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Systematics of wild honey bee species in central Africa: diversity, classification, and challenges

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ABSTRACT

This review synthesizes published data from 2000 to 2024 on the diversity of wild bee species in Cameroon, Gabon, and the Democratic Republic of Congo, with a focus on key subspecies of *Apis mellifera* that contribute to ecosystem functioning and local apiculture. It draws on more than 70 peer-reviewed articles and institutional reports selected based on predefined inclusion criteria, using major databases such as Scopus, Web of Science, ResearchGate, PubMed, Google Scholar, and AJOL. The studies reviewed employed methods such as wing venation morphometric analysis and mitochondrial DNA barcoding. Data were grouped by species, region, and methodology to identify taxonomic patterns, ecological roles, and emerging threats. Key conservation threats identified include deforestation due to agricultural expansion, genetic introgression between native and introduced bee populations, and temperature-related shifts in flowering cycles. The review also highlights the current gaps in regional taxonomic data and monitoring systems. Recommendations include the implementation of region-specific sustainable beekeeping practices, the development of national taxonomic reference databases, and support for integrative field and molecular research. These findings suggest the need for targeted policy interventions by local governments and NGOs to preserve native bee diversity and promote pollinator-friendly agroecological practices.

Keywords: honey bee, Central Africa, taxonomy, stingless bees, biodiversity

RÉSUMÉ

Systématique des espèces d'abeilles sauvages en Afrique centrale : diversité, classification et défis

L'Afrique centrale abrite une grande diversité d'espèces d'abeilles sauvages qui jouent un rôle fondamental dans le maintien des équilibres écologiques et dans l'augmentation de la productivité agricole, principalement grâce à leur action de pollinisation. Malgré leur importance écologique et économique, la taxonomie et la systématique de ces abeilles demeurent insuffisamment étudiées, en particulier dans des pays comme le Cameroun, le Gabon et la République démocratique du Congo, où les données sont encore fragmentaires. La présente revue propose une synthèse actualisée des connaissances sur la diversité, la classification et les principaux enjeux liés à la conservation des abeilles sauvages en Afrique centrale. Une attention particulière est portée aux sous-espèces *Apis mellifera adansonii* et *A. m. scutellata*, ainsi qu'aux abeilles sans aiguillon (tribu des Meliponini), longtemps négligées par la recherche scientifique, bien qu'elles soient des pollinisateurs clés dans les écosystèmes forestiers et agroécologiques de la région.
Les principales menaces identifiées comprennent la perte et la fragmentation des habitats naturels, les effets du changement climatique, les phénomènes d'hybridation naturelle entre sous-espèces, ainsi que le déficit chronique de recherches approfondies en particulier sur les Meliponini. Ces facteurs constituent des freins majeurs à la mise en œuvre de politiques de conservation efficaces. Dans ce contexte, des recommandations concrètes sont formulées : intensifier la recherche de terrain, renforcer les capacités en taxonomie intégrative (combinant données morphologiques et génétiques), et promouvoir des pratiques apicoles durables adaptées aux conditions locales. Les résultats de cette revue soulignent l'urgence de développer des stratégies de conservation ciblées pour préserver la diversité des abeilles indigènes d'Afrique centrale et maintenir les services écosystémiques essentiels qu'elles fournissent à long terme.

Mots-clés : abeilles sauvages, Afrique centrale, taxonomie, Meliponini, conservation, pollinisation, biodiversité

INTRODUCTION

Biodiversity importance of Central Africa

Central Africa, encompassing countries such as Cameroon, the Republic of Congo, the Democratic Republic of the Congo, Gabon, and the Central African Republic, is renowned for its exceptional biodiversity. This region harbors a vast array of ecosystems, from dense tropical rainforests to savannahs, each supporting unique flora and fauna. Among the myriad species, wild honey bees play a crucial role in maintaining ecological balance and supporting agricultural productivity.

Ecological role of wild honey bees

Wild honey bees, especially subspecies such as *Apis mellifera adansonii*, play an integral role in pollinating both wild and cultivated plants. Their foraging activities enhance biodiversity by facilitating the reproduction of over 75% of the world's flowering plants and approximately 35% of global food crops. In Central Africa, these bees contribute significantly to the pollination of various crops, including cowpea (*Vigna unguiculata*) and watermelon (*Citrullus lanatus*), leading to increased fruit and seed yields (Eardley et al., 2009; Fohouo et al., 2009; Heumou et al., 2023). Moreover, Dingha et al. (2021) highlight the vital role of various pollinators, including honey bees, in enhancing cowpea yields, noting that intercropping strategies can further increase pollination efficiency.

Traditional forest beekeeping

The practice of forest beekeeping in Central Africa further underscores the importance of wild honey bees. This traditional method, which utilizes natural bee colonies within forested areas, promotes sustainable land use and forest conservation. Beekeepers' activities, such as tree planting and forest protection, contribute to biodiversity preservation and the mitigation of deforestation (Lowore et al., 2018).

Challenges in bee taxonomy in Central Africa

Despite their ecological and economic significance, wild honey bee species in Central Africa remain poorly documented and insufficiently classified. There is widespread taxonomic confusion, particularly within *Apis mellifera* subspecies and among stingless bees (Meliponini), due to overlapping morphological traits, lack of region-specific genetic references, and limited field surveys. This taxonomic ambiguity hampers effective monitoring, conservation planning, and the development of sustainable beekeeping practices. Furthermore, the absence of a consolidated regional synthesis makes it difficult to compare findings across studies and countries.

