Bio-Science Research Bulletin
Volume 41, Number 2
July-December 2025: P.130-138

Print version ISSN 0970 0889
Online version ISSN 2320 3161

Review Article

http://www.bpasjournals.com

Enhancing Bee Conservation: Advanced Hive Management Strategies to Support Pollinator Vitality and Combat Future Risks

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ABSTRACT
Bees represents a diverse and numerous group of nector-feeding good insects that play a vital role as pollinators for crops and wild plants. For the entirety of their lives, bees rely on floral resources for nourishment. It is nearly hard to imagine the existance of the world without bees. Bees play a crucial role in nearly all terrestrial ecosystems and serve as key pollinators for flowering plants (angiosperms), which are the most common type of vascular plants globally. They are crucial pollinators of numerous economically important crops such as watermelons, pumpkins, squash, grapefruits, apples, coffee, tomatoes, and sunflowers. Bumble bees, together with managed honeybee species, offer essential pollination facilities to a diverse array of farming and native plants species across the Himalayan region. Consequently, they are considered one of the most crucial pollinator species in the area. Projections suggest that by around 2050, bumble bees will face increased threats and may find themselves in less favorable habitats, based on comparisons among nine bumble bee species. To reduce risks and improve the conservation of these essential pollinators, it is crucial to investigate and apply advanced hive management techniques. Specifically, using different types of hives—such as grass hives, wall hives, Langstroth hives, and modern hives—can significantly support both bumblebees and honeybees. By investing in research and innovation in hive designs, we can more effectively protect these vital pollinators from the negative impacts of environmental changes and habitat loss.

KEYWORDS: Hives, Environment, Bumble bee, Pollination, Ecosystem.

Received on 03.09.2025, Revised on 17.10.2025, Accepted on 25.11.2025

How to cite this article: Chaudhary N., Panwar S., Tyagi A. and Kumar P. (2025). Enhancing Bee Conservation: Advanced Hive Management Strategies to Support Pollinator Vitality and Combat Future Risks. *Bio-Science Research Bulletin*, 41(2), 130-138.

INTRODUCTION

Bees are considered to be originated approximately 120 million years ago, during the early Cretaceous period. They are inter-related to predatory wasps, they are ancestor of bees. Although bees have many life history traits in common with sand wasps, they have developed several unique morphological and behavioral characteristics. Notably, bees are typical herbivores in nature and consumes pollen/nectar from flowers, while sand wasps are typical carnivores and provide insects and spiders as main source of protein for their young. They gather resources while the adults are busy—during this period, non-parasitic female bees gather nectar and pollen for their young, while both male and female bees across all species feed on nectar, and sometimes pollen, for their own nourishment (Ogilvie & Forrest, 2017). Bees exhibit species-specific foraging patterns and, with the exception of cleptoparasitic species, typically display central-place foraging behavior (Baude *et al.,* 2016). These traits, coupled with restricted foraging distances (Bukovinszky *et al.,* 2017), outline the time and area of floral resources available to bees. The duration of bee flight seasons can vary greatly, lasting anywhere from a few weeks to several years, and often differs between males and females, as well as among different castes within species. Bees play a crucial role in nearly all terrestrial ecosystems, serving as key pollinators for flowering plants (angiosperms), which are predominant in the global vascular plant community. With over 16,000 identified species, bees have an evolutionary lineage that dates back to the early Cretaceous period, a time marked by significant diversification of angiosperms. It is discovered that bees and angiosperms co-evolved, with bees' diversification possibly driving the diversification of angiosperms and *vice- versa*. Today, bees are vital for ecosystems, pollinating a wide range of plants in both natural and farming settings. They are particularly important for the pollination of valuable crops like apples, watermelons, pumpkins, grapefruits, squash, coffee, tomatoes, and sunflowers. Their role has substantial economic and ecological significance. However, bee populations are declining mainly due to intensified farming practices and habitat loss, which includes a reduction in forage resources and nesting sites (Mokkapati *et al.,* 2024; Pellaton *et al.*, 2024; Chen *et al.,* 2025; Jandt *et al.,* 2025). This reflects a shift from a 'sweet world,' where pollinators were mainly restricted by predators, parasites, and diseases from above, to a 'bitter reality,' where their constraints are now predominantly determined by the availability of floral resources from below (Roulston & Goodell, 2011). In India, it is projected that by around 2050, bumble bees and honeybees will encounter substantial threats, which could make conservation efforts increasingly challenging.

