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Review

Toward Anthophila Conservation in Algeria: Recent Knowledge, Threats, and Perspectives

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Abstract

This study provides an updated overview of Anthophila (wild bees and honey bees) diversity and conservation status in Algeria, explicitly distinguishing between the managed honey bee (*Apis mellifera*) and native wild Anthophila species. Using a systematic PRISMA-based literature analysis, more than 179 bee species have been documented across Mediterranean and semi-arid ecosystems, confirming their irreplaceable contribution to ecosystem resilience and crop pollination and beekeeping systems. The majority of Algeria's Anthophila diversity is represented by endemic and native wild bees that sustain natural ecosystems. However, they are under growing human-caused (anthropogenic) pressures in the Anthropocene, including pressure from habitat loss and fragmentation, agricultural intensification, widespread pesticide use, and climate change. In addition, pathogenic threats such as *Varroa destructor*, *Nosema*, and associated viruses are well documented in honey bees, while evidence for their presence and impact in wild bees in Algeria remains very limited. These stressors not only weaken specialist species but also accelerate biotic homogenization dominated by *A. mellifera*. Recent genomic research on native honey bee populations has revealed adaptive signatures linked to immunity and social behavior, offering new opportunities for innovative conservation strategies based on molecular and genetic tools. Such insights highlight the value of preserving local strains, which may hold key traits for resilience under changing environmental conditions. To safeguard Anthophila biodiversity, this study underscores the urgent need for Algeria to implement proven conservation strategies, including habitat restoration initiatives and Anthophila-friendly farming approaches, which are common internationally but remain largely unaddressed at the national scale. By integrating cutting-edge genetic research, ecological restoration, and sustainable innovation, Algeria, with its diverse habitats and largely unexplored Anthophila fauna, holds considerable potential for advancing biodiversity conservation strategies that also support food security. However, this potential can only be realized through further in-depth research and comprehensive species inventories.

Keywords: wild bees; *Apis mellifera*; pollination; diversity; conservation; Red List; Algeria

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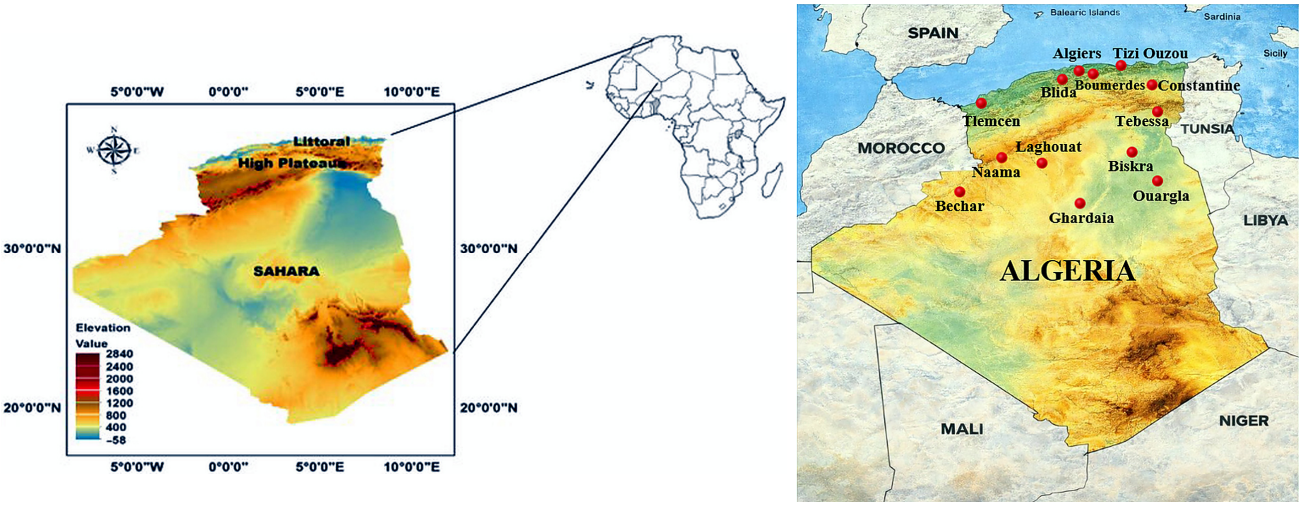
1. Introduction

Bees belong to the clade Anthophila, which includes several families, such as Apidae, Andrenidae, Halictidae, Megachilidae, and Colletidae, and they are essential for biodi-

versity and the productivity of natural and agricultural ecosystems [1,2]. They facilitate sexual reproduction in nearly 90% of flowering plants (≈250,000 Angiosperm species), maintaining ecosystem integrity and enhancing crop yields [3]. The economic value of insect-mediated pollination, mainly by bees, is estimated at €153 billion annually, highlighting their crucial role in food security and sustainable agriculture [4].

Although *Apis mellifera* is often considered native to northern Africa, its current ecological dominance is strongly linked to millennia of human management and recent intensification of beekeeping practices. Unlike wild Anthophila species, which persist exclusively through natural population dynamics, *A. mellifera* populations are actively propagated, transported, and maintained by humans. This fundamental difference complicates direct comparisons between honey bees and endemic wild bees and requires explicit consideration when assessing conservation priorities and ecological interactions.

Algeria occupies a strategic geographic position in northern Africa with diverse terrains that generate a wide range of climatic and ecological zones (Figure 1). Influenced by the Mediterranean Sea, topography, and altitude, it experiences a temperate Mediterranean climate, with summer droughts lasting 3–4 months along the coast and more than 6 months in southern arid regions [5]. The country encompasses six major ecological regions, with average annual temperatures ranging from 11 °C to 20 °C and rainfall varying between 190 and 1000 mm. Algeria, with a total land area of about 2.38 million km^2, is approximately 80% covered by the desert (mainly Sahara), while the remaining landscape includes steppe, high plains, mountains, and a narrow coastal/northern belt with Mediterranean habitats. Agricultural land, including arable land, pastures, and permanent crops, covers approximately 17% of the land area, while permanent forests occupy a much smaller fraction, mainly in the northern and sub-mountain zones [6]. This environmental heterogeneity supports remarkable floral richness and diverse habitats, from northern wetlands to southern deserts [7]. Consequently, Algeria harbors a wide array of pollinators, including bees, butterflies, hoverflies, and beetles, whose activity is essential for the pollination of both wild and cultivated plants.



(**A**) (**B**)

Figure 1. (**A**) Map of Algeria and the different elevation zones from −58 to 2840 m. In the North, the Littoral Zone borders with the Mediterranean Sea, and further the South, the High Plateau is followed by the Sahara desert. (**B**) The locations of surveyed sites and bee monitoring areas (red dots). (**A**) is from Sahabi-Abed et al. [8], and (**B**) is based on Amrani et al. [9] with extra monitoring places based on Fridi et al. [10], Barour and Baylac [11], Ayad et al., [12] Haddad et al. [13], Adjlane et al. [14], Chibani et al. [15], and Haider et al. [16].

