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Spatial and temporal dynamics of *Apis dorsata*'s nest distribution and habitat preferences across different seasons in Pattoki (Pakistan)

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The giant honey bee, *Apis dorsata*, is an ecologically important wild pollinator which is under threat due to habitat alteration, climatic change and anthropogenic hazards. To design effective conservation strategies, it is important to understand its spatial and temporal distribution patterns. The present study aimed to study the seasonal dynamics, habitat preferences and nesting characteristics of the colonies of *A. dorsata* in Tehsil Pattoki, District Kasur, Punjab, Pakistan. Field surveys were carried out in forest, urban, peri-urban and agroforestry habitats. Geographic coordinates, nest characteristics, nesting substrates, host tree species and habitat attributes were recorded. The patterns of nest distribution and habitat associations were examined by GIS-based mapping and statistical analyses. A total of 50 nest sites were identified across the study area. The colonies were most frequently found in forest habitats (58%), peri-urban (18%), agroforestry (14%) and urban habitats (10%), showing a high preference for vegetation-rich habitats. 100% of colonies were built on live trees, with no dead trees or human-made structures. Six tree species were used for nesting substrates, *Ziziphus mauritiana* (32%) and *Syzygium cumini* (22%) being the most common host trees used. Nest height varied between 4.8 and 15.7 m above the ground; the highest was found in *Eucalyptus globulus* (12.67 ± 1.83 m) while *Morus alba* had the lowest nests (5.70 ± 0.28 m). Significant fluctuations in activity of colonies were observed between seasons. In spring, there was 100% colony retention in all 50 colonies. Colony retention was 80% in summer, when 10 colonies were inactive; and 58% in winter, with 21 inactive/abandoned colonies. There was a significant difference in nest height by host tree species ($P < 0.0001$), but no significant difference in nest site location by host tree species ($\chi^2 = 0.477$), or by host tree species by habitat category ($\chi^2 = 0.424$). The results showed that forest habitat and specific host trees are important for *A. dorsata* abundance and nesting. The present study will serve as a baseline for future research on climate-induced migration and conservation of wild honey bee populations. A detailed residue analysis of honey, wax and bee tissue should be performed to quantify the effect of the use of pesticides in a particular region on health and survival of the bees. Policies should be implemented to protect indigenous trees (*Ziziphus*, *Syzygium*) for nesting and to encourage their planting in peri-urban areas.

Keywords: *Apis dorsata*; habitat preference; colony retention; forest habitat; host tree selection; spatial distribution.

Introduction

Among the most significant species in the natural world are honey bees because they are involved in the process of pollination. Honey bees pollinate diverse agricultural crops such as fruits, vegetables and oilseeds, which form an important part of the human diet (Paudel et al., 2015). In the absence of honey bees, food security and biodiversity would be severely affected as most crops would not yield production. As a matter of fact, it is calculated that honey bees pollinate one-third of the world's food. They are not only crucial in agriculture, but they form an essential component of ecosystems since they support the survival of plants and other organisms that rely on them (Kaya et al., 2023). The reduction of honey bee numbers globally and especially in recent decades has become a major cause of concern among the scientific, agricultural and environmental communities. The causes of this reduction are complex and involve habitat loss, pesticide use, global warming and disease. These stressors in certain areas have resulted in colony collapse disorder (CCD) where honey bee colonies die unexpectedly and without apparent cause (Dennis & Kemp, 2016). The declines experienced by other populations are gradual as a result of inaccessible optimal environmental conditions such as lack of floral resources and the nesting sites. This downward trend is detrimental not only to honey bee populations but also affects agricultural productivity and the health of an ecosystem (Kaya et al., 2023).

One of the major threats that honey bees are facing is habitat loss. Natural habitats that offer honey bees a large supply of flowering plants and nesting areas are disappearing rapidly. This habitat destruction is a result of increase in human populations, urbanization, agricultural intensification and deforestation. In addition, monoculture agricultural practices on a large scale decrease the variety of floral resources available to bees. This scarcity of diverse plant species reduces food resources supplied to honey bees, making it difficult for them to support their colonies, especially during winter periods (Steele et al., 2022). Moreover, climate change compounds the difficulty faced by honey bees since they change floral resource timings and availability. Fluctuations in temperatures, altered precipitation patterns and extreme weather could alter the blooming of plants on which honey bees feed (Mishra et al., 2023). Similarly, alterations in climate may influence the geographical distribution of honey bees as well as the plants they pollinate, leading to a lack of correspondence between the patterns of plant flowering and foraging (Mishra et al., 2023).

Another significant threat is the widespread usage of agrochemicals and the use of pesticides (Munir et al., 2024). Plants absorb these chemicals and the whole plant becomes toxic to pollinators (Bonmatin et al., 2014). Insecticides, herbicides, and fungicides may cause both acute and sublethal toxicity. Neonicotinoids are a family of insecticides have been reported to kill honey bees. Honey bees may also become vulnerable to disease as a result of pesticides weakening their immune systems. Low levels of pesticide exposure have been reported to reduce the foraging, navigation and reproduction capabilities of bees in addition to causing the collapse of bee colonies. In addition to these environmental stressors, honey bees are also prone to diseases and pests. A few pathogens such as the *Nosema* and the parasitic *Varroa* mite have been devastating to bee colonies (Klein et al., 2017; Chmiel et al., 2020; Khoury et al., 2021). Being a wild species, *A. dorsata* is particularly susceptible to pesticides across the agricultural landscapes (Chakrabarti et al., 2015).

