



ECOSYSTEMS

Comprehensive assessment of the health condition of managed honey bees potentially exposed to contamination with agrochemical residues

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Abstract: The growing demand for honey bee pollination services induces fluctuations in their populations and changes in bee health status. The current study aims to characterize the health condition of managed honey bees in three territories of the Department of Lambayeque, Peru, from a holistic perspective, considering several factors affecting bee health, including management practices, traits of the beekeepers and their apiaries, colony strength, infestation rates by *Varroa* sp., and the presence of agrochemical residues in bee bread. The results showed changes in land use, with large areas of crops dependent on bee pollination, determining their exposition to agrochemical residues. The 67% of bee bread samples presented pesticide residues, mainly, chlorpyrifos, carbendazim, boscalid, and azoxystrobin. In addition, limited expertise on good management practices by the beekeepers (i.e., inadequate disinfection of beekeeping materials, unsatisfactory varroa mites' surveillance, lack of protein supplements, presence of sanitary gaps) leads to deficiencies in bee colony strength and a high *Varroa* sp. prevalence in the territory, altering the bee health condition. To the best of our knowledge, this article illustrates the impact of the strongly anthropized ecosystems found along Peru's coast's arid zone on managed populations of honey bees in that territory with a One Health perspective.

Key words: agrochemical residues, *Apis mellifera*, honeybee health, one health approach.

INTRODUCTION

Honey bees (*Apis mellifera* L.) are the most prevalent insect pollinator species. The ecological role of pollination concerning land use change is vital for supporting plant biodiversity and all associated organisms in the food chain of life, including the sustainability of agriculture and human food security (El-Seedi et al. 2022, López-Urbe et al. 2020, Topal et al. 2023, Mukhtar & Shankar 2023). The demand for honey and pollination services has continued to grow in many countries worldwide, influencing changes in the population's demographics

of managed honey bees (Phiri et al. 2023). According to FAO reports, while the number of other pollinators has been declining, honey bee populations are thought to be stable worldwide and have even increased recently in response to growing demand for pollination services, despite fluctuations in managed bee populations (Halvorson et al. 2021). However, different levels of colony losses are found in several parts of the world, according to recent monitoring described by Stojanov et al. (2021).

Latest research has identified some of the most significant factors that have been thought to affect honey bee colony losses, including

internal and external influences, such as pests and diseases, bee management (including beekeeping practices and breeding), climate change, agricultural practices, and pesticide use (Hristov et al. 2020, Gregorc 2020, Yang et al. 2023). However, this knowledge has yet to contribute to reversing bee declines successfully. One strategy to ensure honey bee health is to address pollinator health issues and work at the interdisciplinary nexus from a “One Health” perspective that highlights the relationship between environmental quality and human, animal, and honey bee health (Donkersley et al. 2020, López-Urbe et al. 2020). In this context, numerous organisations have studied bee health all over the world, mainly in North America (Kulhanek et al. 2021, Steinhauer et al. 2021) and Europe (Stojanov et al. 2021), but environmental circumstances and other aspects, such as behaviour and performance, that are associated to bee health, vary throughout different regions (Nisbet et al. 2019).

Despite Latin America accounting for roughly 21% of worldwide honey exports (Trade Map 2023), the status of bee health in this region has yet to be documented (Vandame & Palacio 2010). According to Requier et al. (2018), reports about trends in beekeeping activities and honey bee colony losses in Latin America are lacking. Most of the studies focus on pathogens diseases and the impact of pesticides on bee health (Calderón et al. 2012, Maggi et al. 2016, Antúnez et al. 2015, Cagnolo et al. 2023, Balbuena et al. 2023). Nevertheless, a study providing valuable insights into understanding the situation of pollination ecosystem services, the economic contribution of pollinators, and their impact on agricultural productivity in Latin America was recently published, revealing a low productive diversification in the region and the vulnerability of farming ecosystems due to the managed and native bees decline (Basualdo et al. 2022),

increasing the rate at which biodiversity and ecosystem services are lost (Latterra et al. 2019).

Peru is recognised for having some of the most diverse climate conditions in South America and a wide diversity of floral resources due to the Andes’ dividing the territory. Thus, three distinct habitats are distinguished: the coastal plain, mountainous region, and coastline. These regions offer suitable ecosystems for productive activities because of their tropical desert scrub’s dry and hot weather (Quezada-Euán et al. 2003, Britto 2017, Huaranga-Joaquin et al. 2023). Even though many economic and environmental reasons are today endangering these ecosystems and the services they give (Lucich et al. 2015, Schwartz & Mathijs 2017, Blancas et al. 2018, Rojas et al. 2021).