Despite their ecological importance, Anthophila populations have experienced alarming declines globally in recent years due to human-caused (anthropogenic) pressures in the Anthropocene, including habitat loss and fragmentation, excessive pesticide use, pollution, invasive alien species, climate change, and pressures from intensive agriculture [17–24]. While these declines are well-documented in Europe and North America, comparable data for North Africa, including Algeria, remain limited, underscoring a significant lack of regional data compared to Europe and North America.

In Algeria, the study of wild bee biodiversity in Algeria dates back more than a century, with early contributions from Saunders [25,26], Alfken [27], Schulthess [28], and Benoist [29] who conducted the systematic inventory of the country's Anthophila. Since then, few comprehensive taxonomic lists have been published; for example, Louadi [30] listed only species of the genera *Halictus* and *Lasioglossum* from the region of Constantine (eastern Algeria), while Louadi and Doumandji [31] reported additional studies focusing on specific taxonomic groups or regional fauna [32]. Despite these efforts, knowledge of Anthophila is fragmented, geographically restricted, and largely focused on specific taxonomic groups. No consolidated national database or long-term monitoring program exists [33,34]. Moreover, the country lacks both a national Red List of threatened Anthophila and a national conservation framework dedicated to their protection. Addressing these gaps is essential for the maintenance of biodiversity, ecosystem services, and agricultural resilience.

To address these challenges, innovative approaches in biodiversity research and conservation are increasingly important. For example, genomic analyses of native honey bee populations have revealed adaptive traits related to immunity, social behavior, and environmental resilience [16,18]. Such insights can inform genetically informed conservation strategies, including the preservation of locally adapted strains capable of tolerating environmental stressors and pathogens. These approaches are particularly relevant in Algeria, where native honey bee populations are exposed to diverse climatic and ecological pressures [16].

Emerging technologies such as remote sensing, GIS-based habitat mapping, and AI-assisted monitoring offer new ways to track pollinator populations, identify habitat hotspots, and assess ecological connectivity across fragmented landscapes [35,36]. Citizen science platforms and mobile applications can further support real-time monitoring, engaging local communities in conservation efforts while generating valuable data for research and policy [37]. Ecological modeling and predictive tools can anticipate shifts in Anthophila distributions due to climate change, informing proactive habitat restoration and management interventions [36].

Additionally, innovative agricultural practices, including precision agriculture, Anthophila-friendly crop rotation, and integrated pest management, can mitigate anthropogenic pressures on Anthophila while sustaining crop yields [4]. The creation of ecological corridors, urban green spaces, and restored flowering habitats can further enhance Anthophila diversity and ecosystem resilience. These strategies, when combined with scientific innovation, would provide a holistic framework for conservation in Algeria's unique ecosystems [20,21].

Considering these challenges and opportunities, there is an urgent need for coordinated and comprehensive research efforts to document, evaluate, and monitor Anthophila diversity across Algeria. Establishing such basic knowledge is essential to guide evidence-based conservation actions and strengthen the resilience of agricultural systems to climate variability and environmental change. By integrating cutting-edge genomic research, ecological monitoring technologies, and sustainable land-use strategies, Algeria can develop evidence-based policies that ensure the long-term preservation of Anthophila diversity and ecosystem services.

This review compiles and synthesizes the available recent evidence on Algeria's Anthophila to summarize current knowledge, identify major threats, and reveal critical research gaps. Given the scarcity and fragmentation of existing studies, the present work does not claim to provide a full systematic review. Rather, it focuses on recent advances in Algerian bee research published since 2000, building upon earlier comprehensive reviews. It organizes the selected literature following key principles of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [38,39] to ensure transparency and consistency. By contextualizing Algerian Anthophila research within broader regional and global conservation perspectives, this study aims to highlight priorities for future investigation and management. Hence, the present synthesis is intended as a preliminary step to inform and guide future data-driven conservation and research efforts.

2. Methodology

A comprehensive literature search was conducted using PubMed (https://pubmed.ncbi.nlm.nih.gov/, accessed on 15 August 2025) to gather relevant studies published over a 25-year period, from January 2000 to August 2025. The search employed a wide range of keywords relevant to Anthophila in Algeria, including: "Pollinator", "Wild bee", "Solitary bee", "*Apis mellifera*", "Apoidea", and "Bumble bee" (Table 1). This search initially yielded 117 articles (Table 1). To broaden the coverage and retrieve additional relevant studies, complementary searches were also performed using Google Scholar, iNaturalist and ResearchGate.

Table 1. Summary of keywords, their associated topics, and the corresponding number of publications retrieved from PubMed between January 2000 and August 2025.

Searched Topics and Keywords	Number of Publications
Pollinator	22
Wild bee	6
Solitary bee	2
Apis mellifera	47
Apoidea	40
Bumble bee	0

As illustrated in Figure 2, the PRISMA flow diagram was applied to systematically guide the screening, eligibility assessment, and final inclusion of studies. This approach facilitated the identification of pertinent publications and the removal of irrelevant records, starting from an initial pool of over 100 references. During the screening phase, each document was carefully examined, relevant studies were compiled, and eligibility was determined based on predefined exclusion criteria. We included only peer-reviewed journal articles and book chapters addressing Anthophila diversity in Algeria. To ensure consistency and reliability, grey literature, theses, conference abstracts, and local reports were excluded. Duplicate records were also removed. This process resulted in the final selection of 18 studies for inclusion. To broaden the coverage and retrieve additional relevant studies, complementary searches were also performed using Google Scholar, iNaturalist, and ResearchGate (n = 29), leading to a total of 47 included studies (The full list of included studies and selection criteria is provided in Supplementary Table S1).

For bibliometric analysis, VOSviewer software version 1.6.20 (https://www.vosviewer.com/, accessed on 1 August 2025) [40] was employed to generate a visual network of authors and co-authors (Figure 3). Data collected from PubMed were exported as a RIS file, uploaded into VOSviewer, and analyzed to identify prominent contributors to bees' biodiversity and research in Algeria. Mapping collaborative links among authors enabled

the detection of cooperation patterns and the recognition of key researchers in the field (Figure 3).