Pakistan is a country located at the crossroads of the Palearctic and Oriental regions. Pakistan also contains various ecological zones, including alpine and temperate forests in the north and subtropical plains, arid deserts, and coastal ecosystems in the south (Shoaib & Lin, 2025). Such environmental heterogeneity sustains the existence of numerous pollinating insects comprising a variety of honey bees species of the genus *Apis* (Laurenti et al., 2017). Four honey bee species have been reported from Pakistan in the genus *Apis*, including *Apis dorsata* (giant honey bee), *Apis cerana* (Asian honey bee), *Apis florea* (dwarf honey bee) and *Apis mellifera* (western honey bee). *A. cerana* and *A. florea* are native species, adapted to the local climatic conditions. *Apis mellifera* has been introduced into commercial apiculture and is currently managed extensively because of the large honey yield and its adaptation to modern beekeeping methods. *Apis dorsata*, giant honey bee, is a wild species, and one of the most important ecologically important pollinators in forest and agricultural landscapes (Sharma et al., 2021). In Pakistan, populations of honey bees are declining due to many anthropogenic factors. and environmental pressures (Iqbal et al., 2024). Deforestation, specifically the removal of nesting trees, limits the availability of high-quality nesting sites for wild honey bees, which can be a significant limiting factor for their populations. These effects are especially terrible for *A. dorsata*, which relies on tall trees (Oldroyd & Nanork, 2009; Kohl et al., 2023).

These issues are further intensified by climate change, which alters the pattern of temperature regimes, precipitation patterns, and flowering phenology. The changes in the timing and quantity of floral material disrupt the synchrony of the honey bee foraging activities and the food supply resulting in nutritional stress. Climate-induced changes can also alter migration pathways and seasonal colony patterns in migratory species (Mishra et al., 2023). Although there is relatively good documentation on diseases of managed bees, little attention has been given to monitoring the wild populations of *A. dorsata*. All these threats point to the importance of learning about honey bee resilience mechanisms such as gut microbiota, which play a crucial role in facilitating adaptation and survival during environmental stress (Budge et al., 2016).

Apis dorsata build one large comb, usually hanging off high trees, cliffs or buildings. Colonies can have thousands of individuals, and they are all subjected to changes in temperature, humidity, rainfall, and predation. *Apis dorsata* has a pronounced seasonality in its life cycle. There is a strong seasonal growth and decline in the colonies due to the presence or absence of flowers and climatic factors. In good seasons, especially spring and early summer, the colony multiplies rapidly and bees foraging extensively. These times are also marked by abundant sources of nectar and pollen, which promote the storage of energy (Seeley & Visscher, 1985). Conversely, an adverse season characterized by shortage of floral resources or extreme weather conditions, which tend to induce long-distance migration. Colonies can leave their nesting sites and move into places with better habitats. This trait makes *A. dorsata* different from most other honey bee species. Every migration is a crucial ecological transition, and it needs to be well-coordinated (Kastberger et al., 2024). Although honey bees are highly valuable animals ecologically and agriculturally, no detailed information is available regarding the factors influencing their well-being and seasonal distribution. The distribution and functionality of honey bee nests in various seasons are very important in understanding the root causes of their decline and for the formulation of effective conservation strategies (Ricigliano et al., 2019).

The loss of the *A. dorsata* populations due to habitat loss, exposure to pesticides and climate change is a significant challenge to the stability of the ecosystem as well as agricultural output (Kaya et al., 2023). Limited data is available on the patterns of spatial and temporal distributions of *A. dorsata*'s nests during various seasons. The existing body of research mainly focuses on the biology of honeybees, lacking information about nest distribution and bee activity in relation to habitat availability, climatic conditions and changing floral resources. This gap in knowledge may create challenges in creating effective conservation strategies for honey bees. Since *A. dorsata* has a unique migratory behavior, it is important to investigate how the seasonal variability of environmental conditions affects the distribution of the nests. This study fills this gap through a GIS-based spatial and temporal analysis of *A. dorsata* nest distribution and habitat preferences across seasons, providing baseline data on bee resilience to environmental pressures.

Materials and methods

Tehsil Pattoki, in the Kasur District of Punjab, Pakistan is located about 60 kilometers to the south of Lahore. It is characterized by a subtropical climate and three pronounced seasons including winter, spring, and summer, which impact greatly on local flora and fauna. The winter season (December to February) is not very cold with an average temperature of 7 to 20 °C. The spring (March to May) is mild with temperatures between 18 and 30 °C, whereas the summer (June to August) is hot with temperatures between 30 and 45 °C. July–September is the monsoon season with an average precipitation between 700 and 900 mm. The farmland in Pattoki is fertile; it is irrigated by canals from the Ravi River (Ali et al., 2018; Shafique et al., 2026). Some crops that grow in the region are wheat (*Triticum aestivum*), rice (*Oryza sativa*), sugarcane (*Saccharum officinarum*), cotton (*Gossypium* spp.), and maize (*Zea mays*). The other vital vegetation includes acacia (*Acacia nilotica*), eucalyptus (*Eucalyptus camaldulensis*), and neem (*Azadirachta indica*). These plants provide shelter and food to pollinators. Pattoki boasts of abundant vegetation that can feed the various pollinators of the wildflowers and bushes with supplementary nectar and pollen. A high amount of nectar is also provided by other fruit trees such as the guava (*Psidium guajava*), sweet orange (*Citrus sinensis*), pomegranate (*Punica granatum*), and the ber (*Ziziphus mauritiana*). The supply of flowers increases during the monsoon months and spring months to the benefit of the honey bees as it offers them easy source of food (Ali et al., 2016, 2018).

