and made ideas for future improvements in order to acquire better results. We believe that this system has the potential to become an invaluable asset in apiary management if it is able to efficiently collect high-quality acoustic data of bees' waggle dances and successfully develop ML algorithms on these data for pattern classification of dances to obtain spatiotemporal information. In our earlier paper, we stated that reduced availability of food due to forage shortages is one of the primary drivers of bee population reduction [86]. The difficulty to be solved is determining where the bees get nourishment. With the success of our suggested system, we anticipate that beekeepers will be able to predict the location of abundant food supplies and, as a result, determine the ideal place for the relocation of their hives in the field.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agriculture13040769/s1 (accessed on 20 February 2023), Table S1: Summary of the experts' comments compiled during round two for the question asked in a questionnaire; Table S2: Information on the percentage of experts exhibiting their confidence for acoustical monitoring of various factors at different levels of confidence; Table S3: A cross-tabulation of the experts' ratings on importance and confidence regarding the monitoring of multiple factors through beehive colony acoustics; Table S4: The Chi-square coefficient; Table S5: Symmetric measures for the strength of a relationship; Google Form: Containing a questionnaire entitled "A global expert assessment on the role of honeybee colony acoustics associated with apiary monitoring and some ecological factors," was circulated among the global experts to collect their feedback. Figure S1: Participation of each gender (%) in responding to the questionnaire; Figure S2: Age of participants who have given their responses to the questionnaire; Figure S3: Level of education of the experts who provided their feedback via a questionnaire; Figure S4: Employment status of the experts who participated in responding to the questionnaire. While the acoustic files representing the waggle-run phase of dancer bees can be accessed online from the Zenodo website (https://doi.org/10.5281/zenodo.7678084 (accessed on 14 March 2023) and https://doi.org/10.5281/zenodo.7684255 (accessed on 13 March 2023). References [87–89] are cited in the Supplementary Materials.

Author Contributions: Conceptualization, M.Z.S., N.D. and B.Y.; methodology, M.Z.S., N.D. and B.Y.; formal analysis, M.Z.S. and N.D.; investigation, M.Z.S., N.D. and B.Y.; resources, M.Z.S. and N.D.; data curation, M.Z.S. and N.D.; writing—original draft preparation, M.Z.S.; writing—review and editing, conceptualization, M.Z.S., N.D. and B.Y.; visualization, M.Z.S. and B.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in this article.

Acknowledgments: We thank all the anonymous experts who participated in responding to the questionnaire and providing useful feedback on the comments in each round. We are grateful to Tymoteusz Cejrowski for his valuable comments on our first draft and thankful to F. A. Shah for his guidance in producing some figures. The first author is highly thankful to the University of Science and Technology of China (USTC) and the Chinese Academy of Sciences (CAS) for providing scholarships for a Ph.D. study.

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

References

1. Abrol, D.P. *Pollination Biology: Biodiversity Conservation and Agricultural Production*; Springer: Berlin/Heidelberg, Germany, 2012.
2. Klein, A.-M.; Vaissière, B.E.; Cane, J.H.; Steffan-Dewenter, I.; Cunningham, S.A.; Kremen, C.; Tscharntke, T. Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B Biol. Sci.* **2007**, *274*, 303–313. [CrossRef] [PubMed]
3. Chaplin-Kramer, R.; Dombeck, E.; Gerber, J.; Knuth, K.A.; Mueller, N.D.; Mueller, M.; Ziv, G.; Klein, A.-M. Global malnutrition overlaps with pollinator-dependent micronutrient production. *Proc. R. Soc. B Biol. Sci.* **2014**, *281*, 20141799. [CrossRef] [PubMed]
4. Gray, A.; Adjlane, N.; Arab, A.; Ballis, A.; Brusbardis, V.; Bugeja Douglas, A.; Cadahía, L.; Charrière, J.-D.; Chlebo, R.; Coffey, M.F. Honey bee colony loss rates in 37 countries using the COLOSS survey for winter 2019–2020: The combined effects of operation size, migration and queen replacement. *J. Apic. Res.* **2022**, *62*, 204–210. [CrossRef]
5. EPA. *Pesticide Issues in the Works: Honey Bee Colony Collapse Disorder*; Environmental Protection Agency: Washington, DC, USA, 2011. Available online: http://www.epa.gov/pesticides/about/intheworks/honeybee.hlm (accessed on 5 January 2023).