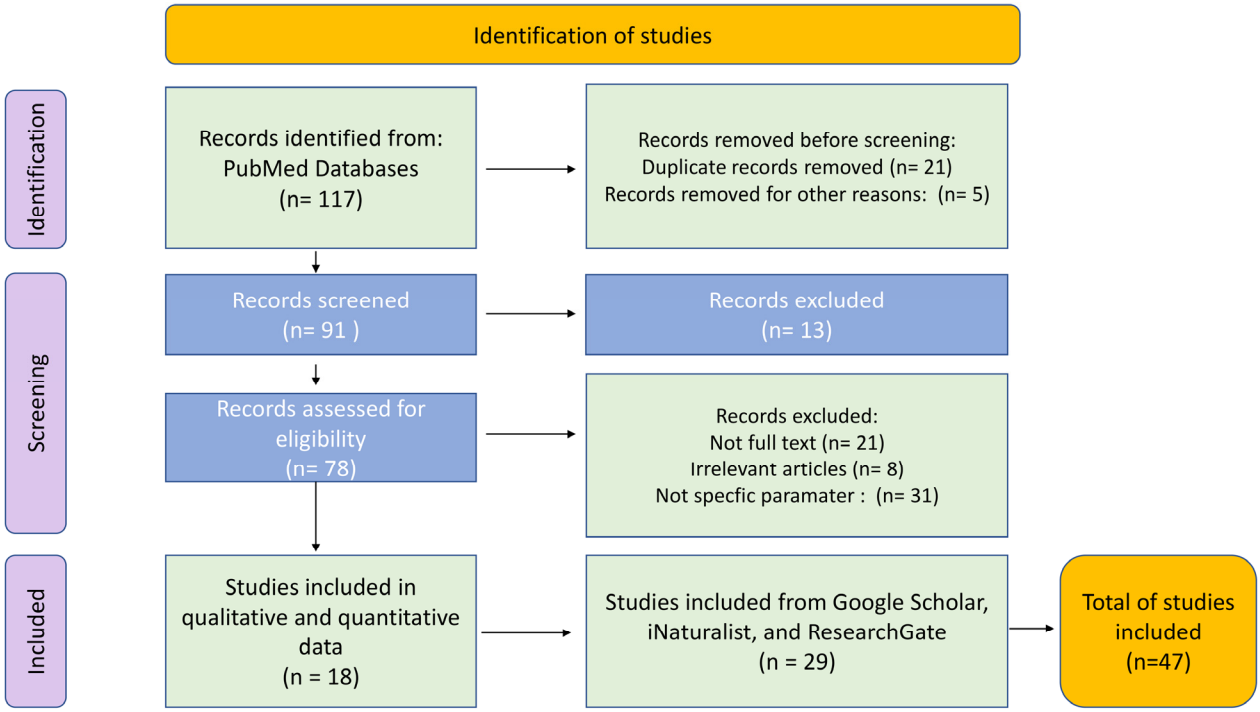


Figure 2. PRISMA flow diagram depicting the literature search method for bee biodiversity in Algeria and related fields in the PubMed database (https://pubmed.ncbi.nlm.nih.gov/, accessed on 15 August 2025) from January 2000 to August 2025.

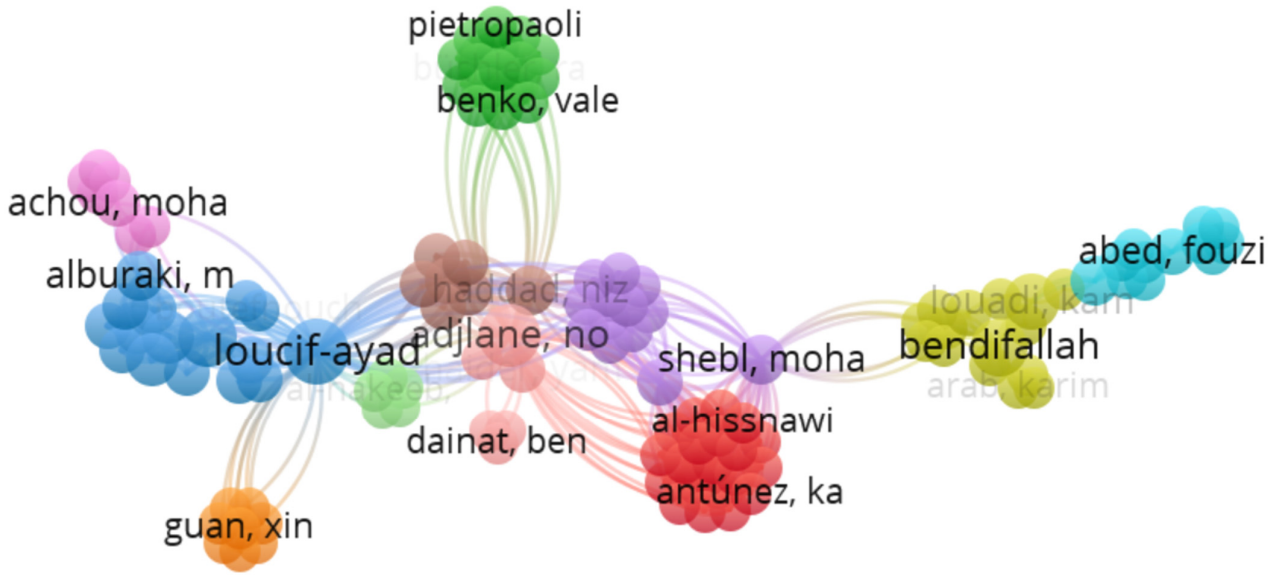


Figure 3. Network of authors and co-authors involved in bee biodiversity research in Algeria and related fields, based on a comprehensive PubMed literature search (https://pubmed.ncbi.nlm.nih.gov/, accessed on 15 August 2025) from January 2000 to August 2025, visualized using VOSviewer. In the network visualization, each circle (node) represents an author; the size of the circle reflects the number of publications or link strength, and the lines between circles indicate co-authorship collaborations. Different circle colors represent distinct collaboration clusters identified by VOSviewer, while font color intensity reflects label visibility based on node weight and overlap optimization.

Additionally, VOSviewer (https://www.vosviewer.com/, accessed on 15 August 2025) [40] was utilized to examine keyword co-occurrences. A threshold of at least three occurrences was applied to identify frequently used terms. Of the 462 original keywords, 19 met this criterion and were selected for further analysis (Figure 4).

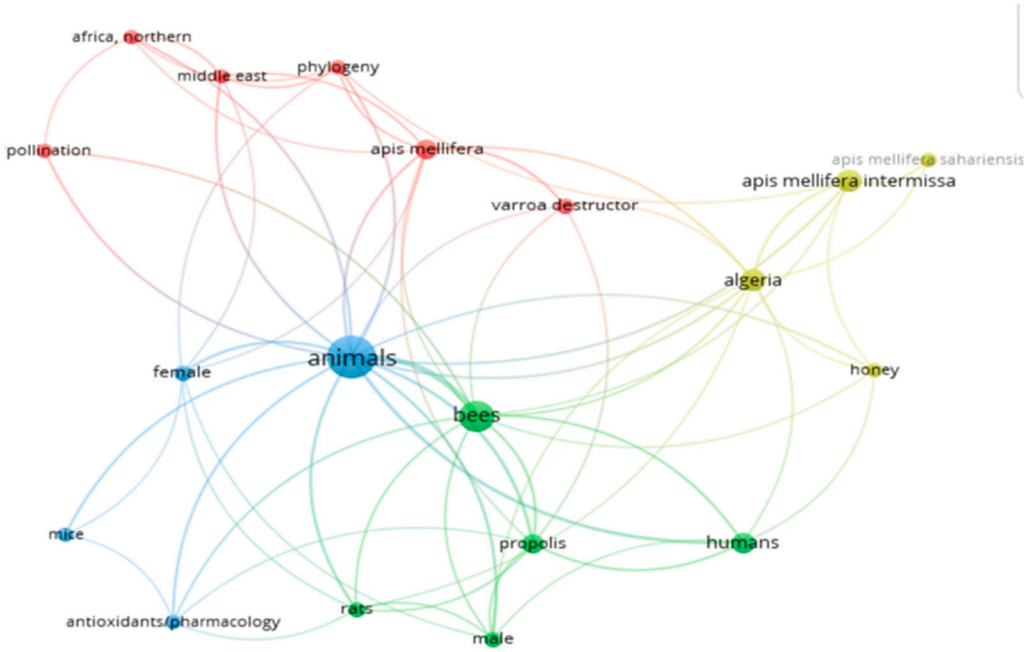


Figure 4. Co-clustering map of high-frequency keywords in studies on bee biodiversity in Algeria and related fields, based on a comprehensive PubMed literature search (https://pubmed.ncbi.nlm.nih.gov/, accessed on 15 August 2025) from January 2000 to August 2025, visualized using VOSviewer. Each circle (node) represents a keyword, and node size reflects the frequency of occurrence. Lines indicate co-occurrence relationships between keywords. Colors were automatically assigned by VOSviewer to represent different clusters of related terms, while font colors were automatically generated for readability and have no additional analytical meaning.

