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Beekeeping as a Sustainable Enterprise: Aspects and Economic Efficiency

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Abstract

Beekeeping, one of the world's oldest apiculture practices, has transformed from ancient honey hunting into a globally significant agricultural and ecological enterprise. Historical records and archaeological evidence highlight its cultural, nutritional, and medicinal importance across civilizations, while the introduction of movable-frame hives in the 19th century marked a pivotal shift toward scientific and sustainable practices. Today, apiculture combines traditional knowledge with modern technologies such as migratory beekeeping, selective breeding, integrated pest management, and artificial intelligence-based hive monitoring to improve colony health, productivity, and pollination efficiency. Globally, annual honey production surpasses 1.8 million metric tonnes, with China, Turkey, Iran, India, and Argentina leading in output, and the United States and European Union emerging as major consumers and importers. Beyond honey, hive products including beeswax, royal jelly, pollen, propolis, and bee venom generate substantial economic value across food, pharmaceutical, cosmetic, and nutraceutical industries, contributing to the diversification of rural incomes and the expansion of high-value markets. Regionally, beekeeping supports poverty reduction, women's empowerment, and export economies in Asia and Africa, while Europe emphasizes pollinator protection policies and the Americas focus on large-scale pollination services vital for commercial agriculture. Ecologically, honey bees function as keystone pollinators, ensuring biodiversity conservation, crop productivity, and ecosystem resilience, thereby reinforcing food and nutritional security. Economically, beekeeping is highly efficient, offering multiple revenue streams with low land and capital requirements, making it accessible to smallholders, landless farmers, and even urban communities. However, the sector faces persistent challenges, including colony losses due to pests and diseases, pesticide exposure, climate variability, habitat degradation, adulteration of honey, and inadequate institutional support. Addressing these constraints requires integrated approaches encompassing pollinator-friendly landscapes, adaptive beekeeping practices, product quality assurance, value addition, cooperative marketing, and enabling policy frameworks. Overall, beekeeping stands at the nexus of ecology, economy, and culture, representing a resilient, inclusive, and future-ready enterprise. Its potential to enhance sustainable agriculture, strengthen rural development, support biodiversity conservation, and contribute to climate change adaptation positions apiculture as a vital component of global sustainability strategies.

***Key words*:** Beekeeping, Sustainable enterprise, Bee products, Economic efficiency, Pollination

Beekeeping, or apiculture, is one of the oldest agricultural practices known to humankind, dating back thousands of years. Traditionally pursued for honey and beeswax production, it has now evolved into a globally recognized bio-resource enterprise with significant ecological, economic, and social importance [1]. In recent decades, beekeeping has emerged as a crucial livelihood activity and environmental service, receiving renewed global attention for multiple reasons. Traditionally, beekeeping was valued primarily for the production of high-value natural commodities such as honey, beeswax, royal jelly, propolis, pollen, and bee venom, each of which has distinctive nutritional, medicinal, and industrial applications [2]. Honey is consumed worldwide not only as a natural sweetener but also for its antimicrobial and antioxidant properties, while beeswax is widely used in cosmetics, pharmaceuticals, and candle-making. Royal jelly and bee venom are gaining importance in nutraceuticals and alternative medicine for their therapeutic potential, whereas propolis and pollen are recognized for their bioactive compounds that support human health [3-4]. The growing consumer demand for natural and organic products has further enhanced the market value of these bee-derived substances, positioning apiculture as a profitable enterprise for both smallholder farmers and commercial producers [5].