A wide variety of plant species characterises the natural ecosystem of Lambayeque, one of Peru’s northern departments, allowing the profitable exploitation of beekeeping activities in this territory. Since the early twentieth century, the development of agriculture, along with the geographical dispersion of the population, has generated technical developments and institutional changes in Peru (Calzada et al. 2017, Urteaga 2022). The Olmos Tinajones Project, which irrigates Peru’s desertic Province of Lambayeque, is one example of this development (Urteaga 2022). Part of the natural ecosystem has been replaced by intense agricultural activity, reaching more than 23,000 cultivated hectares, focused mainly on fruit exportation, such as mango, avocado, lemon, blueberries, and passion fruit, all dependent on honey bee pollination (Britto 2017, Gobierno Regional de Lambayeque 2017, Urteaga 2022, Acosta 2023). The anthropic impact of intensified agriculture and the hybridisation of honey bees (*Apis mellifera* L.) (Quezada-Euán et al. 2003) both offer challenges and opportunities for the sustainability of beekeeping the beekeepers in

the region due to the increasing demand for pollination.

The intensification of agriculture comes with using phytosanitary products to control pests in commercial crops that depend on pollination services. Although large areas of the crops are dependent on pollination by honey bees, the use of phytosanitary products can present a threat to honey bee's survival (Medici et al. 2020, Delkash-Roudsari et al. 2020, Zhang et al. 2021, Tan et al. 2022, Wang et al. 2023, Green et al. 2023). There are no reports on the development of managed beekeeping in this area, nor information on beekeeping management practices or the influence of ecosystems and the use of phytosanitary products on the health of honey bees. Therefore, the current study aims to characterise honey bee health in three limited territories of the Department of Lambayeque, Peru, from a holistic perspective, considering various factors that affect bees' health, including production and management practices, traits of the beekeepers and their apiaries, colony strength, presence of agrochemical residues in bee bread, and the rates of *Varroa* sp. mite infestation. To the best of our knowledge, this article presents data for the first time that enables us to illustrate the impact of the strongly anthropized ecosystems found along Peru's coast's arid zone on the managed populations of honey bees present in that territory with a One Health perspective.

MATERIALS AND METHODS

Selection of the apiaries and bee colonies

Sixty apiaries from sixty different beekeepers spread across three districts of the Lambayeque Province (Motupe, Lambayeque and Olmos) in northern Peru were investigated to obtain information about beekeepers' management practices and to find factors related to the loss

of honey bee health. The apiaries (selected at random) were visited and monitored twice. The first monitoring (300 colonies in 60 apiaries) was carried out between November and December 2022 (when colonies return from the pollination process), while the second monitoring (260 colonies in 52 apiaries) was carried out between May and June 2023 (when pollination of blueberries and avocado begins), coinciding with a period of intense rains caused by the passage of Cyclone Yaku along the Pacific Coast. The monitoring was carried out with the owner's consent, selecting five bee colonies randomly in each apiary. The established colonies were labelled using an alpha-numeric code and kept under the same conditions as the rest.

Field data collection

A survey was used to gather field data (N = 60 beekeepers = 60 apiaries), considering the general characteristics of the beekeepers and their apiaries as well as aspects related to the occurrence of bee diseases, sanitary gaps, environmental features, and management practices, following the recommendations of Olate-Olave et al. (2021). Additionally, beekeepers were interviewed regarding applying treatments against *Varroa* sp., monitoring this parasite throughout the year, and an approximation regarding colony losses during the previous year. Before hive inspection, the temperature (°C), relative humidity (RH%) and the number of bees entering the hive for one minute were recorded. Inspected apiaries and the respective colonies were photographed to record the overall state of the colonies and their distribution.

Honey bee colony strength and field observations

With some modifications, honey bee colony strength was determined using the Liebefeld semi-subjective method (Delaplane et al.

2013). During the inspection of the colonies, the following parameters were recorded for the brood chamber: Number of frames, combs populated with adult bees, combs with closed and open brood, combs with honey and pollen reserves, and frame heads covered with bees. The minimum quantification unit was $\frac{1}{4}$ on each side of the honeycomb (0.25), and the sum of both sides (8×0.25) is equivalent to the result obtained for each frame. Additionally, observations were recorded, such as dead bees at the entrance, general conditions of the colony, and patterns in the closed and open brood.

Infestation rates by Varroa mites

To obtain information on the health status of managed honey bees in the studied territory, the infestation rate by *Varroa* sp. (IRV%) was evaluated according to the standard methodology proposed by Dieteman et al. (2013). For this purpose, a sample of 300 adult bees was taken from the closed brood combs in the brood chamber. The collected bees were kept in hermetically closed glass jars in a hydroalcoholic solution (Ethanol 70%). The vials were labelled, transported to the laboratory, and refrigerated (5-8 °C) until processing and analysis.