This combined approach of systematic literature review, PRISMA-guided screening, and bibliometric visualization allowed for a robust and comprehensive assessment of Anthophila research in Algeria, highlighting both scientific trends and collaborative networks in the field.

The bibliometric analysis carried out with VOSviewer highlights that research on Anthophila in Algeria is structured around several distinct collaboration clusters. Certain authors, notably Loucif-Ayad, Adjlane, and Bendifallah, occupy central positions, reflecting their major contributions to national scientific output. The network also reveals international collaborations, particularly with researchers such as Alburaki and Antúnez, though these remain limited in scope. The clusters indicate that research is still fragmented, with few interconnections between Algerian groups themselves. Furthermore, the majority of studies focus on the honey bee (*A. mellifera*), while wild species remain largely understudied. These findings emphasize both the dynamism of key research hubs and persistent gaps, particularly the lack of inter-institutional collaboration and low thematic diversity, which limit a comprehensive understanding of pollination in Algeria.

3. Diversity and Distribution of Anthophila in Algeria

Anthophila diversity in Algeria comprises two ecologically distinct components: (i) the managed honey bee (*A. mellifera*), including the endemic subspecies *A. m. intermissa* and *A. m. sahariensis*, and (ii) native wild Anthophila species that are not managed and depend

entirely on natural habitats. Although *A. mellifera* often appears as the most abundant species in field surveys, this dominance partly reflects human-mediated colony densities rather than natural population structure.

Anthophila diversity and distribution in Algeria show considerable spatial and temporal variation. A survey conducted between March and June 2022 collected 92 specimens, including 70 individuals from nine Anthophila species across five genera, with *A. mellifera* (33.4%), *Bombus terrestris* (20%), and *Xylocopa pubescens* (17.1%) being the most abundant [5] (Figure 5). Higher Anthophila concentrations were observed in Ahfir and Beni Snous, with diversity greatest in Beni Snous (Shannon–Weaver H′ = 2.65). These results highlight how ecological differences shape species richness, though the limited sample size indicates that broader surveys are needed to fully assess Anthophila diversity in Algeria. Moreover, plant-Anthophila interactions provided only preliminary observations that may indicate specialization, with species such as *A. mellifera* and *X. pubescens* showing strong dependence on particular foraged plants.

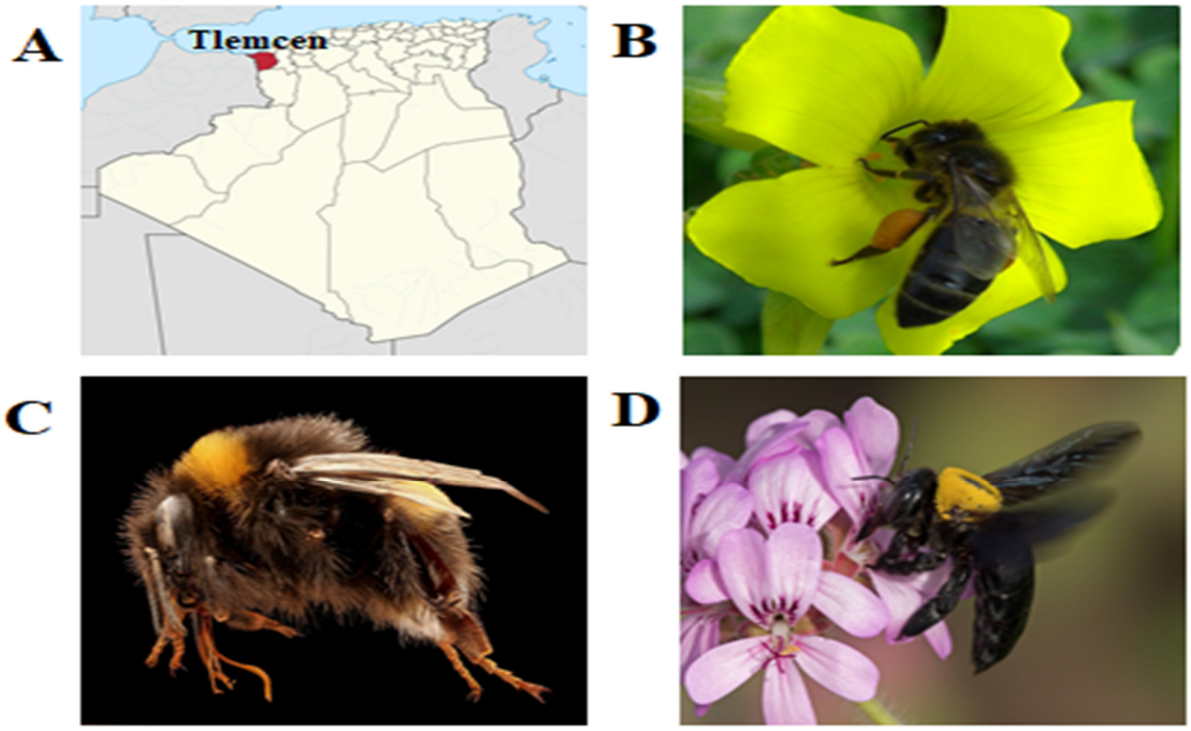


Figure 5. The study of Khedim et al. [5] in regions of Tlemcen (https://commons.wikimedia.org/wiki/File:Tlemcen_in_Algeria.svg, accessed on 26 August 2025) (**A**) indicated *Apis mellifera* as the most abundant species in this limited survey (original photo taken by the authors) (**B**), followed by *Bombus terrestris* (https://www.usgs.gov/media/images/bombus-terrestris-f-left-side-culverden-new-zealand, accessed on 26 August 2025) (**C**), and *Xylocopa pubescens* (https://polinizadoresdecanarias.org/portfolio/xylocopa-pubescens/, accessed on 26 August 2025) (**D**).

This localized evidence aligns with broader studies that have progressively expanded knowledge on Algerian Anthophila fauna. Aouar-Sadli et al. [32] reported the presence of thirteen new species and subspecies of bees across five families (Colletidae, Andrenidae, Halictidae, Megachilidae, and Apidae), with Megachilidae and Apidae dominating in the Tizi-Ouzou region (Figure 6). Their altitudinal distribution (180–840 m) highlighted the combined influence of vegetation and ecological gradients. The phenological patterns were also striking: polylectic species such as *Megachile fertoni* exhibited long flight periods, while specialists were confined to shorter, seasonally restricted activity windows [32].