Apis dorsata is a wild honey bee species that typically nests in trees and other elevated areas. Field surveys were conducted across different habitats and targeting areas that are known to support *A. dorsata* in Tehsil Pattoki, District Kasur. A combination of direct field observations and socio-ecological surveys was employed to locate *A. dorsata* colonies. Following established protocols for wild bee monitoring, semi-structured interviews were conducted with local beekeepers, farmers, and honey hunters to identify traditional nesting sites of *A. dorsata*. This approach is highly effective for mapping migratory species like *A. dorsata*, as it leverages long-term local knowledge of nesting and migration patterns (Misra et al., 2016). For each identified nest, the following data were recorded on filed log book (Hussain et al., 2025).

Exact GPS coordinates (latitude and longitude) were recorded using GPS essential mobile app.

Nest status (active/inactive), height from the ground, and substrate type (tree species or human-made structure) were noted. Each nest and the surrounding habitat was photographed to record the nest structure and habitat characteristics.

For arboreal nests, the species and vitality (alive/dead) of the host tree were recorded as *A. dorsata* often prefers tall trees with sloping branches for stability (Saberioon, 2010).

Ambient temperature and relative humidity were recorded at each site. Spatial analysis was performed to evaluate the influence of environmental variables on nest distribution. Land use land cover framework was used to categorize the landscape into four primary classes such as urban, peri-urban, forest and agroforestry areas (Grison et al., 2023).

Using the ArcGIS Pro/10.x environment, Euclidean distance buffers were generated to calculate the proximity of each nest to water sources and human settlements. Proximity to water is a critical suitability factor for nest maintenance and hydration (Sarı et al., 2020; Elmastaş et al., 2022). Data on rivers, streams, and ponds were obtained from remote sensing data. Proximity to water is an important factor influencing nest location, as bees need access to water for hydration and nest maintenance. GIS buffers were created to measure the distance of each nest from nearby water bodies (Young et al., 2021). Once all the data were collected, ArcGIS 10.0 was used to make the spatial maps. The coordinates obtained in the field using GPS were loaded to the GIS platform. All the nest locations were expressed as points on the map. High-resolution satellite images were used to create a base map of the study area. The base layer contains geographical characteristics such as roads, rivers, forests, and cities. Google Earth and other sources of base maps were used to obtain the necessary context in which nest location may be interpreted (Young et al., 2021). To demonstrate the presence of environmental variables that might affect the distribution of nests, including land use, vegetation, water sources, and temperature, several geospatial layers were included in the GIS map (Calovi et al., 2021). The final GIS maps were developed to represent the spatial patterns of the *A. dorsata* nests within the study area. Hotspot analysis was carried out to determine locations with active *A. dorsata* nests. The pattern of the location of nests was examined to determine whether nests are concentrated on certain areas or scattered throughout the study area.

Mean differences in nest heights across the various tree species were evaluated using a one-way analysis of variance, followed by Tukey's honestly significant difference test for post-hoc pairwise comparisons. Statistical significance for these tests was determined at a threshold of $P < 0.005$ with results presented as mean ± standard deviation (SD). The association between nest distribution and land use categories was analyzed using a Chi-square test to evaluate whether the observed frequencies deviated significantly from an expected uniform distribution. All statistical associations were tested at a 5% level of significance ($P < 0.05$).

Results

A total of 50 *A. dorsata* nest sites were identified and recorded from different locations across Tehsil Pattoki, District Kasur. Thelected nest sites were distributed across diverse habitat categories including forest, peri-urban, urban, and agroforestry landscapes. Among these, forest habitats, particularly the Changa Manga Forest and its associated blocks, contained the highest number of recorded nest sites, indicating a strong preference of *A. dorsata* for relatively undisturbed and vegetation-rich environments. Peri-urban areas such as Mallanwala and UVAS C-Block, along with agroforestry zones including Wan Adhan, Link Canal, and Wan Khara, also supported notable nest occurrences, while comparatively fewer nests were observed in urban settings of Pattoki city. The geographical coordinates recorded through GPS confirmed a wide but localized distribution of nest sites within the study area. Nest site elevation ranged from 635 to 694 ft above sea level, demonstrating that *A. dorsata* colonies occupied habitats with moderate variation in elevation. All recorded nests were established on trees, reflecting the arboreal nesting behavior of this wild honey bee species. Six tree species were identified as nesting substrates, namely *Syzygium cumini* (jamun), *Ziziphus mauritiana* (ber), *Vachellia nilotica* (kikar), *Morus alba* (white mulberry), *Eucalyptus globulus* (safaida), and *Azadirachta indica* (neem). Among these, *Syzygium cumini* and *Ziziphus mauritiana* were the most frequently utilized host trees. Nest height above ground varied considerably, ranging from 4.8 to 15.7 m, suggesting that *A. dorsata* preferred elevated nesting positions, particularly on tall and structurally stable trees. Overall, the observed distribution pattern highlighted the importance of forested and tree-rich habitats in supporting *A. dorsata* nesting ecology in Pattoki.