Determination of agrochemicals in bee bread

Pesticides were determined in bee bread to evaluate the presence of agrochemical residues in the bee colonies, including acaricides, insecticides, herbicides, fungicides, among others. For this purpose, a representative sample of bee bread (10 to 20 g) was taken from each monitored apiary. The samples were frozen at -20 °C and sent to an external and certified laboratory for further analysis. The bee bread samples that were insufficient to carry out the analyses were discarded. The determinations were made through multiple methods for the determination of pesticide residues in foods

of plant origin by analyses based on gas chromatography and liquid chromatography after extraction with acetonitrile and cleaning by dispersion solid phase extraction (QuEChERS method), which is based on the UNE-EN 15662 standard of the Spanish Association for Standardization (UNE 2019).

Statistical analysis

A database was built using the obtained data. The information related to the colony strength, infestation rates by *Varroa* sp. and colony losses was included in their respective units. In contrast, the field information was processed and weighted according to the variable type and for each monitoring. All statistical analyses were performed using IBM SPSS 22.0 software (SPSS Inc., Chicago, IL, USA). The descriptive analysis was reported as the frequency or percentage of the total samples ($N = 60$ apiaries and 60 beekeepers) or as the value of the arithmetic mean, median, standard deviation, standard error of the mean, or the minimum and maximum values, depending on each studied variable. With the values obtained from the quantitative variables, a normality test was carried out (Kolmogorov-Smirnov, 99% confidence), and to find significant differences in relation to the categorical variables (monitoring or sampling location), non-parametric tests were applied (Kruskal-Wallis's test or Mann-Whitney U test, $\alpha = 0.05$).

RESULTS AND DISCUSSION

General characteristics of the territory and the studied apiaries

The studied territory of Lambayeque is characterised by extensive deserts, boardwalks close to the sea and inter-Andean valleys between 2,000 and 4,000 meters above sea level (SINEACE 2020). This territory corresponds to an equatorial

dry forest with deciduous plant formations, low rainfall (between barely 350 to 800 mm per year) and a high level of anthropic impact caused by the development of intensive agriculture, with blueberry and avocado monocultures, among others (Acosta 2023, Delgado Berrocal 2019, Sánchez-Matos et al. 2023, Vansynghel et al. 2023). According to the information obtained during the survey, beekeepers reported as nutritional sources for bees, not only nectar from cultivated plants but also endemic species typical of these ecosystems, with a significant degree of diversity and abundance. Among the primary floral resources stand out *Prosopis pallida*, *Matisia cordata*, *Acacia macracantha*, *Zea mays* L., *Eriotheca ruizii*, *Mangifera indica* L., *Encelia farinosa*, *Loxopteriginum huasango*, *Lens culinaris* L., and *Bursera graveolens*, among others (Table I).

Characteristics of the beekeepers and their management practices

According to Table II, beekeeping is a secondary activity for beekeepers, who primarily provide pollination services (70%) and practice transhumance (60%), mainly for avocado and blueberry pollination. These two crops depend strongly on the density of honey bees during their pollination, which explains the large number of colonies mobilised to meet the high demands for pollination services in the studied territory (Peña & Carabalí 2018, Arrington & DeVetter 2018). More than half of the beekeepers reported participating in training activities (55%), but very few (10%) keep records of their productive activities. 62% of beekeepers have dedicated storage space for beekeeping materials. However, only 23% have access to a honey extraction plant, harvesting mainly in mobile tents. Even though most of the surveyed beekeepers prepare nuclei to multiply their colonies and change the bee queens annually,

Table I. Floral resources found near the apiaries.

Name	Percentage (%) of visited apiaries
<i>Prosopis pallida</i>	75
<i>Matisia cordata</i>	40
Commercial crops (passion fruit, fruit trees, citrus fruits, etc.)	33
<i>Acacia macracantha</i>	32
<i>Zea mays</i> L.	22
<i>Eriotheca ruizii</i>	22
<i>Mangifera indica</i> L.	12
<i>Encelia farinosa</i>	12
<i>Lens culinaris</i> M.	10
<i>Loxopteriginum huasango</i>	10
<i>Bursera graveolens</i>	8
<i>Phaseolus lunatus</i> L.	7
<i>Persea americana</i> L.	7
<i>Capparis ovalifolia</i>	7
<i>Gustavia augusta</i> L.	7
Others	< 5

it can be inferred that the queens mostly come from their own colonies.

Despite many beekeepers mentioning disinfecting the beekeeping materials, the used methods seem to be inappropriate (exposure to the sun, use of chlorine, bleach, alcohol, among others), as none of these techniques guarantees that the material is wholly disinfected or reduces

the amount of potential etiological agents that may be in circulation. Only 37% of beekeepers suspect the presence of diseases or pests in their apiaries. However, 98% of beekeepers monitor their colonies, and the disease diagnosis is the beekeeper's responsibility. Thus, the monitoring of *Varroa* sp. is carried out almost entirely (89%) by simple observation, and very

Table II. General information about the beekeepers and their management practices.