Beyond product-oriented benefits, beekeeping plays an indispensable ecological and agricultural role through the pollination services provided by bees [6-7]. Pollination is a fundamental ecosystem service that ensures the reproduction of a wide variety of flowering plants, including many food crops. Studies indicate that nearly one-third of the global food supply depends directly or indirectly on pollinators, with bees being the most efficient agents [8-9]. Pollination by bees enhances not only the quantity of crop yields but also the quality of produce, improving attributes such as fruit size, seed viability, and

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nutritional content [10]. Crops like fruits, vegetables, oilseeds, legumes, and nuts benefit substantially from bee activity, directly contributing to global food and nutritional security. Furthermore, bee pollination underpins the survival of wild plants, thereby maintaining biodiversity and ecosystem resilience, which in turn supports soil health, water regulation, and climate balance [11]. The resurgence of interest in beekeeping is also tied to broader concerns about environmental sustainability and biodiversity conservation [12]. With alarming reports of pollinator decline due to habitat loss, pesticide use, climate change, and diseases, beekeeping has been recognized as both a mitigation strategy and a conservation tool. By promoting beekeeping, rural and peri-urban landscapes can be enriched with flowering plants and diversified agroecosystems, creating habitats that support not only honey bees but also wild pollinators. This synergistic relationship strengthens ecological balance and safeguards biodiversity [13-14].

From a socio-economic perspective, beekeeping offers inclusive livelihood opportunities, particularly in rural areas where land and resources are limited. Unlike many agricultural enterprises, beekeeping requires relatively low capital investment and land ownership, making it accessible to marginalized groups, including women and landless farmers [15]. It also integrates well with existing farming systems, providing an additional income stream without competing for land or water resources. This multifunctionality of apiculture makes it a sustainable enterprise model, aligning with global development goals related to poverty reduction, food security, gender empowerment, and environmental protection [16]. The renewed attention towards beekeeping reflects a holistic appreciation of its economic, ecological, and social value. It is no longer viewed solely as a source of honey or wax but as a pillar of sustainable agriculture and biodiversity conservation. By strengthening pollination services, enhancing rural livelihoods, and ensuring the availability of high-value natural products, beekeeping stands out as a vital strategy for addressing the intertwined challenges of food security, environmental degradation, and climate resilience in the 21st century [17-18].

Morphology of honey bee (Apis spp.)

The honey bee, belonging to the genus *Apis* (family Apidae), exhibits a well-differentiated body plan that is typical of insects, consisting of three main regions: head, thorax, and abdomen, each specialized for survival, foraging, and colony activities.

Head: The head bears a pair of large compound eyes for detecting movement and light, and three small ocelli (simple eyes) for orientation. The antennae, segmented and highly sensitive, function as primary sensory organs for smell, taste, and touch. The mouthparts are of chewing-lapping type: the mandibles help in wax manipulation, comb building, and defense, while the proboscis (tongue) is adapted for sucking nectar.

Thorax: The thorax is the locomotory center, consisting of three segments, each bearing a pair of legs. Thus, bees possess six legs adapted for different functions: the forelegs clean the antennae, the midlegs assist in handling pollen, and the hind legs have specialized structures such as pollen baskets (corbiculae) for carrying pollen. Two pairs of membranous wings are attached to the meso- and metathorax; these are coupled during flight by tiny hooks called hamuli, enabling efficient and powerful flight.

Abdomen: The abdomen is segmented and contains vital internal organs. The wax glands (in worker bees) secrete wax used in comb construction. The sting apparatus is present in worker bees and the queen, functioning as a defense mechanism (workers have barbed stings, while the queen has a smooth sting for rival queens). The abdomen also houses the digestive, excretory, and reproductive organs. In worker bees, the reproductive system is rudimentary, while in queens it is fully developed, and in drones it is specialized for mating.