The 50 *A. dorsata* nest sites were monitored seasonally and there was a significant variation in the activity and retention of the colonies during the study period (Table 1). During spring, all 50 recorded nests were active, with no inactive or abandoned colonies observed, resulting in a colony retention rate of 100% (Fig. 1). The average temperature during spring season was 28 °C and the relative humidity was 53%. In summer, although the total number of observed nest sites remained unchanged, the number of active colonies declined to 40, while 10 nests were recorded as inactive or abandoned. Thus, the colony retention rate was reduced to 80% (Fig. 2). The highest mean temperature (39 °C) and relative humidity (62%) were recorded in summer. The winter had the highest level of reduction in colony activity. There were 29 nests that were active out of the 50 monitored nest sites, and 21 nests were inactive or abandoned (Fig. 3). The colony retention was significantly reduced to 58% and it was the lowest of all seasons. The minimum mean temperature (16 °C), and maximum relative humidity (73%) were observed during winter. Nest occupancy changed seasonally, as was illustrated by the spatial distribution maps. In spring (Fig. 1), all of the nest sites that were recorded had active colonies, suggesting a high colony density throughout the study area. During summer (Fig. 2), there was a significant decrease in active colony distribution as several nest sites remained inactive. The distribution pattern in the winter indicated that many nests were inactive or abandoned. The overall findings indicated a continuous decrease in the number of nests retained and in colony activity (number of nests identified) from spring to winter, with the total number of identified nest sites remaining the same throughout the study period.

Nesting substrate assessment showed that, of the total 50 nests counted, 100% of *A. dorsata* colonies were found on trees, while no nests were recorded on man-made structures (Table 2). Likewise, none of the colonies were recorded on dead trees and all host trees used for nesting were alive. These results showed that in the study area *A. dorsata* is strongly attracted to the living arboreal nesting substrates. Six species of trees were identified as host trees for establishment of the nests (Table 3). Of these, *Ziziphus mauritiana* (ber) was the most common nesting tree, with 16 nests (32%) while another tree *Syzygium cumini* (jamun) had 11 nests (22%). *Eucalyptus globulus* (safaida) and *Vachellia nilotica* (kikar) had 7 and 6 nests respectively representing 14% and 12% of the total number of nests. *Morus alba* (white mulberry) and *Azadirachta indica* (neem) each supported 5 nests, representing 10% of the total colonies. A significant difference was also noted between the different host tree species in terms of nest height. *Eucalyptus globulus* recorded the highest mean height of the nest (12.67 ± 1.83 m) whereas nest height for *Syzygium cumini* was 11.07 ± 1.56 m and for *Azadirachta indica* 10.64 ± 0.82 m. Nests on *Morus alba* had the lowest mean height (5.70 ± 0.28 m) while those on *Vachellia nilotica* (6.50 ± 0.81 m) and *Ziziphus mauritiana* (6.71 ± 1.38 m) were the next lowest. Nest sites were found in each of the land use and land cover types, but with a distinct clustering of nests within the forest habitat (Table 4). Of the 50 nest locations recorded, 29 (58%) were in a forested setting. 9 nest sites (18%) were found in peri-urban habitats and 7 nest sites (14%) were recorded in agroforestry landscapes. Urban areas had the fewest nest sites with only 5 colonies (10%) counted. The findings showed that *A. dorsata* colonies were mainly found in forested areas, and in living trees, showing a strong affinity for some host tree species for nesting.

Table 1
Seasonal dynamics of *Apis dorsata* nests in the study area

Season	Mean temperature, °C	Humidity, %	Total nests observed, n	Active nests, n	Inactive / abandoned nests, n	Colony retention, %
Spring	28	53	50	50	0	100
Summer	39	62	50	40	10	80
Winter	16	73	50	29	21	58

Chi square association of nest site selection and habitat associations. The data on the height of nests of different species of host trees showed that there was significant difference in the vertical distribution of the colonies of *A. dorsata* (Fig. 4). There was a significant difference in nest height between tree species ($P < 0.0001$), meaning that the host tree species affected nest height when *A. dorsata* established their colonies. *Eucalyptus globulus*, *Syzygium cumini* and *Azadirachta indica* had the highest mean nest heights while comparatively lower nest heights were recorded on *Morus alba*, *Vachellia nilotica* and *Ziziphus mauritiana*. The findings showed a strong correlation between the nest's placement height and the host tree species.

The Chi-square test for association between nest site location and host tree species was not significant ($\chi^2 = 0.477$). The host tree species used as nesting substrates differed among the study sites but their distributions at the various nest locations were not very different, indicating that host tree species were utilized at multiple sites without a distinct site-specific pattern.