Evolution of Bees

Honey Bees are thought to have originated approximately 120 million years ago during the Early Cretaceous period. They are closely related to predatory sand wasps, from which they evolved. While bees and sand wasps share many life history traits, bees have developed several unique morphological and behavioral characteristics. Unlike sand wasps, which are carnivores that feed their young insects and spiders for protein, bees are herbivores, subsisting on pollen and nectar from flowering plants. Notable features of bees include their finely branched, plumose hairs and the expanded hind basitarsus (a segment of the hind leg) found in females. These and other bee characteristics are specifically adapted for collecting pollen instead of capturing invertebrate prey.The superfamily Apoidea comprises bees and the wasp families Heterogynaidae, Ampulicidae, Sphecidae, and Crabronidae (Figure 1).

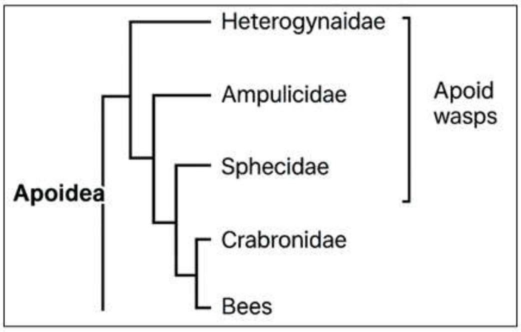

Figure 1: Family phylogeny of the bees

Species of Bees

Although Bees are famous for their social interaction but only few are noticed with these features as, most of the bees are studied like to have solitary nature. It is estimated that only about six percent of bee species are eusocial. Most bees either nest solitarily or are cleptoparasites, preying on other solitary nesters. For instance, solitary bees like Colletes, Dasypoda, Calliopsis, and Anthophora typically have a univoltine life cycle.

Apis mellifera and *Bombus terrestris* (social bee species) and *Osmia bicornis*, *Osmia cornuta*, *Andrena vaga*, *Colletes cunicularius*, and *Megachile rotundata* (solitary bee species) are native to Central Europe and showed a range of characteristics and life history traits (Figure 2). These bee spcies are known to pollinate both farming and native plant species (Westrich, 2019; Amiet & Krebs, 2019).

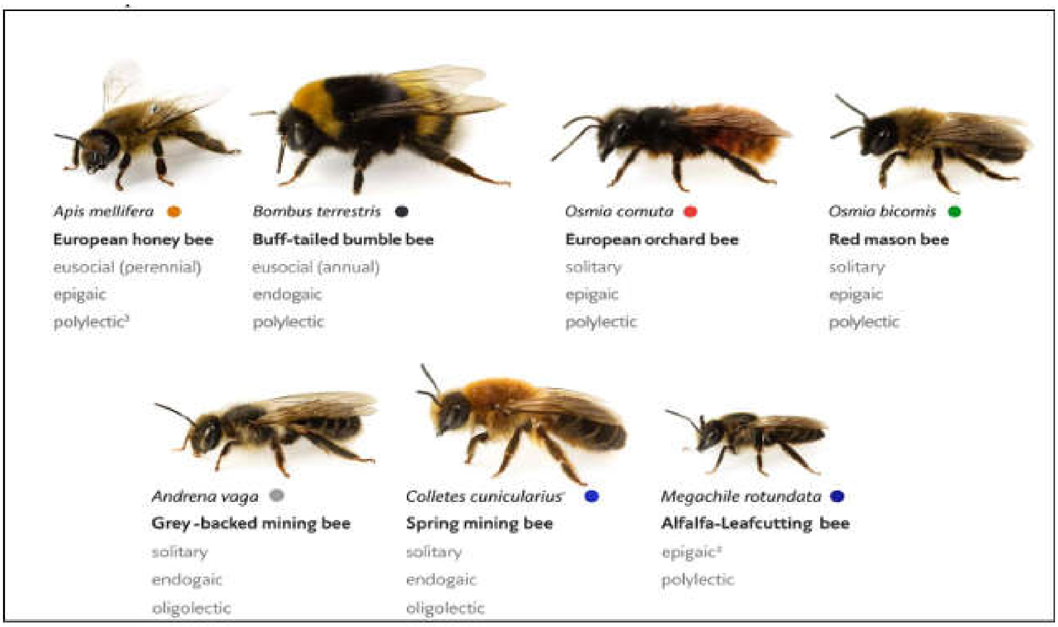

Figure 2: Scientific and common nomenclature of bee species

Bumble bees (*Bombus terrestris*)

These bees are large, colorful, and primitively eusocial, with over two hundred and fifty known species found worldwide (Williams, 2008).

Bumblebees typically forage in cold and temperate environments at higher elevations, which are less suitable for honeybees and solitary bees (Hernandez *et al.*, 2025).