Objectives of the study

This review aims to address these gaps by critically examining the current state of knowledge on wild bee diversity and classification in Central Africa while identifying key challenges and research priorities.

More specifically, this study seeks to

(i) document the diversity and distribution of wild honey bee species across Central African ecosystems, with special focus on *Apis mellifera* subspecies and stingless bees (Meliponini); (ii) clarify taxonomic classification issues using morphological, molecular, and ecological approaches; (iii) identify the main environmental and anthropogenic threats impacting these pollinators; and (iv) propose recommendations for research and conservation strategies adapted to the regional context.

While previous reviews such as Eardley (2009) provided overviews of African bee fauna, their scope largely focused on southern and eastern Africa, leaving Central Africa underrepresented. Since then, new studies employing molecular tools and advanced morphometric techniques have produced valuable but fragmented insights on the bees of Cameroon, Gabon, and the DRC. These data remain scattered across various publications and unpublished reports, without a comprehensive regional synthesis. Given the rapid environmental changes threatening the Congo Basin, an updated review that consolidates existing knowledge, highlights research gaps, and informs conservation efforts is urgently needed.

Methodology

Literature Review Strategy

This literature review adopts a semi-systematic approach aimed at synthesizing knowledge on the taxonomy, diversity, and conservation of wild bee species in Central Africa. The review follows guidelines for narrative synthesis, with transparent documentation of sources and inclusion criteria to ensure scientific rigour.

Data sources and search terms

Information was collected between January and April 2025 using the following search engines and scientific databases:Web of Science, Scopus, Google Scholar, PubMed, AGRIS (FAO), and African Journals Online (AJOL). In addition, institutional repositories (e.g., CIFOR, ICIPE, Université de Yaoundé I) and national research centers (e.g., IRAD Cameroon) were consulted for unpublished reports, theses, and technical bulletins. The search was conducted using combinations of the following keywords and Boolean operators: ("wild bees" OR "stingless bees" OR "*Apis mellifera*" OR "Meliponini") AND ("Central Africa" OR "Cameroon" OR "Gabon" OR "Congo" OR "DRC" OR "Central African Republic") AND ("taxonomy" OR "morphometrics" OR "genetics" OR "diversity" OR "conservation"). All search results were imported into Zotero for organization and deduplication.

Inclusion and exclusion criteria

Inclusion Criteria: Studies published between 2000 and 2025; Language: English or French; Focused on wild bee species in Central Africa; Addressing topics such as taxonomy, distribution, threats, pollination ecology, or conservation. Exclusion Criteria: Studies on domesticated bees used in managed commercial systems outside Central Africa; Papers without original data or synthesis (e.g., editorials); Non-accessible full texts.

Data extraction and thematic categorization

Data were manually extracted into thematic categories: (i)Species documented and their geographical distribution; (ii)Taxonomic methods (morphology, morphometrics, genetics); (iii)Identified environmental threats; (iv)Proposed conservation actions.

RESULTS

Comparative Overview of Key Studies on Wild Bees in Central Africa (2000–2025)

The analysis prioritized comparative synthesis across countries and studies to identify recurring patterns, knowledge gaps, and inconsistencies in classification. To facilitate comparison across studies and highlight the geographic and methodological scope of the literature reviewed, Table 1 summarizes the main scientific and technical publications on wild bee species in Central Africa published between 2000 and 2025. The table categorizes each study by country, target taxa, methodological approach, and key findings. It includes both peer-reviewed articles and grey literature (e.g., theses and NGO reports), thereby reflecting the diversity of available sources and helping to identify research gaps and regional specificities.

Table 1. Summary of major studies on wild bees in Central Africa (2000–2025)

Country	Study (Author, Year)	Taxa Focus	Methods Used	Main Findings
Cameroon	Fohouo et al., 2009	**Apis mellifera**	Field sampling, morphometrics	Documented floral preferences of **A. mellifera adansonii** in northern Cameroon.
Cameroon	Heumou et al., 2023	**Apis mellifera**	Field observations, yield analysis	Demonstrated pollination impact on watermelon and cowpea crops.
Gabon	Koffi et al., 2020	*Meliponini*	Morphology, ecological surveys	Identified 12 stingless bee species in rainforest habitats.
DRC	Tshibangu et al., 2018	**Apis mellifera**	DNA barcoding, morphometrics	Found distinct morphotypes of **A. mellifera** in eastern Congo.
Central African Rep.	NGO report (WWF, 2019)	*Meliponini* & **A. mellifera**	Interviews, ecological monitoring	Noted decline in forest bee populations near logging zones.
Regional (multi)	Eardley et al., 2009	Various bee taxa	Literature synthesis	Provided baseline on African bee diversity, limited focus on Central Africa.