Likewise, the Chi-square test used to assess whether there was an association between habitat category and host tree species showed no significant association ($\chi^2 = 12$). Different host tree species were distributed across forest, peri-urban, urban and agro-forestry habitats with no strong preference for host tree species within the habitat categories. The results indicated that *A. dorsata* used several host tree species, but there was no strong habitat type dependent choice of tree to nest in. The statistical analyses indicated significant differences in nest height among host tree species, but no significant associations were identified between nest site location and host tree species or habitat category and host tree species. The findings suggested that host tree attributes affected the height of nests above the ground, while the frequency of nesting trees was relatively uniform across nest sites and habitat categories.

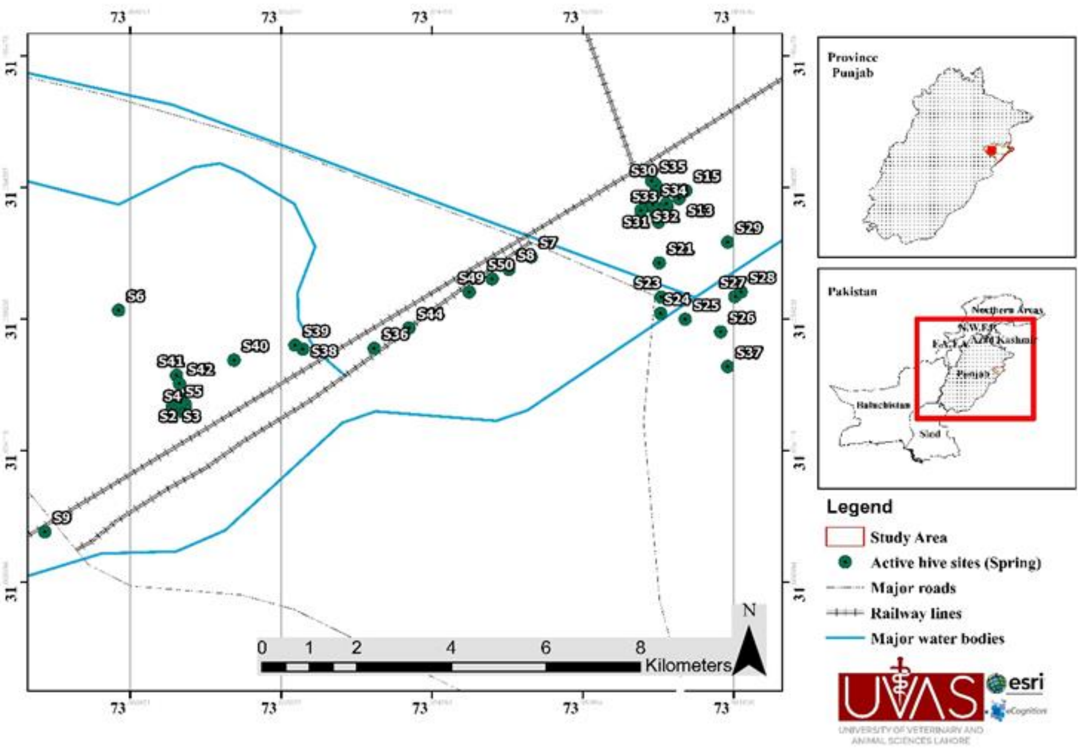

Fig. 1. Distribution of active and inactive *Apis dorsata* nests during the spring season

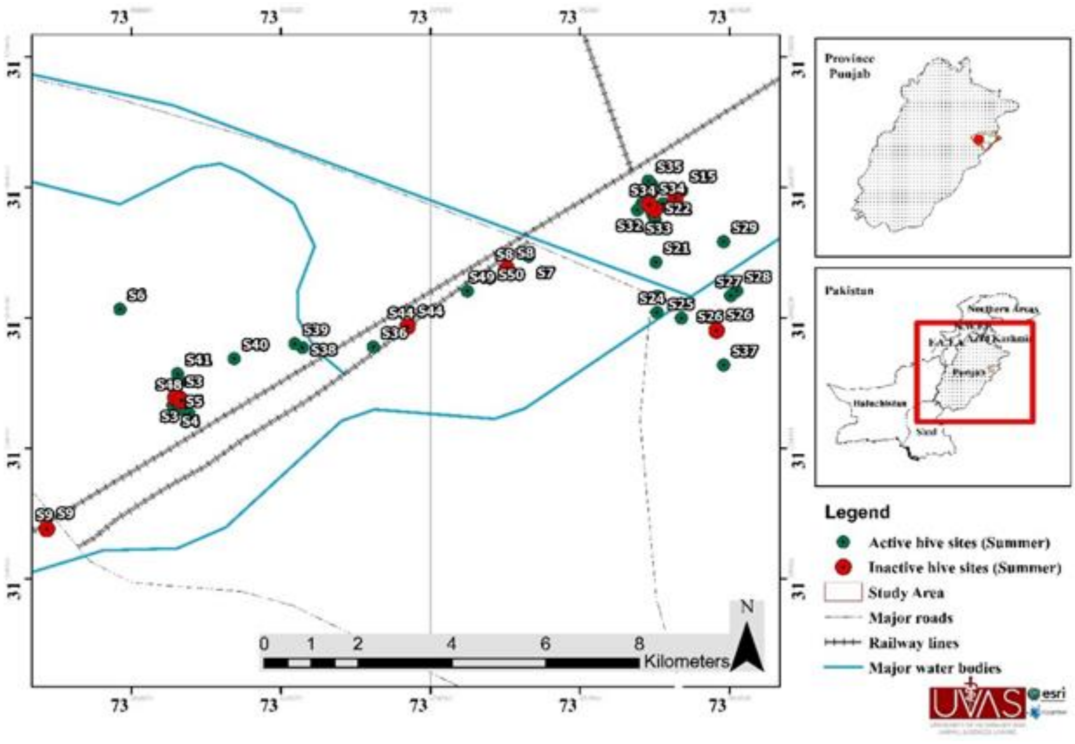

Fig. 2. Distribution of active and inactive *Apis dorsata* nests during the summer season