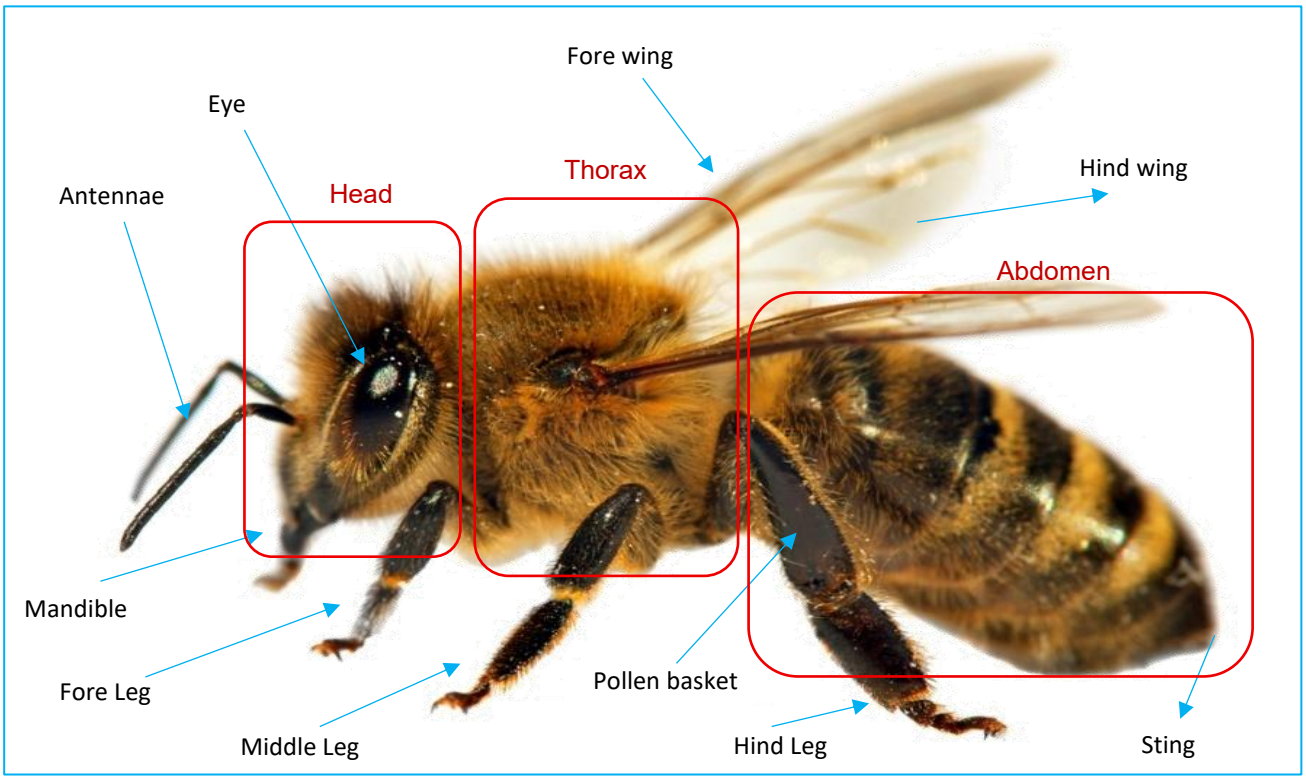

Fig 1 Morphology of a worker honey bee

Bees, as primary pollinators, play a vital role in ensuring food security and ecosystem stability, thereby positioning beekeeping as a sustainable livelihood option in both rural and urban landscapes [19]. Honey bees (*Apis spp*.) are among the most efficient and economically important pollinators on earth [20]. Their foraging behavior, visiting a wide diversity of flowering plants, makes them indispensable agents in natural ecosystems as well as in agricultural production systems [21]. Globally, it is estimated that about 75% of major food crops benefit, at least in part, from animal pollination, with bees accounting for the majority of this service. By facilitating the transfer of pollen grains, honey bees enhance fertilization, seed development, and fruit set, thereby contributing to higher yields, better quality produce, and genetic diversity in plants [22]. This directly influences food availability, nutritional quality, and agricultural profitability, placing bees at the core of food security strategies [23].