As a result, they play a significant role as pollinators, particularly in alpine environments (Yu & Wang, 2012). Bumblebees (*Bombus* spp.) are effective pollinators in greenhouses, thanks to their specialized behavior, particularly "buzz pollination." In India, 48 species of the genus *Bombus* have been documented, with 30 of these species found in the Kashmir, Himalaya (Williams, 2008). So far, bumblebee compositions have been extensively studied in the Western and Central Himalayas, but the eastern Himalayan range has received limited attention, with only a few species reported. Northeast India, a biodiversity hotspot with varied ecological conditions and diverse flora, offers a favorable habitat for bumblebee species. Systematic research on pollinator diversity and insect-plant interactions is crucial for protecting and preserving the region's native vegetation. In recent years, bumblebee species worldwide have been facing decline, with contributing factors likely including the spread of pathogen from commercial breeding and changes in farming practices and land use (Cameron *et al.,* 2011; Jacobson *et al.,* 2018). Climate change also threatens many bumblebee species by reducing the availability of suitable habitats.

Figure 3: A bumble bee working as a pollinator

Honeybee (*Apis mellifera*)
The European honeybee, *Apis mellifera*, is a remarkable pollinator, among the relatively few where evolution has led to the development of an advanced social structure (Wilson & Holldobler, 2005). The notorious African "killer" bees (*Apis mellifera scutellata*) were introduced to Brazil in 1956 (Sheppard *et al.,* 1999). Killer bees are renowned for their aggressive stinging behavior when defending their nests, these bees pose health risks to humans and have spread across the New World, representing a striking example of biological invasion. This was one of the first instances of biological invasion to be examined using molecular tools, and the genetic aspects of this invasion have been a topic of debate (Smith & Brown, 1988). The *A. mellifera* genome exhibits unique features that offer intriguing insights into honeybee biology. It exhibites greater similarities to vertebrate

genomes than to those of *Drosophila* and *Anopheles* in genes associaated with circadian rhythms, RNA interference (RNAi), and DNA methylation, among other factors.

Behavior of bees

Bumblebees are found to be more effective foragers than honeybees on cranberry flowers, largely because they can perform buzz-pollination. They grasp the flower and vibrate their flight muscles to help release the pollen. These are the most efficient pollinators not only for wild plants but also for commercial pollination services, including those used in outdoor and greenhouse horticulture and orchards (Wolf & Moritz, 2008).

Natural beehive structure

A group of bees is referred to as a "colony," and the place they inhabit is known as a "hive." A beehive is essentially any structure designed for honeybees to settle in, functioning as their home and a nursery for raising their young. In nature, honeybees use any suitable cavity for nesting, such as tree hollows, rock crevices, and caves. The modern hive, which has evolved through centuries of human innovation, comes in many shapes and forms. Modern apiculture uses several types of hives. However, contemporary beekeeping faces three significant issues: (i) Honeybees in bee hives experience anxiety and noticed stress free in nature; (ii) Domesticated colonies, lack in genetic fitness and frequently maintained despite the potential for perpetuating undesirable genes; and (iii) Housekeeping tasks, often neglected due to emerging pests, are either left undone or end up adding for the worker bees as workload. Cultivated Bee colonies underwent the most significant changes between the year 1500 to 1851.

Before the advent of improved hives, honey bees were used to housed in primitive styled hives that were quite effective for wild honeybees. However, to extract honey, the bees were typically asphyxiated (suffocated). A typical colony of honeybees consists of approximately 14,000 to 25,000 individuals (Seeley & Morse, 1976). Since the introduction of movable beehives for *Apis mellifera*, beekeepers have employed various strategies to improved populations around 60,000 individuals (Farrar, 1968). The techniques involve expanding the space for offspring (e.g., increasing cavity size), reversing the brood nest, providing supportive feeding, and breeding honeybee units to enhance the production. In honeybees, the establishment of the colonies and levels of honey production depend on the type of hive used (Ande *et al.,* 2008), Open nests produce significantly less honey compared to enclosed nests. The desire to obtain extra honey additionally beeswax efficiently led humans to develop man-made beehives for honeybees, a traditional practice that used several thousand years ago (Anderson & Jones, 2002). Humans have constructed beehives that mimic the wild nests used by bees. With the rising global demand for honey, high-yield beehives have been supported and promoted. Nonetheless, these beehives can be prohibitively costly for many rural people, particularly in Africa. Consequently, study is going on, to work on improving existing hive designs or developing more affordable and efficient options.