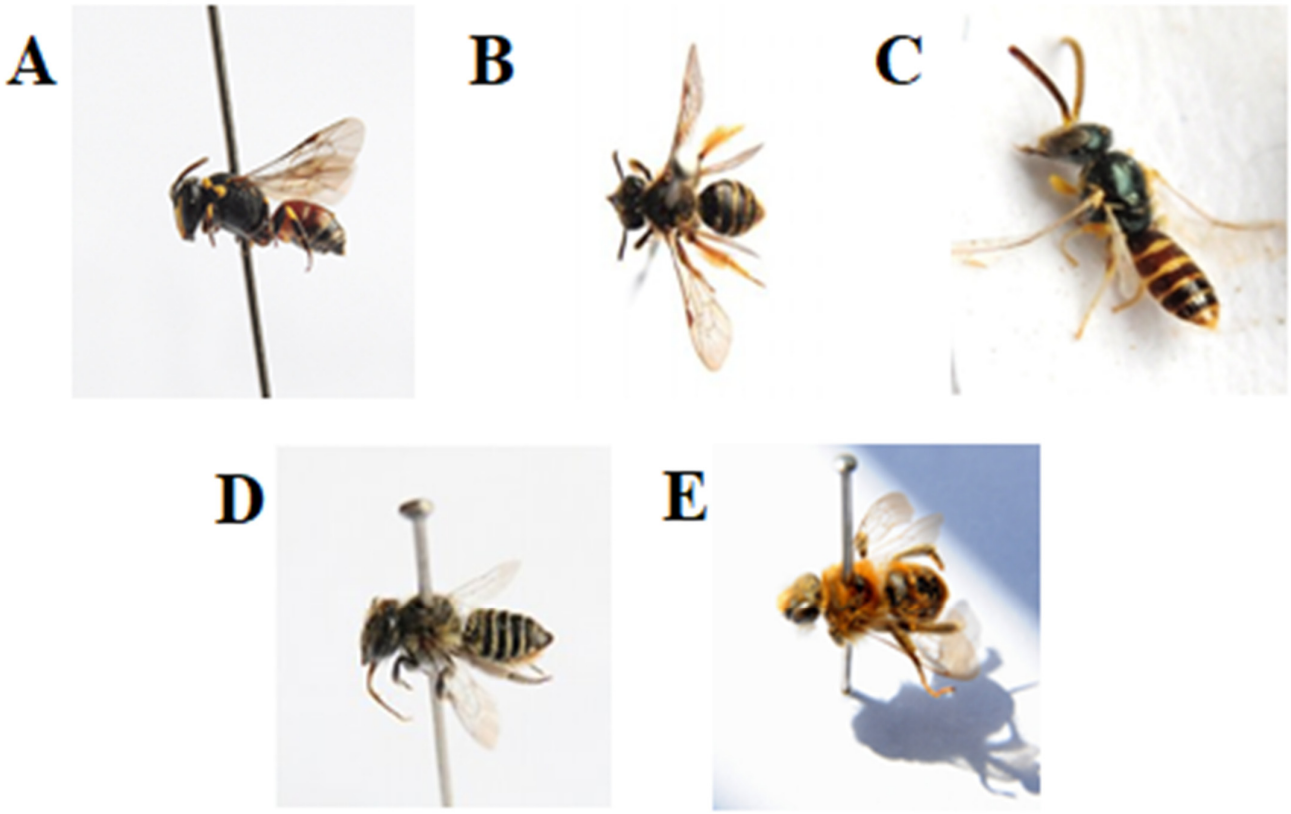


Figure 6. The study of Aouar-Sadli et al. [32] reported the presence of thirteen new species and subspecies of bees across five families (Colletidae, Andrenidae, Halictidae, Megachilidae, and Apidae), with Megachilidae and Apidae dominating in the Tizi-Ouzou region (a mountainous province in northern Algeria, about 100 km east of the capital Algiers). Their altitudinal distribution (180–840 m) highlighted the combined influence of vegetation and ecological gradients. Important species, which are under threat, are the polylectic and oligolectic species such as *Hylaeus meridionalis* (Colletidae)—polylectic (**A**), *Chryandrena fulvago* (Andrenidae)—oligolectic (**B**), *Nomioides facilis* (Halictidae)—polylectic (**C**), *Megachile fertoni* (Megachilidae)—oligolectic (**D**), and *Eucera pannonica* (Apidae)—oligolectic (**E**). All photos from Aouar-Sadli et al. [32].

Additional inventories reinforce this picture of richness. In semi-arid grasslands, Benarfa et al. [33] documented 93 species across six families, with Apidae predominating, followed by Andrenidae and Megachilidae. Their study emphasized that diversity was highest in sites with complex vegetation structures and abundant floral resources, while simplified landscapes showed reduced diversity. Temporal patterns were also evident, with spring flowering peaks supporting the highest Anthophila activity. Similarly, Khedidji et al. [41] demonstrated that Anthophila distributions are closely linked to vegetation cover and the availability of nectar and pollen resources, reaffirming the importance of floral diversity and habitat heterogeneity. Although *A. mellifera* remained dominant, numerous wild species were recorded, some rare and highly specialized.

Studies focusing on plant-Anthophila interactions further illustrate the tight coupling between floral phenology and Anthophila activity. On *Hedysarum flexuosum*, Ikhlef et al. [42] identified 17 bee species from three families, with *A. mellifera* consistently dominating during peak flowering. Likewise, on broad bean (*Vicia faba*), more than 80% of visits were made by *A. mellifera*, highlighting its pivotal role in this crop pollination [43]. Shebl et al. [34] confirmed similar trends in northern Algeria, where *A. mellifera* dominated bee assemblages alongside wild Halictidae and Megachilidae, again with peak activity concentrated in spring.

One of Algeria's most distinctive contributions to Anthophila biodiversity is its endemic honey bee subspecies, *Apis mellifera intermissa* and *Apis mellifera sahariensis* [44], as shown in Figure 7. *A. m. intermissa* is distributed from the Mediterranean to the Atlantic coast between the Atlas Mountains and the coastline (Figure 1B), and is characterized by dark coloration, strong swarming behavior, and intensive use of propolis. By contrast, *A. m. sahariensis* is restricted to Saharan oases and palm groves (Figure 1B) and consists of smaller, yellowish to reddish individuals well adapted to arid conditions, with high tolerance to heat and drought. Both subspecies play an essential role in local pollination systems, yet their survival is increasingly threatened by the introduction of European strains, habitat fragmentation, and rising pressure from diseases and parasites [15]. Importantly, their resilience traits, including climatic tolerance and adaptive foraging strategies, could provide valuable insights for conservation and selective breeding programs aimed at strengthening Anthophila resilience under global environmental change [45]. In this context, citizen science platforms such as iNaturalist offer a complementary source of data. iNaturalist reports 2917 observations of bees from Algeria, encompassing 114 taxa, though most are identified above the species level. Although photo-based platforms such as iNaturalist cannot reliably support species-level identification for most Anthophila, they may nevertheless provide complementary, non-diagnostic information on spatial coverage, phenology, and sampling gaps when interpreted cautiously and validated by experts. These data can thus be considered as a supplementary tool for identifying research gaps and spatial patterns, rather than for formal species-level assessments, and may support future monitoring and conservation planning when combined with expert validation (iNaturalist, observations of bees in Algeria, available at https://www.inaturalist.org/observations?place_id=7300&subview=table&taxon_id=630955&view=species; accessed on 11 December 2025).