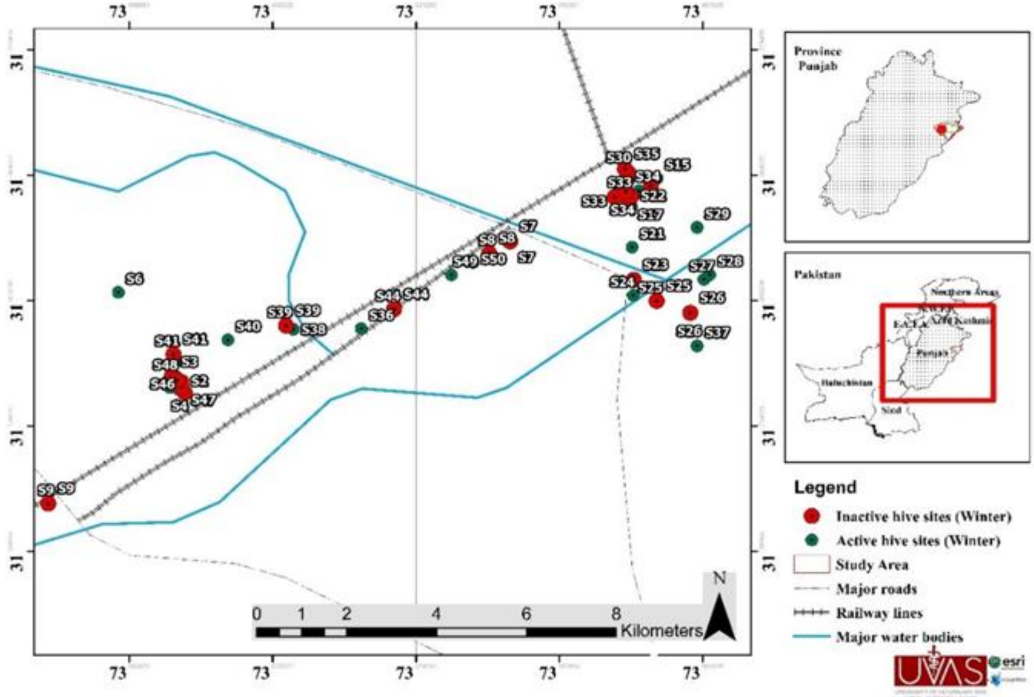

Fig. 3. Distribution of active and inactive *Apis dorsata* nests during winter season

Table 2
Nesting substrate and host tree vitality

Variable	Category	Number of nests, n	Percentage
Nesting substrate	tree nests	50	100
	human-made structures	0	0
Tree vitality	alive	50	100
	dead	0	0

Table 3
Characteristics of nest sites and nesting substrates (mean ± SD)

Tree species	Local name	Number of nests, n	Nest height, m
Syzygium cumini	jamun	11	11.07 ± 1.56^a
Ziziphus mauritiana	beri	16	6.71 ± 1.38^b
Vachellia nilotica	kikar	6	6.50 ± 0.81^b
Morus alba	white mulberry	5	5.70 ± 0.28^b
Eucalyptus globulus	sfaida	7	12.67 ± 1.83^a
Azadirachta indica	neem	5	10.64 ± 0.82^a
Total		50	<0.0001

Note: superscripts on different means within column differ significantly at P < 0.005.

Table 4
Habitat-wise distribution of *Apis dorsata* nests
across land use/land cover (LULC) categories in the study area

Land use / habitat category	Number of nests observed, n	Percentage
Urban	5	10
Peri urban	9	18
Forest	29	58
Agroforestry	7	14
Total	50	100
χ^2	12, P = 0.213	

Discussion

The spatial and temporal dynamic distribution of *A. dorsata* nests in Pattoki, Punjab, provided baseline information on the ecological resilience of *A. dorsata* in a complex subtropical agriculture ecosystem. The results of the current study (50 different nest sites) highlighted the population's strong dependence on seasonal environmental changes, the presence of suitable habitat and detailed architectural characteristics of host plants.

The most noticeable trend in the study area was the marked seasonal difference in colony retention with 100% in spring and only 58% in winter. The result is in line with the work of Singh et al. (2007), which pointed out that temperature and availability of forage plants had a significant effect on nesting by *A. dorsata*. The maximum number of nests was in January when temperatures were moderate (7.8–24.2 °C) whereas winter decline indicated a different local situation in Pattoki, which may be due to extreme minimum temperatures or high relative humidity of 73% (Singh et al., 2007). Low temperatures and high humidity can reduce the efficiency of thermoregulation, especially for open-comb species, by increasing the energetic costs of thermoregulation (Ramsey et al., 2018). The exposed combs of *A. dorsata* are susceptible to heat loss during the winter and heat gain during the summer unlike cavity-nesting bees such as *A. mellifera*.