6. Abdollahi, M.; Giovenazzo, P.; Falk, T.H. Automated beehive acoustics monitoring: A comprehensive review of the literature and recommendations for future work. *Appl. Sci.* **2022**, *12*, 3920. [CrossRef]
7. Sanford, M.T. *Diseases and Pests of the Honey Bee*; University of Florida: Gainesville, FL, USA, 1987.
8. Thimmegowda, G.G.; Mullen, S.; Sottilare, K.; Sharma, A.; Mohanta, S.S.; Brockmann, A.; Dhandapany, P.S.; Olsson, S.B. A field-based quantitative analysis of sublethal effects of air pollution on pollinators. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 20653–20661. [CrossRef]
9. Henry, M.; Decourtye, A.J.S. A Common Pesticide Decreases Foraging Success and Survival in Honey Bees. *Science* **2012**, *336*, 348–350. [CrossRef]
10. APHA. Asian Hornet: UK Sightings. Available online: https://www.gov.uk/government/publications/asian-hornet-uk-sightings (accessed on 12 December 2022).
11. Flores, J.M.; Gil-Lebrero, S.; Gámiz, V.; Rodríguez, M.I.; Ortiz, M.A.; Quiles, F.J. Effect of the climate change on honey bee colonies in a temperate Mediterranean zone assessed through remote hive weight monitoring system in conjunction with exhaustive colonies assessment. *Sci. Total Environ.* **2019**, *653*, 1111–1119. [CrossRef] [PubMed]
12. Zacepins, A.; Brusbardis, V.; Meitalovs, J.; Stalidzans, E. Challenges in the development of Precision Beekeeping. *Biosyst. Eng.* **2015**, *130*, 60–71. [CrossRef]
13. Ramsey, M.-T.; Bencsik, M.; Newton, M.I.; Reyes, M.; Pioz, M.; Crauser, D.; Delso, N.S.; Le Conte, Y. The prediction of swarming in honeybee colonies using vibrational spectra. *Sci. Rep.* **2020**, *10*, 9798. [CrossRef]
14. Terenzi, A.; Cecchi, S.; Spinsante, S. On the importance of the sound emitted by honey bee hives. *Vet. Sci.* **2020**, *7*, 168. [CrossRef]
15. Puswal, S.M.; Jinjun, M.; Liu, F. Effects of temperature and season on birds' dawn singing behavior in a forest of eastern China. *J. Ornithol.* **2021**, *162*, 447–459. [CrossRef]

16. Puswal, S.M.; Mei, J.; Wang, M.; Liu, F. Daily and seasonal patterns in the singing activity of birds in East China. *Ardea* **2022**, *110*, 5–14. [CrossRef]
17. Cejrowski, T.; Szymanski, J. Buzz-based honeybee colony fingerprint. *Comput. Electron. Agric.* **2021**, *191*, 106489. [CrossRef]
18. Vancata, I.O. Using acoustic technology to monitor your hives. *Am. Bee J.* **1995**, *135*, 615–618.
19. Ferrari, S.; Silva, M.; Guarino, M.; Berckmans, D. Monitoring of swarming sounds in bee hives for early detection of the swarming period. *Comput. Electron. Agric.* **2008**, *64*, 72–77. [CrossRef]
20. Robles-Guerrero, A.; Saucedo-Anaya, T.; González-Ramérez, E.; Galván-Tejada, C.E. Frequency Analysis of Honey Bee Buzz for Automatic Recognition of Health Status: A Preliminary Study. *Res. Comput. Sci.* **2017**, *142*, 89–98. [CrossRef]
21. Ruvinga, S.; Hunter, G.; Duran, O.; Nebel, J.C. Use of LSTM Networks to Identify "Queenlessness" in Honeybee Hives from Audio Signals. In Proceedings of the 2021 17th International Conference on Intelligent Environments (IE), Dubai, United Arab Emirates, 21–24 June 2021.