Apis mellifera intermissa *Apis mellifera saharaiensis*

Figure 7. The two endemic honey bee subspecies of Algeria: *Apis mellifera intermissa* (**left**) and *Apis mellifera sahariensis* (**right**). *A. m. intermissa* (original photo by the authors), shown on the left, is characterized by its dark body coloration and is primarily found in northern Algeria, including the coastal and Tell Atlas regions. *A. m. sahariensis* (source: https://abeille-algerie.com, accessed on 26 August 2025), shown on the right, has a lighter body with broad orange-yellow stripes and is adapted to desert environments.

From a conservation standpoint, these findings highlight two key points. First, Anthophila communities are closely linked to vegetation diversity and habitat structure, suggesting that the preservation of floral resources and habitat mosaics should guide future

management actions. Second, although *A. m. intermissa* represents an important component of Algeria's managed Anthophila, its conservation should be considered separately from that of wild species. Further genomic and behavioral studies could nonetheless provide valuable insights into local adaptations that may inform sustainable beekeeping and biodiversity management in the region. Beyond the national context, Algeria's Anthophila diversity and its combination of Mediterranean and semi-arid ecosystems provide a valuable model for global Anthophila conservation. Algeria's unique ecological gradients, together with its endemic honey bee subspecies, make it an ideal case study for understanding Anthophila adaptation to climatic stress, habitat heterogeneity, and agricultural pressures. Lessons from Algeria, particularly in genomic research, habitat-based conservation, and sustainable farming practices, can help shape broader conservation strategies in similar regions worldwide. In this sense, Algeria holds the potential not only to preserve its own biodiversity but also to contribute critical insights for strengthening Apidae conservation and food security on a global scale.

4. The Biodiversity of Wild Bees in Algeria

The study of wild bee biodiversity in Algeria dates back more than a century, with early contributions from Saunders [25,26], Alfken [27] and Schulthess [28]. More recent observations have also reported numerous undetermined species (*Anthophora* sp. 1–10) [46]. Other important species, such as *Amegilla quadrifasciata* [46], *Ceratina cucurbitina* [42], *Eucera numida* [46], *E. pannonica* [32], *E. alternans* [27], as well as representatives of the genera *Nomada* spp., *Thyreus* spp., *Tetralonia* spp., and *Xylocopa* spp., complete this family (Hymenoptera, Apidae). Among them, *Xylocopa violacea* [27,46], *X. valga*, *X. cyanescens*, and *X. amedei* [27] are among the most characteristic of Mediterranean and Saharan environments.

The Andrenidae family, dominated by the genus *Andrena*, also exhibits considerable diversity. Alfken [27] described several species typical of Mediterranean areas, including *A. carbonaria*, *A. nitida*, *A. nigroaenea*, *A. vulcana*, *A. hirticornis*, and *A. punctata*. Other studies have reported *A. flavipes*, *A. marginata*, and *A. ovatula* [5,27,32,46]. These solitary bees play an essential role in the spring pollination of wild flora.

The Megachilidae are represented by genera such as *Megachile* (leaf-cutting bees), *Osmia* (mason bees), and *Anthidium* (carder bees). *Anthidium florentinum* [27,34], *A. manicatum* [27,34,46], and *A. punctatum* [27] are among the most common species. The genus *Osmia* is particularly diverse, with more than forty species reported, including *O. cornuta*, *O. tricornis*, *O. latreillei*, *O. aurulenta*, and *O. adunca* [27], demonstrating a strong ecological adaptation to Mediterranean conditions.

The Colletidae, represented by the genera *Colletes* and *Hylaeus*, include species such as *C. succinctus*, *C. acutus*, *H. cornuta*, and *H. pictipes* [27,46]. These bees are typically adapted to the dry, open environments of northern and central Algeria.

Finally, the *Halictidae* represent one of the most abundant and ubiquitous groups, including *Halictus scabiosae* [27,46], *H. quadricinctus*, *H. xanthopus*, *Nomioides facilis* and *Sphecodes gibbus* [27,32]. Their presence reflects a strong ability to adapt to the country's varied thermal and floristic gradients.

Recent studies have confirmed this biological richness. Bouti Fella's doctoral thesis [47], conducted in three regions (Mitidja, Djurdjura, and Biskra), identified 156 species and subspecies of Anthophila spread across six families and 21 genera, including four new to Algerian fauna. The author notes the predominance of polylectic and ground nesting in sandy soil species, with peak activity in spring [47]. These results confirm that Algeria's bee biodiversity remains underestimated. Overall, these results suggest that Algeria's bee biodiversity is exceptional, but still insufficiently studied. A large proportion of species remain identified only at the genus level, reflecting the lack of recent taxonomic work.

5. Genetics and Behavioral Studies on Local Honey Bees

Recent research on *A. m. intermissa*, the endemic honey bee of northwestern Algeria, highlights the value of combining classical morphometry, morphogeometry, and molecular tools to characterize local populations [11,48–50]. Morphological analyses document phenotypic variability reflecting adaptation to Algeria's diverse Mediterranean, mountainous, and semi-arid regions [49,50], providing a foundation for linking traits to molecular adaptations. Integrating these approaches into conservation programs is crucial to safeguard the genetic integrity and adaptive potential of *A. m. intermissa* [5].

Despite this, much of Algerian Anthophila research has historically concentrated on wild bees and taxonomic surveys, with comparatively fewer studies exploring the genetics and behavior of *A. mellifera*. Yet, behavioral ecology studies have consistently reinforced its central role in local ecosystems. Across more than a decade of research, Bendifallah et al. [7,51–53] demonstrated the species' dominance in both crop and wild flora pollination networks. Its generalist foraging behavior allows it to exploit a wide range of floral resources, while still showing a measure of floral fidelity that ensures effective pollination. However, this competitive versatility also raises questions regarding potential displacement of wild bees, as *A. mellifera* often monopolizes floral resources, potentially altering community dynamics and contributing to biotic homogenization.

Most evidence for the competitive effect of *A. mellifera* on wild bees comes from regions where *A. mellifera* is non-native (e.g., North and South America, Australia, New Zealand) [54]. Regarding Algeria, the situation is indeed different. The honey bee subspecies *A. m. intermissa* and *A. m. sahariensis* are native, yet there is very limited published information on their interactions with wild bee communities. To date, the presence of feral colonies of these subspecies has not been systematically documented, and most available data are derived from managed colonies [48,50]. However, the rapid increase in managed colony densities, combined with floral resource limitation in semi-arid environments, raises concerns about potential resource monopolization and indirect pressure on endemic wild bees.