Beyond direct agricultural benefits, honey bees are equally important for the maintenance of ecosystem stability. Pollination ensures the regeneration of wild plant populations, which support herbivores, predators, and decomposers within ecological food webs. A stable pollination system helps maintain floral diversity, prevents the collapse of plant populations, and contributes to the resilience of ecosystems against environmental stresses. In times of climate change and habitat fragmentation, pollination by honey bees becomes even more crucial to sustaining ecosystem services that humans depend on such as soil fertility, water regulation, and carbon sequestration [24]. This ecological significance of honey bees has profound implications for sustainable livelihoods. Beekeeping, or apiculture, represents a nature-based solution that leverages the ecological role of bees for economic and social gain. Unlike many agricultural practices, beekeeping requires relatively low land and capital investment, making it accessible to smallholder farmers, women, and marginalized groups. It can be practiced on a small scale in rural areas as an additional source of income, or even in urban environments where rooftop and backyard beekeeping are increasingly popular due to the availability of flowering plants in city gardens and parks [25]. Moreover, beekeeping is not land-intensive and can be integrated with crop farming, horticulture, and forestry, creating synergies between pollination services and agricultural productivity [26].

The products derived from bees honey, beeswax, royal jelly, pollen, propolis, and bee venom provide multiple income streams with significant market demand in food, pharmaceuticals, and cosmetics industries [27]. Beyond commercial value, the presence of honey bees contributes indirectly to farmers' income stability by enhancing crop yields and reducing dependence on external inputs such as synthetic fertilizers. In rural landscapes, beekeeping strengthens community resilience, supports biodiversity conservation, and provides opportunities for sustainable enterprise development [28]. In urban landscapes, it promotes environmental awareness, enhances green spaces, and contributes to reconnecting people with nature. Furthermore, promoting beekeeping aligns with global sustainability goals. It addresses SDG 2 (Zero Hunger) by improving agricultural productivity, SDG 1 (No Poverty) by generating income opportunities, and SDG 15 (Life on Land) by safeguarding biodiversity. It also contributes to climate adaptation by stabilizing ecosystems and enhancing agricultural resilience to changing weather patterns [29]. Honey bees are not merely producers of honey but keystone species that underpin agricultural success and ecological integrity. Their role as primary pollinators directly supports food security and ecosystem health. Beekeeping, therefore, is more than an economic activity it is a sustainable livelihood strategy that bridges ecological conservation with socio-economic development in both rural and urban settings. Strengthening policies, research, and community initiatives in apiculture is thus essential to safeguard pollinators and harness their full potential for a secure and sustainable future [30].

The economic potential of beekeeping lies in its dual role

Direct income generation through marketable hive products and indirect enhancement of crop yields through pollination. Studies have shown that the economic value of pollination services often surpasses the revenue derived from hive products alone [31]. Furthermore, the growing global demand for organic and natural health products has expanded market opportunities for honey and other bee-derived substances, creating avenues for entrepreneurship, export trade, and small-scale rural industries. For resource-poor farmers, landless laborers, and women in particular, beekeeping provides a low-cost, low-input enterprise that can be integrated with existing farming systems, thereby contributing to poverty alleviation and rural development [32]. From a sustainability perspective, beekeeping offers multiple advantages. Unlike many intensive agricultural practices, it requires minimal land, does not deplete natural resources, and instead promotes ecological balance by supporting pollinator diversity [33]. Moreover, the adaptability of honey bees to diverse climatic and floral conditions allows beekeeping to be practiced across a wide range of geographical regions, from temperate to tropical zones. Its compatibility with agroforestry, horticulture, and organic farming makes it a complementary enterprise that enhances overall farm productivity and resilience [34]. Beekeeping is increasingly recognized as a model of sustainable agricultural practice because it harmonizes economic, ecological, and social dimensions of development. Unlike conventional farming systems, which often depend heavily on land, irrigation, synthetic fertilizers, and pesticides, beekeeping is a low-resource enterprise [35]. Honey bees do not consume crops or compete with humans for food; instead, they rely on nectar and pollen, which are naturally replenished by flowering plants [36]. This characteristic makes apiculture inherently non-extractive and environmentally benign, thereby contrasting with many intensive farming methods that degrade soil, deplete water, or contribute to biodiversity loss. One of the most important sustainability features of beekeeping lies in its positive ecological footprint [37]. By supporting pollination, honey bees enhance the reproduction of both cultivated and wild plant species. This not only increases agricultural productivity but also contributes to maintaining pollinator diversity, as managed honey bee colonies coexist with wild bees, butterflies, and other insects [38]. In landscapes where monocultures and pesticide use have reduced biodiversity, beekeeping acts as a restorative practice, fostering ecological balance and ensuring the survival of key pollinator communities [39].