22. Papachristoforou, A.; Sueur, J.; Rortais, A.; Angelopoulos, S.; Thrasyvoulou, A.; Arnold, G. High frequency sounds produced by Cyprian honeybees Apis mellifera cypria when confronting their predator, the Oriental hornet Vespa orientalis. *Apidologie* **2008**, *39*, 468–474. [CrossRef]
23. Mattila, H.R.; Kernen, H.G.; Otis, G.W.; Nguyen, L.T.; Pham, H.D.; Knight, O.M.; Phan, N.T. Giant hornet (Vespa soror) attacks trigger frenetic antipredator signalling in honeybee (Apis cerana) colonies. *R. Soc. Open Sci.* **2021**, *8*, 211215. [CrossRef]
24. Sharif, M.Z.; Wario, F.; Di, N.; Xue, R.; Liu, F. Soundscape indices: New features for classifying beehive audio samples. *Sociobiology* **2020**, *67*, 566–571. [CrossRef]
25. Pérez, N.; Jesús, F.; Pérez, C.; Niell, S.; Draper, A.; Obrusnik, N.; Zinemanas, P.; Spina, Y.M.; Letelier, L.C.; Monzón, P. Continuous monitoring of beehives' sound for environmental pollution control. *Ecol. Eng.* **2016**, *90*, 326–330. [CrossRef]
26. Gentry, K.E.; Luther, D.A. Spatiotemporal patterns of avian vocal activity in relation to urban and rural background noise. *J. Ecoacoustics* **2017**, *1*, Z9TQHU. [CrossRef]
27. Dröge, S.; Martin, D.A.; Andriafanomezantsoa, R.; Burivalova, Z.; Fulgence, T.R.; Osen, K.; Rakotomalala, E.; Schwab, D.; Wurz, A.; Richter, T. Listening to a changing landscape: Acoustic indices reflect bird species richness and plot-scale vegetation structure across different land-use types in north-eastern Madagascar. *Ecol. Indic.* **2021**, *120*, 106929. [CrossRef]
28. Clay, Z.; Smith, C.L.; Blumstein, D.T. Food-associated vocalizations in mammals and birds: What do these calls really mean? *Anim. Behav.* **2012**, *83*, 323–330. [CrossRef]
29. Von Frisch, K. *The Dance Language and Orientation of Bees*; Harvard University Press: Cambridge, MA, USA, 1967.
30. Dyer, F. The biology of the dance language. *Annu. Rev. Entomol.* **2002**, *47*, 917–949. [CrossRef] [PubMed]
31. Wario, F.; Wild, B.; Rojas, R.; Landgraf, T. Automatic detection and decoding of honey bee waggle dances. *PLoS ONE* **2017**, *12*, e0188626. [CrossRef]
32. Wario, F.; Wild, B.; Couvillon, M.J.; Rojas, R.; Landgraf, T. Automatic methods for long-term tracking and the detection and decoding of communication dances in honeybees. *Front. Ecol. Evol.* **2015**, *3*, 103. [CrossRef]
33. Okada, R.; Ikeno, H.; Sasayama, N.; Aonuma, H.; Kurabayashi, D.; Ito, E. The dance of the honeybee: How do honeybees dance to transfer food information effectively? *Acta Biol. Hung.* **2008**, *59*, 157–162. [CrossRef]
34. Mukherjee, N.; Huge, J.; Sutherland, W.J.; McNeill, J.; van Opstal, M.; Dahdouh-Guebas, F.; Koedam, N. The Delphi technique in ecology and biological conservation: Applications and guidelines. *Methods Ecol. Evol.* **2015**, *6*, 1097–1109. [CrossRef]
35. Barron, A.B.; Maleszka, R.; Vander Meer, R.K.; Robinson, G.E. Octopamine modulates honey bee dance behavior. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 1703–1707. [CrossRef]
36. Linn, M.; Glaser, S.M.; Peng, T.; Grüter, C. Octopamine and dopamine mediate waggle dance following and information use in honeybees. *Proc. R. Soc. B Biol. Sci.* **2020**, *287*, 20201950. [CrossRef]
37. Harris, J.W.; Woodring, J. Effects of stress, age, season, and source colony on levels of octopamine, dopamine and serotonin in the honey bee (Apis mellifera L.) brain. *J. Insect Physiol.* **1992**, *38*, 29–35. [CrossRef]