Diversity and Distribution of Wild Bees

Apis mellifera in Central Africa

Apis mellifera adansonii (Latreille, 1804)

Apis mellifera adansonii, commonly referred to as the West African honey bee, is predominantly found across the tropical and semi-arid regions of West and Central Africa, including countries such as Senegal, Nigeria, Cameroon, and the Republic of Congo. This subspecies thrives in diverse habitats, ranging from humid forests to savannahs, demonstrating remarkable adaptability to varying environmental conditions. Morphologically, *A. m. adansonii* is characterized by its relatively smaller body size and a distinctive yellowish coloration, traits that are believed to be adaptations to its native environments. These physical attributes facilitate efficient foraging and thermoregulation in the often hot and humid climates of its range. Morphometric analyses have confirmed its distinctiveness in the region (Dukku & Danailu, 2020). Ecologically, *A. m. adansonii* plays a pivotal role in the pollination of native flora. Studies conducted in Cameroon have demonstrated its effectiveness in enhancing fruit and seed yields of various plant species. E.g., research on *Callistemon rigidus* revealed that pollination by *A. m. adansonii* significantly increased fruiting rates and seed quality (Tope et al., 2012). Similarly, its foraging activity on *Citrullus lanatus* (watermelon) in Yaoundé contributed to a substantial increase in fruit set and seed production (Ela et al., 2010). Ecologically, *A. m. adansonii* holds significant cultural and economic importance in traditional beekeeping practices throughout its range. Beekeepers in regions like the Adamawa area of Cameroon rely on this subspecies for honey production (Fohouo et al., 2009), benefiting from its adaptability and foraging efficiency.

Apis mellifera scutellata (Lepeletier, 1836)

Apis mellifera scutellata, commonly known as the East African lowland honey bee, is a subspecies of the western honey bee (Apis mellifera) native to eastern and southern Africa. Its range extends into the eastern parts of Central Africa, including areas of the Democratic Republic of the Congo, where it thrives in savannah and lowland environments. This subspecies is renowned for its adaptability to diverse ecological conditions, particularly the savannah ecosystems. It exhibits traits such as high resilience, prolific swarming behavior, and efficient foraging strategies, which contribute to its success in various habitats (Frazier et al., 2024). These characteristics have also made *A. m. scutellata* a subject of interest in studies on bee behavior and ecology (Kashulwe et al., 2024). The introduction of *Apis mellifera scutellata* into Brazil in the 1950s and its subsequent hybridization with European honey bee populations led to the emergence of Africanized honey bees in the Americas. In 1956, Brazilian scientist Warwick Kerr imported this subspecies, aiming to improve honey production through crossbreeding. However, 26 colonies escaped, leading to the creation of hybrid colonies known as Africanized honey bees (Ellis & Ellis, 2009). These hybrids spread rapidly across the Americas. They were highly adaptive and productive, resulting in increased honey production—from approximately 5,000 tons per year in the 1950s to around 40,000 tons (Gonçalves & De Jong, 2005). In the Amazon region, studies show that Africanized honey bees are predominantly found in urban and open/disturbed areas, rarely penetrating dense forests (Oliveira & Cunha, 2005). This suggests limited competition with native bees in intact ecosystems.

Stingless Bees (Meliponini)

In Central Africa, several genera and species of stingless bees have been documented (Chakuya et al., 2022). Stingless bees, belonging to the tribe Meliponini, represent a significant yet often underrecognized component of the pollinator community in Central Africa. These eusocial bees are vital for the pollination of a wide array of native plants and contribute to the maintenance of biodiversity in tropical ecosystems.

Meliponula bocandei (Friese, 1900)

Widely distributed across Central African countries, this species exhibits adaptability to various habitats, nesting in tree cavities and underground (Kajobe, 2007).

Dactylurina staudingeri (Gribodo, 1893)

Found in countries such as Cameroon and the Democratic Republic of Congo, this species is known for its distinctive elongated nest entrances and preference for nesting in tree trunks.

Despite their ecological importance, stingless bees have received less research attention compared to *Apis mellifera*. Their role in traditional beekeeping practices, known as meliponiculture, and their potential in sustainable agriculture underscore the need for further studies on their biology, ecology, and conservation (Chakuya et al., 2022).

Adaptation to dense forest environments

Stingless bees exhibit a strong association with forested habitats, especially tropical rainforests. Their nesting preferences often include tree cavities and other natural structures within forests, indicating their adaptation to such environments. E.g., a study in the Atlantic Forest of Brazil highlights the tight relationship between stingless bees and mass-flowering trees in the forest canopy, emphasizing their role in these ecosystems (Atmowidi et al., 2024; T. A. Heard, 1999; Liadi et al., 2013).

Primary or exclusive pollinators of native plants

Research indicates that stingless bees are effective pollinators for many plant species in tropical forests. In the lowland Neotropics, stingless bees, including Melipona and other genera, have been observed visiting a vast number of plant species, suggesting their significant role in pollination. For example, studies have shown that stingless bees are the most abundant and effective pollinators of certain understory trees in Malaysian rainforests and Costa Rica (Grüter, 2020; T. A. Heard, 1999; Liadi et al., 2013). Moreover, stingless bees have been confirmed as pollinators for various plant species, including epiphytic orchids in Australia and other specialized plants in tropical regions. Their foraging behavior and floral preferences make them indispensable for the pollination of many native plants, particularly in dense forest habitats where other pollinators may be less effective.The role of stingless bees (tribe Meliponini) in pollinating economically important crops such as cocoa (Theobroma cacao), coffee (Coffea spp.), and various fruits and vegetables is well-documented, particularly in regions where *Apis mellifera* populations are low or absent.