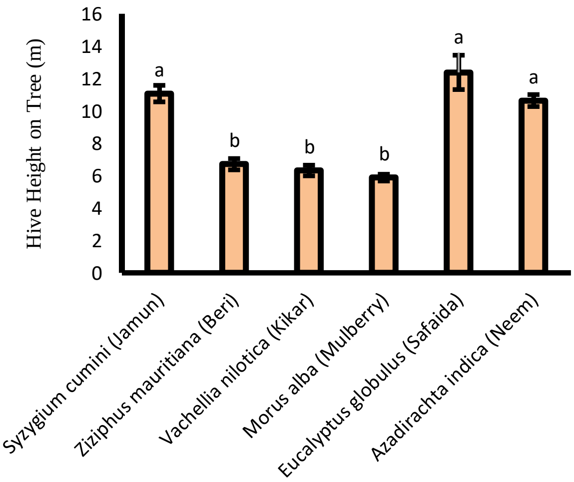

Fig. 4. Variation in the nesting height of *Apis dorsata* nests among different host tree species: bars represent mean ± SE nest height (m), and different letters indicate statistically significant differences between tree species (P < 0.0001)

That 100% retention rate during spring was recorded when the averages temperature was 28 °C, and is typical of what Robinson calls "surfing the sweet wave" when migratory colonies follow the flowering of the nectariferous plants from one part of the landscape to the other (Robinson, 2021). This "sweet wave" in Pattoki is due to the availability of sufficient amount of available nectar and pollen from various plants such as *Citrus sinensis*, *Trifolium alexandrinum* and *Brassica* species (Singh et al., 2007; Ali et al., 2017). The drop to 80% colony retention (mean 39 °C) in summer suggested thermal stress as a significant limitation. Normally as temperature goes up to 40–45 °C, foraging decreases and colonies may move to find a cooler micro-climate or a more plentiful water source for nest cooling (Singh et al., 2007; Ramsey et al., 2018). The thermal sensitivity of *A. dorsata* is also indicated by the fact that their flight is greatly curtailed at temperatures below 10 °C, which is frequently reached during winter nights in Punjab.

The spatial distribution showed a strong preference for the forest habitat, where 58% of the nest sites identified were found. This observation was in line with earlier observations in Northern Punjab where *A. dorsata* showed a higher occurrence in protected forest areas and sub-mountainous topography (Bashir et al., 2023). The Changa Manga forest is among the largest planted forests in the region, which created a stable micro-climate and high density of tall nesting trees, that is crucial in mitigating terrestrial predators. In contrast, the low occupancy in urban areas (10%) indicates that urbanization with its associated toxic air quality, electromagnetic interference and habitat fragmentation is an unwelcoming environment for the wild honey bee (Munir et al., 2024). *Apis dorsata* is generally believed to be a synanthropic species and can be found in man-made structures, but in Pattoki, it is associated 100% with living trees (Kastberger et al., 2024). This is probably related to the physiological requirement of the colony; flexibility of the branches and thermal buffering are better provided by living trees than by concrete structures (Sihag, 2017). However, in semi-arid regions of North West India where timber is scarce, as many as 22.3% of colonies have been reported on buildings, and thus show the species' adaptability in the face of habitat loss (Sihag, 2017). This aggregation of nests in the forest patches of Pattoki highlights the significance of "stepping stone" habitats to support the migratory corridor across the Punjab plains.

Based on the present study, it was found that *Ziziphus mauritiana* (32%) and *Syzygium cumini* (22%) are the most common trees used for nesting. This choice is not only structural, but is closely related to the foraging ecology of bees. Singh et al. (2007) singled out *Syzygium cumini* as one of the importance nectar sources that provides nectar during critical times. Similar observations were made in Bengaluru that *A. dorsata* intensely and preferably forages *S. cumini* for its pollen and nectar, which is generally observed during the morning hours (Amaravathi & Reddy 2021; Eswarappa et al., 2025). In the same way, *Ziziphus mauritiana* is an important source of floral visits in South Asian countries and thus offers a good amount of food during flowering season and also insect diversity. The vertical stratification of nests from 4.8 to 15.7 m is a complex method of escaping predators and adapting to the climate. The large difference in nest height among the tree species ($P < 0.0001$) indicated that *A. dorsata* may actively select tree species of certain heights such as *Eucalyptus globulus* (mean 12.67 m) while choosing the more accessible species, such as *Morus alba* (mean 5.7 m), only when necessary. The tall trees give a form of "safety buffer" from human disturbance and ground dwelling predators (Thomas et al., 2009). In Karnataka, a similar study revealed that *A. dorsata* colonies were found on a diverse range of heights on different substrates, with greater heights being more common on trees than on rock cliffs. This preference for smooth slightly inclined branches (0–45°) for comb attachment is another reason why specific tree architectures are preferred (Sihag, 2017) as described in North-Western India.