In natural cavities, the combs that bees build stick to the hives ceiling and walls, with limited air exchange between the large, undulating combs. The "bee space," the gap between combs, is typically between 4.5 and 8 mm, though reports also cite ranges from 6 to 9 mm. This measurement is not variable but rather falls within specific ranges: either 5.3 mm ± 0.5 mm or 9.0 mm ± 0.0–1.0 mm. Gaps smaller than 4 mm are consider too narrow, and Any openings, such as spaces, cracks, or crevices are packed with propolis or a mix of wax and propolis. A gap of 6 mm represents the minimum that bees will maintain between adjacent comb surfaces outside of their clustering areas, as it allows them to work individually and defend the space more effectively.

Artificial Beehives

We have designed two types of hives: grass hives and wall hives, which must meet essential criteria such as energy conversion, Indoor air quality, water control, insulation performance and adequate ventilation. A colony's survival relies heavily on cleanliness and hygienic behavior. Our goal is to encourage bees to build their nests in a manner that makes them easier for beekeepers to manage and utilize.

The Langstroth hive design build up for large size to manage population. For instance, the moveable frames create spaces that significantly alter airflow within the hive. This strength for enhancing air movement is further improved by the beekeeper's continuous efforts to ventilate the artificial hives and provide a larger access point at the bottom of the cavity. However, while the regularly spaced frames of a Langstroth hive may seem convenient for the beekeeper, they might not always meet the bees' ventilation needs effectively.

Grass Hive

Grasses are woven together to form cylindrical or conical shapes, usually featuring entrances at both ends. These hives are often utilized by certain communities and are typically placed high in tree canopies to avoid termite damage, promote colonization, and minimize the risk of fire damage. At harvest time, beekeepers typically lower the hives carefully, although some may drop them haphazardly by cutting the suspension rope. Due to the fragile nature of the materials, these grass beehives generally last less than a year (Adjare, 1990), and it is common for beekeepers to discard them after a single harvest shown in figure 4.

Figure 4: Traditional hive of bees

Wall Hive

Wall hives are integrated into constructed walls, which are typically made up of stones and pebbles (either dry or mortared), brick, or dried mud reinforced with straw (Figure 5). These hives are usually rectangular, which is often the simplest designed to build. Free-standing wall hives were historically limited to regions where thick walls could be constructed from available materials, where rainfall was low, and where land boundaries were defined by walls than hedges or bushes. Artificial hives, as well as the carved into soft rock, are found only in regions with mild winters that allow to survive the colonies to survive in stone or rock cavities.

Figure 5: Wall hive is a recess built into a wall

Wall hives are considered to have a more lifespan due to their enhanced security against stolen and exploitation by animals and they can be cost-effective where suitable building materials are readily available.

Modern beehives

Modern beehives have lower usage in continent like Africa where they create less than 30 % of beehives used in most countries. In other continents Europe, America and Asia, such hives form the large number of hives (96.8 % in Turkey) (Sirali, 2002). The structure of modern beehives is based on Lorenzo Lorraine Langstroth's discovery that bees consistently maintain a specific space, called as the bee space, in-between their combs. Utilizing this insight, Langstroth created a hive with frames spaced according to this bee space, allowing bees to build their combs efficiently. Modern beehives are usually constructed in rectangular or square structured, offering good air flow and not being restricted by floors or ceilings. The frames are designed to be removable individually without disturbing other combs or crushing bees, while also providing excellent support for the combs.

Several beehive boxes can be stacked on top of each other, and a queen excluder can confine the queen to the brood chamber. This setup ensures that only workers can access the upper chambers, which are thus reserved for honeycombs (Oluwatusin, 2008). The strong frames facilitate easy hive inspection and management. Consequently, almost all commercial hives today follow the Langstroth design, although they may have between 10 to 13 frames. While movable-frame hives are used for keeping oriental honeybees, their success varies, largely due to the bees' biological characteristics rather than the hive design or size.

Langstroth Hives

Langstroth hives are known for producing extra honey with being more profitable in modern artificial beekeeping (Oluwatusin, 2008). Their design features movable frames that facilitate inspection for potential parasites and diseases. This design also allows beekeepers to easily perform queen rearing and other necessary manipulations.

CONCLUSION

Although global honey production has enhanced over the last 50 years, the growth is uneven and underscores the need for stable, bee-friendly environments. Traditional hives, especially in Africa, pose limitations in colony management and productivity. India could strengthen pollinator conservation—particularly for bumblebees—by adopting proven designs such as wall hives and Langstroth hives. Despite their benefits, even advanced hives do not eliminate the challenges bees face from environmental stressors, highlighting the need for continuous innovation in hive design and management. Advancing hive technology and implementing evidence-based management strategies will be essential to sustaining bee populations and safeguarding ecosystem stability.

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