Cocoa (*Theobroma cacao*)

Stingless bees have been identified as potential pollinators for cocoa, especially in shaded agroforestry systems. Their small size allows them to navigate the intricate floral structures of cocoa flowers, which larger insects cannot access. Studies have highlighted that certain stingless bee species, such as *Tetragonisca angustula*, can effectively transfer pollen within and between cocoa trees, aligning their foraging activity with the peak receptivity of cocoa stigmas. This synchronization enhances the potential for successful pollination. Moreover, the perennial nature of stingless bee colonies ensures year-round foraging activity, which is advantageous for crops like cocoa that have extended flowering periods. Implementing managed stingless bee colonies in cocoa plantations has been suggested as a strategy to improve fruit set and yield, especially in areas where traditional pollinators are scarce or ineffective (Maia-Silva et al., 2024).

Coffee (*Coffea* spp.)

Research indicates that stingless bees contribute significantly to the pollination of coffee plants. In regions like Brazil and Indonesia, stingless bees have been observed visiting coffee flowers, with studies reporting that their activity can lead to increased fruit set and improved bean quality. E.g., in Brazilian coffee plantations, the presence of stingless bees has been associated with a 15% increase in production, highlighting their role in enhancing crop yields. These bees are particularly valuable in coffee-growing areas adjacent to natural forests, where their populations are more robust due to the availability of nesting sites and diverse floral resources (Slaa et al., 2006).

Various fruits and vegetables

Beyond cocoa and coffee, stingless bees have been documented as effective pollinators for a range of other crops, including acai (*Euterpe oleracea*), apple (*Malus domestica*), macadamia (*Macadamia integrifolia*), watermelon (*Citrullus lanatus*), avocado (*Persea americana*), and coconut (*Cocos nucifera*). Research shows the introduction of managed stingless bee colonies can lead to significant improvements in fruit set and overall yield for these crops. Their generalist foraging behavior, coupled with their ability to operate in diverse environmental conditions, makes them suitable pollinators for various agricultural settings (Maia-Silva et al., 2024; Muto et al., 2020). The ecological importance of stingless bee species such as *Meliponula bocandei* and *Dactylurina staudingeri* in West and Central African ecosystems is well-documented in scientific literature.

Approaches to bee systematics

Morphometric methods

Morphometric analysis has long been a cornerstone in the classification of honey bees, particularly before the advent of molecular techniques. By measuring physical traits and applying statistical analyses, researchers can distinguish between subspecies that might appear very similar superficially. This method allows for an objective comparison and helps define clear boundaries between different groups.

E.g., a study by Tofilski demonstrated that geometric morphometrics and standard morphometry could effectively discriminate between three honey bee subspecies—*Apis mellifera mellifera*, *A. m. carnica*, and A. m. caucasica—based on forewing venation. Both methods achieved high classification success rates, with geometric morphometrics slightly outperforming standard morphometry (Tofilski, 2008). Additionally, a strong correlation was found between wing morphometrics and microsatellite data in distinguishing *Apis mellifera mellifera* and *A. m. carnica*, indicating that wing morphometrics can be a cost-effective alternative to molecular methods for subspecies identification. The study further emphasized that morphometric analysis may be equally reliable, particularly in contexts where molecular data are lacking (Oleksa & Tofilski, 2014).

These studies underscore the value of morphometric analysis in honey bee classification, offering a practical and effective approach for distinguishing subspecies based on measurable physical traits.

Wing Venation and Geometric Morphometrics

The forewing venation patterns of honey bees (*Apis mellifera*) are crucial for distinguishing between subspecies, as these patterns reflect evolutionary adaptations to different environments. Research has shown that specific wing traits, such as the cubital index, discoidal shift angle, and other venation markers, vary among subspecies and can be used for accurate identification (Rodrigues et al., 2022). For example, one study analyzed wing venation measurements of *Apis mellifera caucasica*, *A. m. carnica*, and *A. m. mellifera*, along with their hybrids and backcrosses, using a dataset of 9,590 wings and applying geometric morphometrics to assess subspecies identity. The results showed that wing venation is a key trait for distinguishing subspecies, revealing clear differences among the groups. This approach offers a cost-effective and reliable alternative for identification, particularly when molecular data are not available (Węgrzynowicz & Łoś, 2020).

Antenna shape and segment proportions are indeed vital indicators in distinguishing honey bee subspecies. The antennae of honey bees, essential for sensory perception, exhibit subtle variations among subspecies, reflecting adaptations to their environments.

Research has shown that the length of antennal segments, the ratios between different segment lengths, and the overall structure of the antennae can vary among honey bee subspecies. E.g., studies have observed differences in the total antennal length and the length of specific segments like the scape, pedicel, and flagellum among various bee species and castes. These variations are often associated with ecological factors and behavioral adaptations (Ren et al., 2023).

Furthermore, the distribution and density of sensilla—sensory structures on the antennae—also differ among subspecies. For example, a study comparing the antennal sensilla of queen and worker honey bees found significant differences in the types, sizes, and densities of sensilla across different antennal segments. These differences are linked to the bees' sensory needs and behaviors (Abdelmegeed, 2015).

These morphological differences in antennae are not merely structural but are functionally significant. They influence how honey bees perceive their environment, including their ability to detect chemical signals, forage efficiently, and communicate within the colony. Such adaptations underscore the role of antennal morphology in the ecological success and behavioral specialization of honey bee subspecies.

Body measurements and proboscis length

Body dimensions such as head width and length, thorax width, abdomen length, and proboscis length are valuable indicators for distinguishing honey bee subspecies. Honey bees adapted to temperate climates, like *Apis mellifera mellifera*, typically exhibit larger and more robust bodies compared to tropical subspecies such as *A. m. scutellata*. These physical traits often reflect adaptations to local ecological pressures, including climate, predators, and foraging strategies.