At the genetic level, Algeria has produced several pioneering contributions that position *A. m. intermissa* as a key model for studying adaptation. Notably, Haddad et al. [44], Achou et al. [55] and Hu et al. [56] sequenced its draft genome (240 Mb, Illumina), now available in international databases. This resource revealed genetic pathways linked to heat tolerance and resistance to *Varroa destructor*. The subspecies also shows distinctive behaviors, including hygienic and grooming activity, strong parasite defense, intensive cleaning, and frequent swarming, illustrating the link between behavioral traits and genomic adaptation [44]. Additionally, Haddad et al. [13] reported the complete mitochondrial genome of *A. m. sahariensis* (16,569 bp), comprising 13 protein-coding genes, 22 tRNAs, 2 rRNAs, and an AT-rich region.

Complementary studies have identified genomic regions associated with immunity, detoxification, and social behavior [57,58]. Berrached et al. [57] reported that these regions reflect adaptations to parasites, pathogens, and agrochemicals. Collective behaviors like allogrooming and social hygiene are heritable and show genetic reinforcement.

More recent genetic surveys have confirmed the uniqueness and richness of Algeria's honey bee populations. Using a DraI in silico test, Ayad et al. [12], Fridi et al. [10] and Chibani et al. [15] showed that honey bee populations across different Algerian regions belonging exclusively to *A. m. intermissa* and *A. m. sahariensis* (Figure 7), both assigned to the African lineage A. Mitochondrial COI-COII, revealed striking haplotype diversity (H = 0.908), with 17 distinct haplotypes identified, 14 of which were reported for the first time. Among these, three haplotypes (A9-828-2-DZA, A8d, and A8-828-2-DZA) accounted for nearly half of the individuals sampled. Such diversity indicates a deep reservoir of intra-

population variability, reflecting both historical biogeography and ecological adaptation across Mediterranean, mountainous, and Saharan habitats. This genetic wealth underpins resilience to environmental pressures, including climate variability and emerging pathogens, while also emphasizing the need to preserve locally adapted strains rather than replace them with imported stocks.

These findings carry major implications for biodiversity conservation and sustainable agriculture. By linking morphology, behavior, and genetics, Algerian research illustrates how Anthophila conservation can move beyond species counts to focus on functional and adaptive diversity.

6. Threats Identified

Overall, Anthophila species in Algeria, including *A. mellifera* and wild bee genera such as *Bombus*, *Andrena*, *Osmia*, and *Halictus*, among others, face multiple interacting environmental, anthropogenic, and health-related pressures that threaten species survival, community stability, and essential ecosystem services. Climate change is one of the main pressures affecting bees by disrupting the timing between bee activity and flowering plants. In the mountains of Tlemcen, mismatches between bee emergence and plant flowering have been observed, causing food shortages and higher mortality [46]. Droughts and late springs further reduce the availability of floral resources [5]. Complementary studies in Tizi-Ouzou and Constantine confirmed that climatic variables such as temperature, humidity, and wind profoundly influence foraging efficiency and pollination success [32,43]. These disruptions lead to ecological desynchronization and heighten the risk of local extinction among specialized taxa [58].

Agricultural intensification adds another dimension of risk. Widespread pesticide use, monocultures, and simplified agricultural landscapes drastically reduce forage diversity [16,58]. Beyond direct lethality, pesticides cause sublethal effects on bee behavior, immunity, and reproduction, weakening colonies and reducing their resilience. Menail et al. [59] and Benchaabane et al. [60] further showed how these practices fragment ecological networks, creating landscapes inhospitable to diverse pollinator assemblages. However, most studies were observational, limited to small areas and sample sizes, which restricts broader conclusions. Despite this, the results support global concerns about agrochemical effects and provide local evidence of how these pressures act in arid and semi-arid environments.

Habitat loss and degradation emerged as another consistent threat across Algerian regions. Agricultural expansion, overgrazing, and urbanization fragment ecosystems, eroding floral diversity and nesting opportunities [46,51]. Comparative studies show that protected areas host higher bee richness, underscoring the conservation value of intact habitats [61]. In semi-arid regions, where human activities add to climate stress, bee communities are particularly vulnerable [33]. These results stress the need for habitat-focused conservation in land-use planning.

Wild bee studies also reveal critical vulnerabilities tied to life-history traits. Aouar-Sadli et al. [32] observed that species such as *Nomioides facilis* and *Hylaeus meridionalis* (Figure 6) have extremely short flight periods, which are sometimes only a week, making them highly sensitive to climatic fluctuations and floral resource shifts. The occurrence of kleptoparasites like *Stelis punctulatissima* illustrates the fragility of these ecological networks: the disappearance of even a single host species can cascade into broader community collapse. Such finely tuned interactions highlight the urgency of conserving both Anthophila and their plant partners as coupled ecological units.

For managed Anthophila, local honey bee populations, particularly *A. m. intermissa*, face significant health-related threats. Pathogens such as *Paenibacillus larvae* (the bacterium causing American foulbrood), *Nosema* spp., and deformed wing virus (DWV) have

been documented, though prevalence in Algeria remains lower than in many global regions [14,44,62]. Most of these pathogen surveys relied on limited colony numbers and observational sampling rather than controlled experiment studies or laboratory tests, making their epidemiological estimates indicative rather than definitive. However, the global parasite *V. destructor* remains a dominant threat, weakening colonies and amplifying viral transmission [57]. Compounding these risks, beekeepers' introduction of non-native subspecies such as *A. m. ligustica* leads to genetic introgression, undermining the purity and adaptive resilience of local lineages [55]. Finally, a national survey conducted by Haider et al. [63] on beekeeping in Algeria highlighted several major challenges: drought, high colony mortality, the presence of the *V. destructor* parasite, and declining honey yields.

Overall, the decline of wild and managed bees in Algeria is caused by combined pressures, including climate change, habitat loss, intensive farming, pesticides, diseases, and genetic loss [16,53,58,64]. Although existing studies are limited in size, methods, and locations, they consistently show strong cumulative effects. From a conservation perspective, the current studies suggest general conservation directions rather than fixed solutions. Protecting Anthophila in Algeria requires better surveys, habitat protection, reduced agrochemical use, and conservation of native honey bee subspecies (*A. m. intermissa* and *A. m. sahariensis*). Efforts should prioritize natural habitats and Anthophila-friendly farming, supported by integrated taxonomic, ecological, and genetic research.

7. Gaps and Research Priorities

As our review compiles fragmented and geographically restricted studies, it highlights that, despite recent progress, knowledge and conservation of Anthophila in Algeria remain limited by persistent gaps. Vast areas, particularly outside protected regions, are poorly studied, restricting understanding of species distribution and ecological diversity [5]. Long-term monitoring is scarce, making it difficult to assess population trends, while the identification of numerous rare taxa underscores the lack of data on their ecology, dynamics, and conservation status [32].

Research highlights strong seasonal and spatial variability in species richness, especially in semi-arid zones [33]. Yet most studies remain localized and short-term, preventing a comprehensive understanding of Anthophila population dynamics across the country [42]. Moreover, a disproportionate focus persists on *A. mellifera*, while wild bees remain underdocumented, despite their critical role in ecosystem functioning [34]. Targeted studies on Halictidae, Megachilidae, and Andrenidae are therefore urgently needed to document their species richness, life-history traits, and plant-bee interactions, which remain poorly characterized compared to *A. mellifera*. Priority should therefore be given to large-scale, multi-year inventories encompassing varied habitats, complemented by functional data such as life-history traits, floral specialization, and phenological patterns [7,51–53].