Seasonal winter abandonment of 42% of nests may be an indicator of a wider migration cycle vital for the species' survival in a variable environment (Robinson, 2012). *Apis dorsata* exhibits high spatial and temporal fidelity towards "traditional" stopover locations during migration and migrates to the same bivouac sites year after year (Robinson, 2012). These locations are usually close to rivers and in orchards, serve as key resting and feeding sites before the bees reach their highland or lowland destinations (Robinson, 2021). The reduction in winter presence at Pattoki indicated a possible shift of these colonies to more favourable wintering areas which may be in response to the blooms of *Brassica* in other districts. There is a need for conservation along the entire migratory corridor, and no single migratory endpoint will be protected unless this is done. Loss of a single "traditional" site can negatively impact the transfer of knowledge of migration routes from one generation to the next, and has been observed in Thai populations (Robinson, 2021). The 50 sites listed in Pattoki could be a network of traditional sites, which enable the yearly "sweet wave" of migration across Punjab.

Several anthropogenic drivers pose a threat to the survival of *A. dorsata* in Pattoki. Pollinator decline in Pakistan is mainly due to the wrong use of pesticides. The wild honey bee directly faces the use of insecticides and fungicides in agroforestry and agricultural fields, which can cause both immediate and indirect (sublethal) effects on foraging behaviour. For instance, it has been reported that neonicotinoids can cause significant impact on the fitness of the colony and weaken the immune system of honey bees (Ghosh et al., 2023; Nautiyal et al., 2023; Munir et al., 2024; Ntwari et al., 2024; Olabode et al., 2025). Moreover, due to climate change, the "fragile balance" of these ecosystems is disturbed (Noman & Zafar, 2023). The MaxEnt model for Pakistan indicated that there may be as much as a 79% loss of suitable habitat for *A. dorsata* by 2070, with an increase in the distribution of suitable habitat in the north and higher altitudes, such as Khyber Pakhtunkhwa (Khan et al., 2025). The greatest drivers of this habitat loss are the rise in temperature in the wettest quarter, and patterns of precipitation in the warmest quarter (Khan et al., 2025). Such changes pose threats to the bees as well as the crops valued at 1,590 million US$ in Pakistan, which rely on bees for pollination such as strawberries, pumpkins, and tomatoes (Ali et al., 2014; Bashir, 2019; Sajjad et al., 2023). These risks are further increased by deforestation and the loss of mature nesting trees (Oldroyd & Nanork, 2009). The loss of tall timber needed for the nesting of *A. dorsata* is due to the conversion of primary forest to short cycle forestry or urban areas. Deforestation in provinces such as Khyber Pakhtunkhwa has a direct correlation with the decreasing population of honey bees and socio-economic losses for communities that depend on honey production (Noman & Zafar, 2023; Hamzah et al., 2024; Mose et al., 2024; Mohanty et al., 2025).

Patterns seen in Pattoki are similar to patterns for *A. dorsata* populations found in South and Southeast Asia. The results of the present study are similar to those on the nesting behaviour of *A. dorsata* reported in Karnataka, where colonies were found most commonly in trees during the winter months and rock cliffs during the summer months, but the total lack of human-made structure nesting in Pattoki is different from the Indian landscape where up to 27.43% of colonies were found on buildings. The preferences of *Syzygium cumini* and *Ziziphus mauritiana* were also observed in other parts of India such as New Delhi, where *S. cumini* was identified as a preferred nesting site of other indigenous bee species, which also depicts the importance of the plant in the region (Thomas et al., 2009; Mir et al., 2023; Hadimani et al., 2024; Modu et al., 2024; Sihag, 2025; Rahimi et al., 2026).

A critical suitability factor is proximity to water, as bees need water in hot summer weather to keep the nest cool, and for hydration. As Ramsey et al. mentioned, there can be as much as a 2 °C difference between the regional weather station data and actual measurements taken locally at nest sites, so future studies should consider using local sensors at the nest locations to account for fine-scale variation in the environment. The situation of wild pollinator decline is a "One-Health" issue which impacts biodiversity, food security, and human livelihoods (Ramsey et al., 2018; Munir et al., 2024). The concept of the 'holobiont' (treating the bees as a whole, including the microbiota) may provide a more detailed understanding of the effects of stressors such as pesticides and microplastics on the fitness of *A. dorsata* in Pakistan.

Conclusion

The findings of the present study revealed the adaptability and vulnerability of *A. dorsata* as a pollinator, emphasizing the need for conservation efforts to safeguard its populations in the region. Maximum colony retention in spring is related to the optimum temperatures, and the steep drop in the winter is a response to the environmental stress and migratory behaviour. The strong avoidance of non-forested habitats, coupled with strong preference for forested habitats and certain host tree species (i.e. *Ziziphus mauritiana* and *Syzygium cumini*) underlines the importance of conservation of native vegetation in agricultural landscapes. The vertical stratification between tree architecture showed that *A. dorsata* is maximizing the avoidance of predators and microclimatic stability. But the species faces many challenges in Pakistan for its long-term survival due to multiple threats including pesticide exposure, loss of habitat, and reduction of suitable habitat due to climate change. Future research needs to involve local temperature and humidity sensors, at various nest heights, on several species of trees, to gain a better understanding of the bees' thermoregulatory limits. A detailed residue analysis of honey, wax and bee tissues should be conducted to quantify the effect of the use of pesticides in a particular region on health and survival of the bees. Policies should be implemented to protect indigenous trees (*Ziziphus*, *Syzygium*) for nesting and to encourage their planting in peri-urban areas.

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