Variable	Percentage (%) of beekeepers		Observations
	Yes	No	
Is beekeeping the main source of income?	33	67	
Pollination services?	70	30	Avocado (68%), blueberries (47%), others (6%)
Colony migration (transhumance)	60	40	
Training activities	55	45	Annually (29%), biannually (8%), more than two years (18%)
Records of their productive activities	10	90	
Are beekeeping materials stored in a dedicated storage space?	62	38	
Does the beekeeper have a plant for honey extraction?	23	77	Mobile tent (68%)
Creation of nuclei	77	23	
Disinfection of beekeeping materials	45	55	Flaming (2%), boiling water (5%), sun (20%), others (18%, i.e., chlorine, bleach, alcohol)
Does the beekeeper monitor diseases or pests? Who carry out the diagnostics?	98	2	The beekeeper himself (80%); a more experienced beekeeper (13%), a specialist (5%)
Does the beekeeper suspect pests or diseases in adult bees or their brood?	37	63	<i>Varroa</i> sp. (32%), others (5%)
Does the beekeeper monitor <i>Varroa</i> sp.?	60	40	Simple observation: 89% Drone larvae: 6% Powdered sugar: 3%
Application of treatments against <i>Varroa</i> sp.	30	70	Amitraz: 7%, others: 23% (smoker with aromatic species, or sulfur)
Supplementary feeding	88	12	Energy food: 70% Protein food: 5% Both: 13%
Other nearby apiaries (< 3 Km)	62	38	

few beekeepers apply treatments against this parasite (Table II). Even the few beekeepers who reported monitoring *Varroa* sp. or administering varroicidal treatments appear to do so whenever the mood strikes and without following a set plan (Figure 1a).

In the case of feeding, it is favourable that 70% of the participants supplement their bee colonies with diluted sugar syrup during practically the entire year, even in the presence of abundant nectar flows. This fact is related to preparing honey bees for pollination rather than for honey harvest. However, only a small percentage (5%) provide protein supplements, and only 13% combine both, even when the colonies return from pollinating crops with significant amino acid deficiencies or following

the physiological damage that the harvest denotes. Such nutritional dynamics and its impact on the colonies' survival is evidenced in Figure 1b. This fact could explain the months of the year in which the most significant colony loss occurs. In this regard, it is crucial to understand that the studied territory has been significantly altered by human activity, with extensive blueberry and avocado cultivation areas. The colonies of beekeepers who specialise in pollination services are moved to blueberries in May, where they can stay for several months (May to August). As a result, the colonies that survive that season become depressed from accessing a deficient amino acids monofloral protein diet, which is why colony losses dramatically increase during July and August.