E.g., a study on *Apis mellifera* populations in Kashmir reported significant variations in body dimensions among bees from high, mid, and low altitudes. Measurements such as head width, thorax length, abdomen length, and proboscis length showed positive correlations with altitude, suggesting that bees in higher altitudes tend to have larger body sizes. Specifically, proboscis length was found to be 6.35 ± 0.06 mm at high altitude, which is consistent with measurements reported for *A. m. ligustica*, a subspecies known for its larger size (Masrat, 2019). Furthermore, research on *Apis mellifera carnica* populations across different climate zones revealed that bees from the foothill zone exhibited the highest proboscis length and sternite dimensions. These morphological traits are believed to be adaptations to the specific environmental conditions of the foothill zone, including temperature and floral availability, which influence foraging behavior and efficiency (Sheralieva et al., 2023).

Statistical techniques (PCA, DFA, Cluster Analysis)

To analyze morphometric measurements and effectively classify honey bee subspecies, researchers employ various statistical techniques that facilitate the interpretation of complex datasets.

Principal component analysis (PCA)

Principal Component Analysis (PCA) is a multivariate statistical method used to reduce the dimensionality of large datasets while preserving as much variability as possible. In honey bee morphometrics, PCA helps identify the most significant traits contributing to variation among subspecies. E.g., a study on *Apis mellifera* populations in Kashmir utilized PCA to analyze body dimensions and found that the first two principal components explained a significant portion of the variance, aiding in subspecies differentiation (Aglagane et al., 2022).

Discriminant Function Analysis (DFA)

Discriminant Function Analysis (DFA) is employed to classify individuals into predefined groups based on measured variables" and that "in honey bee studies, DFA has been used to distinguish between subspecies by analyzing wing venation patterns and other morphological traits" is well-supported by existing literature. A notable example is the study by Tofilski, which utilized DFA to classify three honey bee subspecies—*Apis mellifera mellifera*, *A. m. carnica*, and *A. m. caucasica*—based on forewing venation patterns (Oleksa & Tofilski, 2014). The study reported high classification success rates, with geometric morphometrics achieving 84.9% and standard morphometry 83.8% accuracy in discriminating individual wings. When analyzing colonies, both methods correctly classified all samples, indicating the effectiveness of DFA in subspecies classification (Tofilski, 2008). Furthermore, other studies have corroborated the use of DFA in honey bee subspecies classification. E.g., a study in South Africa employed DFA on wing geometry and standard morphometric variables, achieving an 87% classification rate with a cross-validation error of 13.11%. Similarly, a study in Cuba reported 96% correct identification using DFA based on forewing venation patterns (Eimanifar et al., 2018).

Cluster Analysis

Cluster Analysis is another statistical method used to group individuals based on similarities in their morphometric traits without prior knowledge of their classification. This technique has been applied in various studies to identify natural groupings within honey bee populations. E.g., a study on Ethiopian honey bees employed cluster analysis to reveal distinct population structures, correlating with geographical and ecological factors (Hailu et al., 2021). Morphometric methods remain essential tools for studying honey bee diversity due to their cost-effectiveness and the minimal requirement for complex laboratory equipment. These methods allow researchers to assess physical traits such as wing venation patterns, body dimensions, and antennal structures to differentiate among subspecies. However, several limitations must be considered to ensure accurate classification. One significant limitation is the influence of environmental factors on morphological traits. Variables such as nutrition, developmental temperature, and habitat conditions can cause phenotypic plasticity, leading to variations that may not reflect genetic differences. E.g., a study on honey bee populations in southeastern Morocco found significant differences in wing shape among populations, which could be attributed to environmental factors and hybridization events (Aglagane et al., 2022).

Additionally, natural hybridization between different subspecies can complicate morphometric analyses. In regions where hybridization occurs, such as the natural honey bee hybrid zone in Argentina between Africanized and European populations, the overlapping of morphological traits can lead to misclassification. This overlap reduces the resolution power of morphometric methods, making it challenging to distinguish between subspecies based solely on physical characteristics (Litvinoff et al., 2023).

Molecular methods

Molecular techniques, particularly the analysis of mitochondrial DNA (mtDNA), have significantly advanced the field of evolutionary biology. In most animals, mtDNA is maternally inherited and does not undergo recombination, which simplifies the reconstruction of evolutionary lineages and is foundational to the field of phylogeography (Dowling & Wolff, 2023; Galtier et al., 2009). Additionally, mtDNA exhibits a higher mutation rate compared to nuclear DNA, which enhances its utility in resolving recent evolutionary events and subspecies differentiation, allowing for the detection of genetic differences over shorter evolutionary timescales (Dowling & Wolff, 2023). The unique properties of mtDNA—its maternal inheritance, lack of recombination, and high mutation rate—make it an effective marker for tracing evolutionary lineages and clarifying boundaries between subspecies, providing a consistent genetic record that enables the detection of recent divergences (Pakendorf & Stoneking, 2005). Collectively, these sources affirm that molecular methods, especially mtDNA analysis, have revolutionized evolutionary biology by providing precise tools to investigate genetic relationships, trace evolutionary lineages, and understand subspecies differentiation.