38. Tan, K.; Dong, S.; Li, X.; Liu, X.; Wang, C.; Li, J.; Nieh, J.C. Honey bee inhibitory signaling is tuned to threat severity and can act as a colony alarm signal. *PLoS Biol.* **2016**, *14*, e1002423. [CrossRef] [PubMed]
39. Dong, S.; Wen, P.; Zhang, Q.; Wang, Y.; Cheng, Y.; Tan, K.; Nieh, J.C. Olfactory eavesdropping of predator alarm pheromone by sympatric but not allopatric prey. *Anim. Behav.* **2018**, *141*, 115–125. [CrossRef]
40. Villanueva-Rivera, L.J.; Pijanowski, B.C.; Doucette, J.; Pekin, B. A primer of acoustic analysis for landscape ecologists. *Landsc. Ecol.* **2011**, *26*, 1233–1246. [CrossRef]
41. Boelman, N.T.; Asner, G.P.; Hart, P.J.; Martin, R.E. Multi-trophic invasion resistance in Hawaii: Bioacoustics, field surveys, and airborne remote sensing. *Ecol. Appl.* **2007**, *17*, 2137–2144. [CrossRef]
42. Sueur, J.; Aubin, T.; Simonis, C. Seewave, a free modular tool for sound analysis and synthesis. *Bioacoustics* **2008**, *18*, 213–226. [CrossRef]
43. Mammides, C.; Goodale, E.; Dayananda, S.K.; Kang, L.; Chen, J. Do acoustic indices correlate with bird diversity? Insights from two biodiverse regions in Yunnan Province, south China. *Ecol. Indic.* **2017**, *82*, 470–477. [CrossRef]
44. Eskov, E.K. The diversity of ethological and physiological mechanisms of acoustic communication in insects, Biophysics (Moscow). *Biophysics* **2017**, *62*, 466–478. [CrossRef]

45. Robles-Guerrero, A.; Saucedo-Anaya, T.; Guerrero-Mendez, C.A.; Gómez-Jiménez, S.; Navarro-Solís, D.J. Comparative Study of Machine Learning Models for Bee Colony Acoustic Pattern Classification on Low Computational Resources. *Sensors* **2023**, *23*, 460. [CrossRef]
46. Esch, H.; Burns, J. Distance estimation by foraging honeybees. *J. Exp. Biol.* **1996**, *199*, 155–162. [CrossRef]
47. Hasegawa, Y.; Ikeno, H. How do honeybees attract nestmates using waggle dances in dark and noisy hives? *PLoS ONE* **2011**, *6*, e19619. [CrossRef]
48. Hu, Z.; Miao, C.; Di, N.; Zhou, C.; Zhang, Y.; Yang, J.; Xun, L.; Li, Y. Decoding the dance parameters of eastern honeybee, Apis cerana. *Apidologie* **2023**, *54*, 10. [CrossRef]
49. Kohl, P.L.; Thulasi, N.; Rutschmann, B.; George, E.A.; Steffan-Dewenter, I.; Brockmann, A. Adaptive evolution of honeybee dance dialects. *Proc. R. Soc. B* **2020**, *287*, 20200190. [CrossRef] [PubMed]
50. Tautz, J.; Casas, J.; Sandeman, D. Phase reversal of vibratory signals in honeycomb may assist dancing honeybees to attract their audience. *J. Exp. Biol.* **2001**, *204*, 3737–3746. [CrossRef]
51. Michelsen, A.; Kirchner, W.H.; Andersen, B.B.; Lindauer, M. The tooting and quacking vibration signals of honeybee queens: A quantitative analysis. *J. Comp. Physiol. A* **1986**, *158*, 605–611. [CrossRef]
52. Wenner, A.M. Communication with queen honey bees by substrate sound. *Science* **1962**, *138*, 446–448. [CrossRef]
53. Michelsen, A.; Towne, W.F.; Kirchner, W.H.; Kryger, P. The acoustic near field of a dancing honeybee. *J. Comp. Physiol. A* **1987**, *161*, 633–643. [CrossRef]
54. Cecchi, S.; Terenzi, A.; Orcioni, S.; Piazza, F. Analysis of the sound emitted by honey bees in a beehive. *Audio Eng. Soc. Conv.* **2019**, *147*, 10255.
55. Cejrowski, T.; Szymański, J.; Mora, H.; Gil, D. Detection of the bee queen presence using sound analysis. In Proceedings of the Asian Conference on Intelligent Information & Database Systems, Dong Hoi, Vietnam, 19–21 March 2018; pp. 297–306.