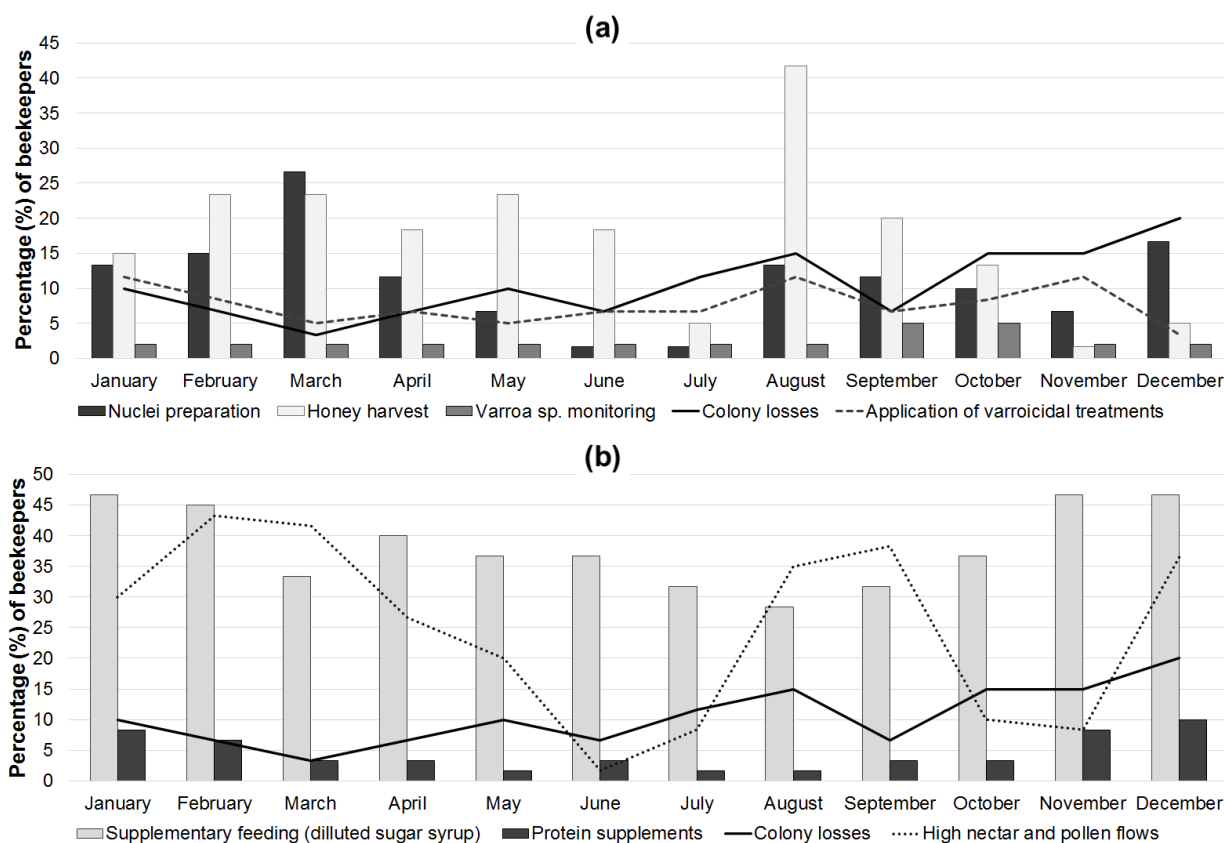


Figure 1. Some management practices reported by the beekeepers and colony losses during the year. a) Nuclei preparation, honey harvest and application of varroicidal treatments vs. Colony losses during the year. b) Availability of floral resources and supplementary feeding, vs. Colony losses.

It is important to remember that bees can travel over several kilometres, depending on the availability of food, the population density, or adverse environmental conditions (Rutschmann et al. 2023, Vijayan & Somanathan 2023). Honey bee colonies are thought to have a flight radius of at least three kilometres (OIE 2013), which means that during foraging activities, the flight radius of bees from various apiaries can be intercepted. In this case, 62% of beekeepers reported nearby apiaries that were less than 3 km away (Table II), which is evidence of a high level of hygienic promiscuity and competition for floral resources among bee populations in the region where they were kept located (Phiri et al. 2023).

Figure S1 (Supplementary Material - Figure S1) shows that the surveyed beekeepers have broad experience in the field (between 0 and 40 years of experience). A small percentage of beekeepers (around 3%) do not have previous experience in this field, and close to 40% have between 1 and 5 years of experience. Despite this, beekeepers with an intermediate level of experience (between 6 and 10 years) and an advanced level (more than ten years) were also found, corresponding to 18% and 38%, respectively. Half of the beekeepers (50%) manage their colonies in 2 apiaries, while 43% keep them in one apiary. Only a small percentage of the beekeepers (7%) manage their colonies in three apiaries. The number of colonies each beekeeper manages varies between 7 and 1,000, but most of them, manage just between 7 and 50 colonies, and almost all (98%) correspond to modern Langstroth-type hives. About half of the surveyed beekeepers (55%) own between 7 and 50 colonies, while 25% manage between 60 and 100 colonies; the rest (around 20%) have more than 100 hives in their apiaries.

Weather conditions and honey bee colony

strength

Concerning weather conditions, Table III shows that the temperature was around 30 °C in both monitoring. Still, the relative humidity was significantly different (47 vs. 69% for the first and the second monitoring, respectively). On the other hand, an indicative parameter about the global status of the colony is the flight activity of honey bees, defined as the number of bees entering the hive during a given time interval (Alleri et al. 2023). This value should be around 60 worker bees/minute (Morammazi & Shokrollahi 2020, Olate-Olave et al. 2021). As shown in Table III, this number was 23 and 26 bees per minute for the first and the second monitoring, respectively. Even though the temperature and weather conditions could influence this value (Harun et al. 2015, Morammazi & Shokrollahi 2020), in this case, the low number of bees entering the hive in one minute does not seem to be related to the season or the climatic conditions. Still, it could suggest potential deficiencies inside the brood chamber. When inspecting the interior of the colonies, it was observed that most of the colonies presented few combs with adult bees, closed and open brood, and few food reserves (honey and pollen), and a poor number of frame heads covered with bees. In addition, the number of frames in the brood chamber ranged between 3 and 10 combs, but generally, the brood chamber contained ten combs (median) (Table III).

Infestation rates by *Varroa* sp.