Researchers collect mitochondrial DNA (mtDNA) samples from various tissues such as blood, feathers, or muscle to investigate genetic relationships and evolutionary histories. Specific regions of the mtDNA, notably the cytochrome b gene and the control region (D-loop), are sequenced and compared across individuals and populations. These markers are chosen for their variability and utility in phylogenetic studies. E.g., the cytochrome b gene exhibits moderate evolutionary rates, making it suitable for distinguishing between species or genera. Similarly, the D-loop region, known for its higher mutation rate, provides insights into recent evolutionary events and population structures (Castresana, 2001; Tang et al., 2006).

The genetic differences observed in these mtDNA regions are analyzed to construct phylogenetic trees, which reveal evolutionary relationships and historical divergences among populations. For example, studies on the Siberian salamander have identified two major phylogenetic haplotype groups, AB and C, with an intergroup divergence indicating a separation approximately 1.5 million years ago. Similarly, research on Ammotragus species has utilized cytochrome b and D-loop sequences to delineate distinct lineages, suggesting the presence of cryptic subspecies (Malyarchuk et al., 2011; Wright et al., 2022).

By comparing mtDNA sequences, scientists can identify distinct evolutionary lineages, estimate divergence times between groups, and clarify taxonomic ambiguities where morphological traits overlap or vary inconsistently. These molecular analyses are crucial for detecting cryptic subspecies or evolutionary significant units (ESUs) that may not be apparent through traditional morphological methods. E.g., the identification of distinct mtDNA lineages in free-ranging Ammotragus populations has led to a reexamination of subspecific status, highlighting the importance of molecular data in taxonomic revisions (Wright et al., 2022).

Extensive mitochondrial DNA (mtDNA) analyses across birds, reptiles, and marine mammals have revealed that species previously considered widespread are often composed of multiple genetically distinct subspecies or even separate species. E.g., studies on emu-wrens (*Stipiturus* spp.) have shown significant phylogeographic differentiation, indicating that populations once thought to be part of a single species are genetically distinct and may require separate conservation management strategies. Similarly, research on reptiles has demonstrated that mtDNA analysis can uncover hidden genetic diversity, leading to the recognition of previously unrecognized subspecies (Donnellan et al., 2009). These insights are crucial for conservation efforts, as they ensure that management plans protect the full diversity within a species. By identifying distinct evolutionary lineages through mtDNA analysis, conservationists can establish more accurate conservation units, prioritize areas of high genetic diversity, and implement strategies that maintain the evolutionary potential of species. Moreover, recognizing cryptic subspecies can prevent the mismanagement of populations that may require different conservation approaches due to their unique genetic characteristics.

Integrative Taxonomy Approaches

Given these limitations, it is recommended to use large, representative samples to account for within-subspecies variation and environmental influences. Moreover, combining morphometric analysis with molecular techniques, such as microsatellite analysis or mitochondrial DNA sequencing, can provide a more comprehensive understanding of honey bee classification. Integrating both morphological and genetic data enhances the accuracy of subspecies identification and helps in understanding the evolutionary relationships among honey bee populations.

Ecological and adaptive behaviors

Ecological and adaptive behaviors are essential in understanding how species interact with their environment and ensure their survival across varying conditions. These behaviors can be categorized into three main aspects: aggressiveness level, survival strategies, and adaptability to climatic variations.

Aggressiveness and territoriality

The aggressiveness level of a species is often influenced by environmental pressures, social structure, and the need for territory or resources. E.g., species that engage in aggressive behavior typically exhibit territorial instincts, where competition for mates or food resources plays a central role. Aggression can be a mechanism for protecting key resources, deterring potential threats, or asserting dominance within a social hierarchy. In some species, aggression is more pronounced during breeding seasons or when there is a shortage of resources, while in others, such behaviors may be reduced under favorable environmental conditions, allowing for cooperative interactions.

Studies on free-ranging domestic dogs (*Canis familiaris*) have shown that intergroup agonistic behavior varies with season, sex, and reproductive status. Aggressive interactions were more frequent during the late monsoon months when females were in estrus, while submissive interactions peaked during winter when females were lactating. Male dogs exhibited more aggression during mating contexts and at territory boundaries, whereas females displayed more aggression in feeding contexts and near the den. These findings suggest that environmental pressures and reproductive status significantly influence aggression levels in this species (Pal, 2015). The Challenge Hypothesis offers a framework for understanding the relationship between testosterone and aggression in mating contexts, particularly in seasonal breeders. It posits that testosterone promotes aggression when it would be beneficial for reproduction, such as mate guarding or deterring intrasexual rivals. This hypothesis predicts that seasonal patterns in testosterone levels are influenced by mating systems, paternal care, and male-male aggression in seasonal breeders.

Testosterone and aggression in mating contexts

The original formulation of the Challenge Hypothesis suggests that testosterone levels increase during periods of social instability—such as territory establishment or confrontations with rival males—to promote reproductive aggression (Wingfield et al., 1990). This increase in testosterone supports behaviors like mate guarding and deterring rivals, which are advantageous for reproduction (Cavigelli & Pereira, 2000).

Seasonal patterns in testosterone level

Seasonal breeders exhibit variations in testosterone levels that align with reproductive needs. In species like the campo miner (*Geositta poeciloptera*), testosterone levels are higher during the breeding season, supporting increased aggression for territory defense and mate guarding. However, these levels decline after egg laying, coinciding with a reduction in aggressive behavior as parental care becomes more prominent (Lopes et al., 2021).