In parallel, genetic and genomic studies on *A. m. intermissa* are still limited, despite their importance for identifying mechanisms of adaptation, climate resilience, and resistance to pathogens [44,57]. Integrating these approaches with ecological and taxonomic studies would provide a more holistic understanding of Anthophila responses to environmental pressures.

Ultimately, the development of a coordinated national Anthophila monitoring initiative should be considered a key research goal. However, its implementation depends on first creating a reliable checklist of Algeria's Anthophila and establishing comprehensive species inventories and ecological baselines. A multidisciplinary framework integrating ecological, taxonomic, genetic, and socio-environmental approaches will be essential to document Anthophila diversity more accurately and to support the conservation of both wild species and locally adapted honey bee lineages.

8. Perspectives Toward a Future National Red List of Anthophila

At present, recent available data on Algeria's Anthophila remain scarce, fragmented, and far from exhaustive, likely representing only a fraction of the national fauna (estimated at 20–25%). In addition to incomplete field sampling, many historical specimens of Algerian Anthophila are preserved in museum collections, particularly in Paris, and were not included in this synthesis. This highlights that current knowledge likely covers only a subset of the national species pool. The creation of a national Red List is currently not feasible due to limited and incomplete knowledge of Anthophila species, their biology, and the threats they face. Many taxa are identified only to the genus level, which limits the usefulness of current checklists and highlights the need for renewed taxonomic studies.

Because managed species such as *A. mellifera* and its subspecies are generally excluded from biodiversity inventories, future research should focus on wild species to compensate for this underrepresentation. Efforts should focus on strengthening species identification, expanding sampling efforts, and improving data quality to produce a reliable checklist of Algeria's bees. Research efforts in the next 10–20 years should focus on producing a reliable checklist of Algeria's bees. In recent decades, more than 179 bee species have been reported in Algeria, offering a first overview of national diversity but remaining low compared to neighboring Morocco, where nearly 1000 species have been documented [65].

Field inventories should extend beyond well-studied areas [5] and be complemented by biological and ecological assessments, supported by molecular data on *A. m. intermissa* and *A. m. sahariensis* [44,57].

Plant and bee diversity are closely linked, as Anthophila richness depends on native floral resources [33]. Conservation should prioritize native plant communities, particularly in semi-arid and mountainous regions under habitat fragmentation [50].

In the longer term, conservation frameworks may eventually consider the development of a national Red List; however, such an initiative is not currently feasible given existing knowledge gaps. Current priorities are the expansion of field sampling, comprehensive species inventories, and improved species identification, including the integration of molecular tools (e.g., DNA barcoding) alongside classical taxonomy to improve species-level identification, as well as ecological monitoring, and strengthening systematic and taxonomic studies, including protection of endemic honey bee subspecies (*A. m. intermissa* and *A. m. sahariensis*) threatened by hybridization [55].

9. Recommendations for Conservation

To ensure the long-term survival of Anthophila diversity in Algeria, the following priorities are recommended:

- Expand Anthophila inventories across under-explored regions, improving taxonomic accuracy through updated identification.
- Combine appropriate biological, ecological, and when relevant, morphometric, morphogeometric, and genetic tools with multi-year monitoring programs integrating floristic and faunistic data to build exhaustive datasets and track climate-driven trends, providing a foundation for future large-scale conservation assessments, which may eventually include a national Red List once sufficient data are available.
- Future inventories should also consider museum collections, particularly those in Paris, which contain historical Algerian specimens, to complement field data and provide a more complete picture of the national Anthophila fauna.
- Link plant and bee diversity studies to inform ecological restoration and optimize habitat management.
- Preserve and restore habitats with high floral diversity, avoid fragmentation of nesting sites, and create ecological corridors to enhance connectivity.

- Promote sustainable agricultural practices: reduce pesticide use, diversify crops, and adopt integrated pest management.
- Safeguard endemic honey bees by conserving genetic diversity, avoiding uncontrolled hybridization, and promoting breeding programs that integrate natural resistance traits.
- Integrate genomic data into conservation programs to better anticipate environmental impacts and guide adaptive strategies.
- Strengthen awareness and cooperation: engage farmers and local communities through education programs, and encourage regional and international scientific collaboration to pool data and expertise.
- Incorporate citizen science data for distribution and phenology analyses, with expert validation and integration alongside standardized surveys.

10. Conclusions & Perspectives

Although not a full systematic review, this work summarizes the best available data and places Algeria's Anthophila research in a conservation context. Studies show both the high potential of bees in Algeria and the increasing pressures they face. Surveys report more than 179 bee species in northern Algeria, but this number is likely underestimated compared to neighboring countries such as Morocco, where nearly 1000 species are known. This highlights the need for broader and long-term inventories. Overall, bee diversity in Algeria plays a key ecological, agricultural, and socio-economic role and represents an important part of the country's natural heritage.

Despite their ecological and agricultural importance, Algeria's Anthophila face increasing pressures from habitat degradation, pesticide use, and climate change. These stressors disproportionately affect wild bee communities, while research efforts remain largely focused on *A. mellifera*, limiting knowledge of native wild species. In addition, persistent taxonomic and ecological knowledge gaps constrain effective conservation planning, emphasizing the need to strengthen species-level identification and integrated ecological and molecular approaches.

From a conservation perspective, long-term strategies should prioritize habitat protection, restoration of native floral resources, and preservation of endemic honey bee subspecies (*A. m. intermissa* and *A. m. sahariensis*), whose genetic integrity is threatened by hybridization. While the establishment of a national Red List may be considered a future objective, current priorities remain the improvement of baseline data, standardized monitoring, and taxonomic capacity building to ensure reliable conservation assessments.

Looking forward, effective Anthophila conservation in Algeria will depend on the synergy between scientific innovation and ecological stewardship. Priority actions include: (i) expanding and refining national inventories with accurate species-level identification, including under-studied groups; (ii) strengthening taxonomic and ecological research before implementing large-scale conservation tools; (iii) protecting and restoring habitats through conservation of native flora, ecological corridors, and nesting sites; (iv) promoting sustainable agricultural practices through reduced pesticide use, crop diversification, and increased floral resources; and (v) preserving the genetic integrity of native honey bee subspecies (*A. m. intermissa* and *A. m. sahariensis*) by preventing uncontrolled hybridization and supporting locally adapted lineages.

These actions highlight that Anthophila conservation extends beyond insect protection to securing ecosystem services essential for biodiversity, food security, and rural livelihoods. As key components of both natural and agricultural ecosystems, bees directly link biodiversity conservation with sustainable development objectives.

In conclusion, Algeria's Anthophila represents both a valuable natural heritage and an opportunity for advancing conservation science in North Africa. By combining biodiversity monitoring, taxonomic strengthening, genomic tools, and integrated conservation strategies, Algeria can build a scientifically robust framework to preserve Anthophila diversity and enhance ecosystem resilience under accelerating environmental change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d18020126/s1, Supplementary Table S1. Studies retrieved and included after PRISMA screening, with criteria of inclusion in the synthesis of Anthophila research in Algeria.

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