In relation to *Varroa destructor*, it has been reported that when effectively controlling the presence of Varroa mites (i.e., less than 3.0 mites/100 bees), colony mortality is significantly reduced (Kulhanek et al. 2021). According to Table IV, which summarises the results obtained for the infestation rates by *Varroa destructor* according to the monitoring and the

Table III. Weather conditions and parameters associated with colonies inspection and colony strength in the brood chamber. Values represent the mean, minimum (Min.), and maximum (Max.) for each parameter according to the monitoring. (*) Significant differences according to the monitoring (Mann-Whitney U test, $p < 0.05$).

Parameter	First monitoring			Second monitoring		
	Median	Min.	Max.	Median	Min.	Max.
Temperature	29.9	17.5	46.0	31.3	25.0	40.0
Relative Humidity (%) (*)	47.0	12.0	83.0	69.0	27.0	99.0
Bees entering the hive per minute	23	0	125	26	0	96
Number of frames	10	3	10	10	3	10
Frame heads covered with bees (*)	0.1	0	10	2	0	10
Number of combs covered with:						
Adult bees	3.3	0	10	2.9	0	10
Closed brood	1.3	0	4.9	1.3	0	4.4
Open brood (*)	1.3	0	3.5	1.1	0	3.6
Honey	1.4	0	6.3	1.3	0	6.1
Pollen	0.3	0	2.6	0.1	0	3.4

location of the apiaries, there is a 2.4% global infestation rate, with a maximum value of 25%. While this is a significant rate when compared to other countries in the Region (Maggi et al. 2016, Olate-Olave et al. 2021), there were no significant differences found in the monitoring (Mann-Whitney U test, $p = 0.382$) or apiary location (Kruskal-Wallis's test, $p = 0.141$). On the other hand, the global prevalence of varroosis for monitoring 1 and 2 was 89% and 76%, respectively, which is close to previous reports for other Latin American countries (Maggi et al. 2016). It is worth mentioning that this is the first report on the presence of *Varroa* mites in this territory. However, numerous variables, e.g., agroecology, type of hive, management system, and colony management, could influence this result (Robi et al. 2023). Therefore, for a better understanding, future research should focus on the prevalence of *Varroa* mite infestation and its rates. Consequently, it can be concluded that the mite *Varroa* sp. should be considered

a significant health concern in the development of modern beekeeping in the analysed region.

Multiresidue agrochemical analysis

According to the multi-residue analysis of pesticides in bee bread, it is possible to mention that 67% of the analysed samples were positive for this analysis, detecting a total of 41 different compounds, whose concentrations were variable, from trace levels (< 0.005 mg/Kg or < 0.010 mg/Kg, depending on the quantification limit for each analyte) up to 8.7 mg/Kg, which are listed in Table V. The most frequent agrochemicals (found in around 50% of the samples) were the insecticide organophosphate chlorpyrifos and the fungicides carbendazim, boscalid, and azoxystrobin. Chlorpyrifos is an organic thiophosphate and a chlorpyridine widely used in homes, and on farms; it has a role as an acetylcholinesterase and cholinesterase inhibitor, acaricide and an insecticide, and it is highly toxic for bees (Martin-Culma &

Table IV. Infestation rates (%) by *Varroa* sp. and its prevalence, in relation to the monitoring and the location. Values represent the total (N), mean, median, standard deviation (SD), standard error of the mean (SEM), and maximum value in each case (minimum was “zero” in all cases).

Monitoring	Location	N	Mean	Median	SD	SEM	Maximum	Prevalence (%) of varroosis
First	Motupe	50	2.7	2.0	2.6	0.4	11.4	86
	Lambayeque	76	2.7	1.8	2.8	0.3	11.4	84
	Olmos	100	1.9	1.6	1.6	0.2	8.7	93
	Total	226	2.4	1.74	2.3	0.2	11.4	89
Second	Motupe	59	1.6	1.2	1.7	0.2	7.0	76
	Lambayeque	75	2.7	0.8	4.9	0.6	25.0	55
	Olmos	100	2.6	2.3	1.7	0.2	7.6	92
	Total	234	2.4	1.5	3.1	0.2	25.0	76

Arena-Suárez 2018, PubChem 2023). It has been reported that chlorpyrifos is one of the most detected pesticide-active substances in beehive products (Végh et al. 2023).

Carbendazim is a member of the class benzimidazoles that controls Ascomycetes, Fungi Imperfecti, and Basidiomycetes on a wide variety of crops, including bananas, cereals, cotton, fruits, grapes, mushrooms, ornamentals, peanuts, sugar beet, soybeans, tobacco, and vegetables (PubChem 2023). On the other hand, boscalid is an active fungicide against a broad range of fungal pathogens, including *Botrytis* spp., *Alternaria* spp., and *Sclerotinia* spp., and it is used on a wide range of crops, including fruit, vegetables, and ornamentals (PubChem 2023). Azoxystrobin is a methoxyacrylate strobilurin antifungal agent with the broadest spectrum of activity of all known antifungals, protecting plants and fruit/vegetables from fungal diseases (PubChem 2023).