Influence of mating systems and paternal care

The Challenge Hypothesis also accounts for differences in testosterone responses based on mating systems and paternal care. In monogamous species that provide paternal care, testosterone levels are expected to rise during periods of reproductive aggression but decrease during parental care to facilitate investment in offspring. Conversely, in species with litle paternal care, testosterone levels may remain elevated throughout the breeding season to support continuous aggression and mate guarding (Goymann et al., 2007).

Evidence from avian studies

Studies on birds provide empirical support for the Challenge Hypothesis. E.g., research on black-headed gull chicks demonstrated that social challenges induce brief elevations in plasma testosterone levels, which in turn enhance aggression toward conspecifics. This indicates exposure to elevated testosterone increases sensitivity to social challenges, facilitating territorial defense (Ros et al., 2002).

Aggression and territorial behavior in animals are strongly influenced by environmental factors and resource availability, often intensifying during breeding seasons when access to food, mates, and nesting sites becomes critical for reproductive success. Animals defend territories to secure these vital resources, thereby improving their chances of survival and reproduction. Aggression typically manifests through non-lethal means such as vocalizations, visual displays, and scent marking, which serve to deter intruders without the high risk of injury. Physical confrontations occur only when these signals fail. Despite its importance in territorial defense, aggression is generally restrained, as most animals avoid potentially harmful fights that could compromise their fitness (Duque-Wilckens et al., 2019).

In summary, the aggressiveness level of a species is shaped by a complex interplay of environmental pressures, social structure, and the need for territory or resources. Aggression serves as a vital mechanism for survival and reproduction, with its expression varying across species and contexts. Understanding these dynamics is crucial for comprehending animal behavior and the evolutionary strategies that shape interactions within and between species (Duque-Wilckens et al., 2019).

Swarming and Honey Production

Survival strategies such as swarming and honey production are vital behaviors that have evolved in honey bees to enhance their chances of survival under various environmental and ecological pressures. Swarming is a collective behavior where a portion of the colony, including the queen, leaves the original hive to establish a new one. This strategy serves multiple purposes: it helps in reproduction by forming new colonies, reduces competition for resources within the original colony, and allows bees to relocate to more favorable environments when conditions deteriorate. E.g., unmanaged *Apis mellifera carnica* colonies have been observed to swarm multiple times per year, particularly during late spring and early summer, as a natural response to environmental cues and colony health (Rutschmann et al., 2025). Honey production is another critical survival strategy. Bees collect nectar from flowers and convert it into honey, which serves as a food reserve, particularly during periods when foraging is not possible, such as during winter or droughts. Honey production is influenced by various factors, including climate conditions. In regions like Chile, beekeepers have reported declines in honey production due to droughts, prompting them to adapt by relocating their apiaries to areas with more favorable conditions (Gajardo-Rojas et al., 2022).

These survival strategies not only ensure the bees' immediate survival but also contribute to maintaining ecological balance. Honey bees play a crucial role in pollination, facilitating the reproduction of many plants, including crops vital for human food production. Their ability to adapt through behaviors like swarming and honey production underscores the intricate relationship between species and their environments, highlighting the importance of understanding and preserving these behaviors for ecological sustainability.

Adaptation to climatic variability

Based on recent research available on ResearchGate, several studies highlight the critical role of adaptability to climatic variations in determining the long-term survival of species. As climate change accelerates, many species are compelled to adjust their behaviors, breeding patterns, and physiological functions to cope with shifting environmental conditions.

Behavioral Plasticity

Behavioral traits are pivotal in determining the resilience of animal species to rapidly changing global climates. While increasing temperatures have garnered significant attention, animals must contend with more than just extreme heat to persist in the Anthropocene. Research emphasizes the importance of behavioral traits in enhancing resilience to climate change (Buchholz et al., 2019). Insects, birds, and mammals exhibit various adaptive strategies, such as adjusting their feeding habits, hibernating, or changing reproductive timings to cope with unpredictable weather patterns or changing resources. E.g., short-distance temperate migrants have shown higher variability in behavior and greater responses to local weather than longer-distance tropical migrants, indicating different adaptive strategies to environmental changes (Calvert et al., 2012).

Migration and Seasonal Adjustment

Species that exhibit high levels of adaptability tend to be more resilient to environmental changes. The fossil record suggests that most species persisted through past climate changes, whereas forecasts of future impacts predict large-scale range reductions and extinctions. Many species have altered range limits and phenotypes through 20th-century climate change, but responses are highly variable (Moritz & Agudo, 2013). Additionally, behavioral plasticity allows species to adjust behavior to suit the conditions of their immediate environment, thereby increasing their fitness. This adaptability is crucial for coping with environmental changes (Buskirk, 2012).

Systematic and conservation challenges of bees in Central Africa

The study of bees in Central Africa faces multiple challenges that impede a comprehensive understanding of their systematics and conservation. These challenges include a lack of field studies, absence of reference collections, natural hybridization, and environmental stressors. Addressing these issues is crucial for biodiversity preservation, ecological balance, and sustainable development in the region.