56. Zgank, A. Bee swarm activity acoustic classification for an IoT-based farm service. *Sensors* **2020**, *20*, 21. [CrossRef]
57. Voudiotis, G.; Kontogiannis, S.; Pikridas, C. Proposed smart monitoring system for the detection of bee swarming. *Inventions* **2021**, *6*, 87. [CrossRef]
58. Sharif, M.Z.; Di, N.; Liu, F. Monitoring honeybees (Apis spp.) (Hymenoptera: Apidae) in climate-smart agriculture: A review. *Appl. Entomol. Zool.* **2021**, *57*, 289–303. [CrossRef]
59. Tlačbaba, J.; Černý, M.; Dostál, P.; Přidal, A. The Acoustic Emission in the Nest of the Honey Bee Depending on the Extreme Weather Conditions. *Acta Univ. Agric. Et Silvic. Mendel. Brun.* **2014**, *62*, 27. [CrossRef]
60. Abdollahi, M.; Henry, E.; Giovenazzo, P.; Falk, T.H. The Importance of Context Awareness in Acoustics-Based Automated Beehive Monitoring. *Appl. Sci.* **2022**, *13*, 195. [CrossRef]
61. Kawakita, S.; Ichikawa, K.; Sakamoto, F.; Moriya, K. Sound recordings of Apis cerana japonica colonies over 24 h reveal unique daily hissing patterns. *Apidologie* **2019**, *50*, 204–214. [CrossRef]
62. Collison, C. A Closer look: Sound Generation and Hearing. *Bee Culture: The Magazine of American Beekeeping*, 22 February 2016.
63. Nieh, J.C.; Contrera, F.A.; Rangel, J.; Imperatriz-Fonseca, V.L. Effect of food location and quality on recruitment sounds and success in two stingless bees, Melipona mandacaia and Melipona bicolor. *Behav. Ecol. Sociobiol.* **2003**, *55*, 87–94. [CrossRef]
64. Farina, A.; Lattanzi, E.; Malavasi, R.; Pieretti, N.; Piccioli, L. Avian soundscapes and cognitive landscapes: Theory, application and ecological perspectives. *Landsc. Ecol.* **2011**, *26*, 1257–1267. [CrossRef]
65. Retamosa Izaguirre, M.I.; Segura Sequeira, D.; Barrantes-Madrigal, J.; Spínola Parallada, M.; Ramírez-Alán, Ó. Vegetation, bird and soundscape characterization: A case study in Braulio Carrillo National Park, Costa Rica. *Biota Colomb.* **2021**, *22*, 57–73. [CrossRef]
66. Joo, W.; Gage, S.H.; Kasten, E.P. Analysis and interpretation of variability in soundscapes along an urban–rural gradient. *Landsc. Urban Plan.* **2011**, *103*, 259–276. [CrossRef]
67. Patricelli, G.L.; Dantzker, M.S.; Bradbury, J.W. Differences in acoustic directionality among vocalizations of the male red-winged blackbird (Agelaius pheoniceus) are related to function in communication. *Behav. Ecol. Sociobiol.* **2007**, *61*, 1099–1110. [CrossRef]
68. Otto, C.R.; Roth, C.L.; Carlson, B.L.; Smart, M.D. Land-use change reduces habitat suitability for supporting managed honey bee colonies in the Northern Great Plains. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 10430–10435. [CrossRef]
69. Morawetz, L.; Köglberger, H.; Griesbacher, A.; Derakhshifar, I.; Crailsheim, K.; Brodschneider, R.; Moosbeckhofer, R. Health status of honey bee colonies (Apis mellifera) and disease-related risk factors for colony losses in Austria. *PLoS ONE* **2019**, *14*, e0219293. [CrossRef]
70. Kulhanek, K.; Steinhauer, N.; Rennich, K.; Caron, D.M.; Sagili, R.R.; Pettis, J.S.; Ellis, J.D.; Wilson, M.E.; Wilkes, J.T.; Tarpy, D.R. A national survey of managed honey bee 2015–2016 annual colony losses in the USA. *J. Apic. Res.* **2017**, *56*, 328–340.
71. Vijayakumar, K.; Neethu, T.; Shabarishkumar, S.; Nayimabanu Taredahalli, M.K.; Bhat, N.; Kuberappa, G. Survey, biology and management of greater wax moth, Galleria mellonella L. in Southern Karnataka, India. *J. Entomol. Zool. Stud.* **2019**, *7*, 585–592.