In addition, other frequent agrochemicals found in around 40% of the analysed samples

were the fungicides sulfur, difenoconazole, and tebuconazole, and the insecticide cypermethrin (alpha+beta+gamma), among others (Table V). In accordance with recent studies, the present results indicate that a considerable list of agricultural pesticides can be transferred to apicultural matrices such as bee bread or honey, and the presence of unauthorised pesticides has even been detected in various fruit and animal matrices (Delgado-Zegarra et al. 2018, Murcia-Morales et al. 2022). However, ubiquitous varroicide substances (i.e., coumaphos, tau-fluvalinate, amitraz) were not found in the analysed samples, probably because a small portion of the beekeepers apply this kind of product (Table II), since these products are scarce in local markets. Still, also it could be attributable to the growing trend of using more “green” substances (Murcia-Morales et al. 2022). Because of the present results, it is highly recommended to reorganise the agrochemical control system in the territory of Lambayeque (Peru) and to establish an integrated pest

Table V. List of the agrochemicals found in bee bread and their family or pesticide group. Percentage (%) of the total samples, and concentration (range) of the residues.

Name	Family or group	% of samples	Concentration (mg/Kg)
Bifenazate	Acaricide / carbamates	3.3	0.01
Dimetomorph	Fungicide	3.3	0.019
Diphenylamine	Fungicide	6.7	< 0.005 - 0.005
Sulfur	Fungicide	43.3	0.047 - 8.738
Metalaxyl	Fungicide / acetylalanine	3.3	0.006
Thiabendazole	Fungicide / benzimidazole	16.7	0.014 - 0.801
Carbendazim	Fungicide / benzimidazoles	50.0	< 0.010 - 0.059
Boscalid	Fungicide / carboxanilide	50.0	< 0.010 - 0.089
Iprodione	Fungicide / imidazole	3.3	< 0.005
Fludioxonil	Fungicide / pyrrole	3.3	< 0.005
Azoxystrobin	Fungicide / strobilurine	46.7	< 0.010 - 0.22
Kresoxim-methyl	Fungicide / strobilurine	3.3	< 0.010
Difenoconazole	Fungicide / triazole	36.7	< 0.005 - 0.034
Epoconazole	Fungicide / triazole	3.3	< 0.010
Tebuconazole	Fungicide / triazole	36.7	< 0.005 - 0.034
Paclobutrazol	Fungicide and growth regulator / triazole	10.0	0.011 - 0.088
Uniconazole	Growth regulator / triazole	3.3	0.028
3,4-Dichloroaniline	Herbicide	3.3	0.018
Cyhalofop butyl	Herbicide / aryloxyphenoxy propionic acid	3.3	< 0.010
Atrazine	Herbicide / chlortriazine	16.7	< 0.010 - 0.030
Pendimethalin	Herbicide / dinitroaniline	20.0	< 0.005 - 0.017
Ametryn	Herbicide / triazine	16.7	< 0.010 - 0.012
Terbutryn	Herbicide / triazine	3.3	< 0.010
Linuron	Herbicide / urea derivate	3.3	0.195
Chlorpyrifos	Insecticide / organophosphate	53.3	< 0.005 - 0.093
Profenofos	Insecticide / organophosphate	3.3	< 0.005
Dimethoate	Insecticide / organophosphate	10.0	< 0.010 - 0.023
Indoxacarb	Insecticide / oxadiazine	3.3	< 0.010

Table V. Continuation.

Cyhalothrin	Insecticide / pyrethroide	3.3	0.038
Cyhalothrin Gamma	Insecticide / pyrethroide	3.3	0.018
Cyhalothrin Lambda	Insecticide / pyrethroide	3.3	0.02
Cypermethrin (alpha+beta+gamma)	Insecticide / pyrethroide	40.0	< 0.005 - 0.02
Spirodiclofen	Insecticide and acaricide / ketoenole	3.3	0.038
Methoxyfenozide	Insecticide / diacylhydrazine	10.0	0.049 - 0.197
Acetamiprid	Insecticide / neonicotinoid (cyano-substituted)	20.0	< 0.010 - 0.035
Clothianidin	Insecticide / neonicotinoid (nitro-substituted)	3.3	< 0.010
Imidacloprid	Insecticide / neonicotinoid (nitro-substituted)	26.7	< 0.010 - 0.048
Thiamethoxan	Insecticide / neonicotinoid (nitro-substituted)	13.3	< 0.010 - 0.055
Etoxazole	Insecticide and acaricide	6.7	0.019 - 0.090
Chlorfenapyr	Insecticide and acaricide / pyrroles	6.7	< 0.005 - 0.012
Buprofezin	Insecticide and acaricide / thiadiazinane	13.3	< 0.005 - 0.016