Gaps in scientific research and infrastructure

A major limitation in bee systematics in Central Africa is the scarcity of in-depth, contemporary field studies. Much of the available entomological data stems from the colonial era, with specimens housed in European institutions (Tshibungu et al., 2023). As a result, current knowledge is outdated and regionally biased. The Democratic Republic of the Congo (DRC), despite its rich biodiversity, remains underexplored (Rodger & Balkwill, 2004). Another significant issue is the absence of reference collections. These are vital for accurate taxonomic identification and monitoring of species distribution. Without well-maintained collections, it is difficult to classify new species or trace shifts in bee populations. Digitizing historical collections and establishing local repositories would enhance accessibility and data sharing (Popov et al., 2021; Pearce et al., 2020). Investment in research infrastructure, digitization, and international collaborations is essential to advance taxonomic understanding and fill existing knowledge gaps.

Natural hybridization and taxonomic complexities

Natural hybridization among bee subspecies poses a serious challenge to taxonomy. Crossbreeding creates genetic and morphological ambiguities, which complicate species identification and classification. In regions like South Africa and Morocco, hybrid bees exhibit traits from multiple parental lineages, leading to inconsistencies in genetic markers and morphological features (Aglagane et al., 2023; Aglagane et al., 2022). These complexities blur subspecies boundaries and challenge traditional taxonomic methods. Integrative taxonomy, which combines morphological, genetic, and ecological data, is necessary for accurate classification in biodiversity-rich regions like Central Africa (Karbstein et al., 2024). Hybridization also carries conservation implications, as it may obscure species boundaries, compromise genetic integrity, and hinder targeted conservation efforts (Fournier & Aron, 2021; Rougerie et al., 2012).

Conservation and environmental threats

Bee populations in Central Africa are increasingly threatened by habitat loss, agricultural expansion, and climate change. Deforestation for farming, logging, and urbanization leads to habitat fragmentation, reducing nesting sites and floral resources (Iloweka, 2004; Tyukavina et al., 2018). This isolation limits gene flow and increases vulnerability to inbreeding and local extinction. Climate change further exacerbates these challenges by disrupting flowering cycles and reducing forage availability (Gérard et al., 2020; Soroye et al., 2020). Extreme weather events, such as droughts and floods, negatively impact bee health, reproduction, and survival (Fellendorf et al., 2004). Additionally, the spread of pests and diseases is accelerated by warming temperatures (Rahimi & Jung, 2024). Sustainable conservation strategies must prioritize habitat preservation, climate resilience, and ecological connectivity. Efforts should include reforestation, pollinator-friendly agricultural practices, and reducing pesticide use (Belsky & Joshi, 2019).

Underappreciation of stingless bees (Meliponini)

Research in Central Africa has disproportionately focused on *Apis mellifera*, often overlooking the ecological and economic importance of stingless bees (Meliponini). These bees are crucial pollinators of native flora and are well-adapted to tropical ecosystems (Chakuya et al., 2022). They also produce honey valued for its nutritional and medicinal properties (Al-Hatamleh et al., 2020). Despite their significance, stingless bees remain understudied. Initiatives like ICIPE's training programs and recent studies in Ghana, Uganda, and Kenya have begun addressing this gap (ICIPE, s.d.; Kidane et al., 2021). However, more structured support for meliponiculture and ecological research is needed to harness their full potential in conservation and rural development (Barbiéri Júnior & Francoy, 2020).

Ecological and economic importance of bees

Bees play a foundational role in biodiversity maintenance and agricultural productivity. As pollinators, they are essential for the reproduction of many crops and wild plants (Delaplane & Mayer, 2000; Aizen & Harder, 2009). Their decline threatens food security, ecological stability, and rural livelihoods. Pollination services enhance crop yields and support ecosystem functions like soil health and carbon sequestration (Katumo et al., 2022; Khan, 2023). Sustainable beekeeping, particularly with locally adapted species, offers economic benefits, promotes biodiversity, and supports environmental stewardship. In many African regions, stingless beekeeping provides culturally significant, eco-friendly income sources (Simms & Porter-Bolland, 2022; Prodanović et al., 2024).

CONCLUSION

This review consolidates two decades of fragmented research on wild honey bee species in Central Africa, with a focus on *Apis mellifera* subspecies and stingless bees (Meliponini). It highlights the significant ecological and economic roles of these pollinators in maintaining biodiversity and supporting agriculture in Cameroon, Gabon, and the Democratic Republic of the Congo. Despite their importance, wild bees remain under-documented, and their taxonomy is complicated by hybridization, morphometric overlap, and limited regional reference collections. The findings reveal four critical gaps: (i) insufficient field-based studies, particularly in remote forested regions; (ii) lack of integrative taxonomic frameworks combining morphometric and genetic data; (iii) minimal policy engagement in protecting native pollinators; and (iv) weak institutional coordination in conservation and data sharing.

To address these challenges, we recommend: (i) Developing country-specific taxonomic reference databases and digitized collections through collaboration between national universities and international research institutes; (ii) Strengthening integrative field research, including systematic surveys, molecular diagnostics, and ecological monitoring; (iii) Promoting sustainable beekeeping models, such as meliponiculture, that respect local environmental conditions; (iv) Engaging local communities and indigenous knowledge systems in conservation programs, especially in areas vulnerable to deforestation and climate change; (v) Encouraging cross-border partnerships between Central African countries for pollinator monitoring, genetic resource conservation, and environmental policy development. By contextualizing conservation actions at the country level, including support for decentralized training programs, local market integration, and policy incentives, Central Africa can protect its native bee diversity while enhancing ecosystem resilience and food security.

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