72. Sohail, M.; Aqueel, M.A.; Ellis, J.D.; Afzal, M.; Raza, A.M. Seasonal abundance of greater wax moth (Galleria mellonella L.) in hives of western honeybees (Apis mellifera L.) correlates with minimum and maximum ambient temperature. *J. Apic. Res.* **2017**, *54*, 416–420. [CrossRef]
73. Core, A.; Runckel, C.; Ivers, J.; Quock, C.; Siapno, T.; DeNault, S.; Brown, B.; DeRisi, J.; Smith, C.D.; Hafernik, J. A new threat to honey bees, the parasitic phorid fly Apocephalus borealis. *PLoS ONE* **2012**, *7*, e29639. [CrossRef] [PubMed]

74. Strauss, U.; Pirk, C.W.W.; Dietemann; Crewe, R.M.; Human, H. Infestation rates of Varroa destructor and Braula coeca in the Savannah honeybee (Apis mellifera seutellata). *J. Apic. Res.* **2014**, *53*, 475–477. [CrossRef]
75. Uthoff, C.; Homsi, M.N.; von Bergen, M. Acoustic and vibration monitoring of honeybee colonies for beekeeping-relevant aspects of presence of queen bee and swarming. *Comput. Electron. Agric.* **2023**, *205*, 107589. [CrossRef]
76. Oldroyd, B.P. What's killing American honey bees? *PLoS Biol.* **2007**, *5*, e168. [CrossRef]
77. Cox-Foster, D.; VanEngelsdorp, D. Saving the honeybee. *Sci. Am.* **2009**, *300*, 40–47. [CrossRef]
78. Celis-Murillo, A.; Deppe, J.L.; Allen, M.F. Using soundscape recordings to estimate bird species abundance, richness, and composition. *J. Field Ornithol.* **2009**, *80*, 64–78. [CrossRef]
79. Morrison, C.; Auniņš, A.; Benkő, Z.; Brotons, L.; Chodkiewicz, T.; Chylarecki, P.; Escandell, V.; Eskildsen, D.; Gamero, A.; Herrando, S. Bird population declines and species turnover are changing the acoustic properties of spring soundscapes. *Nat. Commun.* **2021**, *12*, 6217. [CrossRef]
80. Di, N.; Sharif, M.Z.; Hu, Z.; Xue, R.; Yu, B. Applicability of VGGish embedding in bee colony monitoring: Comparison with MFCC in colony sound classification. *PeerJ* **2023**, *11*, e14696. [CrossRef] [PubMed]
81. Dicks, L.V.; Breeze, T.D.; Ngo, H.T.; Senapathi, D.; An, J.; Aizen, M.A.; Basu, P.; Buchori, D.; Galetto, L.; Garibaldi, L.A. A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nat. Ecol. Evol.* **2021**, *5*, 1453–1461. [CrossRef] [PubMed]
82. Espregueira Themudo, G.; Rey-Iglesia, A.; Robles Tascón, L.; Bruun Jensen, A.; da Fonseca, R.R.; Campos, P.F. Declining genetic diversity of European honeybees along the twentieth century. *Sci. Rep.* **2020**, *10*, 10520. [CrossRef]
83. Pijanowski, B.; Napoletano, B.; Pieretti, N.; Krause, B.; Bernie, L.; Villanueva, L.; Dumyahn, S.; Farina, A. Sounscape ecology: The Science of Sound in the Landscape. *Bioscience* **2011**, *61*, 203–216. [CrossRef]
84. Tarpy, D.R. Genetic diversity within honeybee colonies prevents severe infections and promotes colony growth. *Proc. R. Soc. London Ser. B Biol. Sci.* **2003**, *270*, 99–103. [CrossRef]
85. Gardner, M.G.; Schönrogge, K.; Elmes, G.; Thomas, J. Increased genetic diversity as a defence against parasites is undermined by social parasites: Microdon mutabilis hoverflies infesting Formica lemani ant colonies. *Proc. R. Soc. B Biol. Sci.* **2007**, *274*, 103–110. [CrossRef]
86. Sharif, M.Z.; Renjie, X.; Puswal, S. Foraging performance of honeybee (Apis mellifera) affected by food richness and experience. *Uludağ Arıcılık Derg. Uludag Bee J.* **2020**, *20*, 132–144. [CrossRef]
87. Eskov, E. *The Origin and Organization of the Bee Colony Apis mellifera L.*; Cambridge Scholars Publishing: Newcastle upon Tyne, UK, 2019.
88. Shostak, S.; Prodeus, A. Classification of the bee colony condition using spectral features. In Proceedings of the 2019 IEEE International Scientific-Practical Conference Problems of Infocommunications, Science and Technology (PIC S&T), Kyiv, Ukraine, 8–11 October 2019; pp. 737–740.
89. Spangler, H.G. Do honey bees encode distance information into the wing vibrations of the waggle dance? *J. Insect Behav.* **1991**, *4*, 15–20. [CrossRef]