management program, promoting organic production and encouraging the use of biological control agents or natural products (Delgado-Zegarra et al. 2018). In addition, education programs could be essential for helping land managers decide on the most efficient ways to apply integrated crop pollination strategies, which are focused on combining tactics that are appropriate for the crop's dependence on insect-mediated pollination, including the use of wild and managed bee species, and enhancing the farm environment for these insects through directed habitat management and pesticide stewardship (Isaacs et al. 2017). Finally, policies to reverse current trends ensuring global food safety should be implemented in the short term to achieve more sustainable regional development to avoid the high vulnerability of the agricultural ecosystems, the potential loss in food production, and the associated socio-economic consequences (Basualdo et al. 2022).

In this sense, to put these principles into effect, cooperation and communication between all parties involved in the beekeeping chain are essential.

Field observations in the colonies: Sanitary gaps

According to the observations collected in Table VI, 79% of the colonies have one body (one box), while a small percentage (21%) grows in two bodies. The poor colony strength and the effects of insufficient feeding could explain the colonies' limited vertical growth. Above all, it leaves beekeeping populations predisposed to various health risks and numerous sanitary gaps (Olate-Olave et al. 2021). In this way, it stands out that just 35% of the colonies are placed separately from each other, and 47% are separated from the ground. It results in increased humidity inside the hive, promoting the presence of pests and predators, making the thermo-regulation and the cleaning of the colonies difficult. As evidence,

Table VI. Field observations in the monitored colonies, and main observations reported by the beekeepers for dead colonies during the previous year. Values represent the percentage (%) of the total number of inspected colonies.

Observations	Percentage (%) of monitored colonies
From the hive:	
One body (one box)	79
Two bodies (two boxes)	21
Dead bees in the hive entrance	7
Is the hive placed separately from each other?	35
Is the hive separated from the ground?	47
Accumulation of detritus, larvae, pupae, dead or calcified bees at the bottom of the hive	24
Presence of predators or pests (*)	32
Feces on the top or fronts	< 1
From the open brood:	
Colour change	< 1
Position change	1
Smell change	25
From the closed brood:	
Dark combs, deepset, or perforated capping	6
Spotted brood	22
Mummified or calcified larvae	2
From dead colonies during the previous year:	
Dead bees in the hive entrance	48
Dead bee brood inside the cells	25
Food reserves within dead colonies	32
Was the colony loss a result of natural disasters?	7
Was the colony loss due to evasion, swarming, or unknown causes	40

(*) Birds (13%), lizards (5%), ants (4%), others (10%).

24% of the monitored colonies presented an accumulation of detritus, larvae, pupae, dead or calcified bees at the bottom of the hive, and 32% of them had diverse predators or pests, mainly birds, lizards, ants, among others. On the other hand, odour change in open brood was

observed in 25% of the total monitored colonies and spotted brood in 22% of cases (Table VI). Additionally, information was obtained about the dead colonies during the last year, where it is notable that in 48% of the cases, dead bees were observed in the hive entrance and dead

brood inside the cells (25%). Only in 32% of the dead colonies were food reserves found, and it is estimated that around 7% of the losses were due to natural disasters, while 40% of the total losses were attributed to evasion, swarming or other unknown reasons.

CONCLUSIONS

The change in land use in Peru's northern desert has resulted in large areas of crops dependent on honey bee pollination. Thus, the bee bread samples analysed in this study show an increased risk of exposure of managed honey bees to agrochemical products. Additionally, the limited expertise on good management practices, which is reflected in the inadequate disinfection of beekeeping materials, unsatisfactory varroa mites' monitoring, lack of protein supplements, as well as the presence of sanitary gaps, lead to deficiencies in the colony strength and high *Varroa* sp. prevalence in the territory, altering the health status of honey bees. Considering these results, it is highly recommended that the agrochemical control system be reorganised in the studied territory, integrated crop pollination strategies be applied, and adequate public policies be implemented to reverse the current trends. It is strongly advised to plan the georeferencing of bee colonies in the territory, develop territorial planning policies, working with a One Health perspective, and coordinate strategies with farmers, including organised flows of colonies during pollination, according to the demand. On the other hand, it is relevant to ensure the safety of the beekeeping production chain, which is susceptible to the accumulation of agrochemical residues that affect not only the quality of bee products, but also bee health and, consequently, the survival of honey bee colonies.

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SUPPLEMENTARY MATERIAL

Figure S1.

How to cite

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