Another advantage is the adaptability of honey bees. They thrive in a wide spectrum of climates and habitats, from temperate orchards and alpine meadows to tropical forests and dryland ecosystems. Their flexibility in foraging behavior enables them to utilize diverse floral resources, making beekeeping feasible across regions with different ecological characteristics [40]. This adaptability has allowed apiculture to become a globally distributed livelihood activity, contributing to rural incomes in Africa, Asia, Europe, and the Americas alike. Importantly, honey bees can be reared in both rural and urban landscapes, further demonstrating the scalability and inclusiveness of beekeeping as a sustainable enterprise.

Beekeeping also integrates seamlessly with other forms of land use, making it a complementary enterprise rather than a competitive one. In agroforestry systems, bees enhance pollination of fruit trees, fuelwood species, and timber crops, thereby improving productivity and regeneration rates. In horticulture, crops such as cucurbits, apples, almonds, and citrus fruits benefit significantly from bee pollination, which increases yield and fruit quality [41-42]. Within the context of organic farming, where synthetic inputs are avoided, honey bees provide a natural pollination service that is consistent with ecological principles and enhances farm biodiversity. This synergy between beekeeping and other farming systems improves not only crop output but also the resilience of agricultural landscapes to environmental stresses, including climate variability [43].

From a socio-economic angle, the sustainability of beekeeping is reinforced by its low environmental cost and high livelihood potential. It does not demand deforestation, water diversion, or large-scale mechanization; instead, it thrives on preserving and planting flowering vegetation, which in turn enriches ecosystems [44]. Moreover, because beekeeping requires relatively low capital investment, it provides a viable income source for smallholders, women, and landless farmers, thereby promoting social inclusion and poverty reduction [45]. The diversification of farm enterprises through beekeeping also reduces economic risks for farmers by spreading income sources across crop yields and bee products such as honey, wax, propolis, and royal jelly. Beekeeping exemplifies a sustainability-oriented livelihood practice that aligns environmental conservation with agricultural productivity [46]. By requiring minimal land, conserving rather than depleting resources, supporting biodiversity, and adapting to diverse ecological contexts, it offers a replicable and scalable model for sustainable development. Its compatibility with agroforestry, horticulture, and organic farming further enhances the resilience of agricultural systems, positioning apiculture as a cornerstone of climate-smart, ecologically sound, and socially inclusive rural development [47]. Despite these benefits, challenges such as climate change, pesticide exposure, habitat degradation, disease outbreaks, and fluctuating market conditions threaten the sustainability and profitability of apiculture. Addressing these issues through scientific innovation, policy support, and improved management practices is essential to ensure that beekeeping continues to thrive as an economically efficient and environmentally sustainable enterprise [48]. While beekeeping is widely recognized for its ecological and economic value, the sector faces multi-dimensional challenges that directly impact bee health, productivity, and beekeeper livelihoods. These challenges stem from environmental, biological, and socio-economic factors, many of which are interlinked and exacerbate one another. One of the most pressing threats is climate change, which alters flowering cycles, nectar secretion, and the synchronization between plant blooming and bee foraging. Unpredictable weather patterns such as prolonged droughts, unseasonal rains, and extreme temperatures reduce forage availability, leading to colony stress and reduced honey yields [49]. Climate-induced shifts also affect the distribution of pests and pathogens, creating new risks for apiculture [50].

Pesticide exposure is another critical challenge, especially in regions with intensive farming. The widespread use of systemic insecticides such as neonicotinoids has been linked to colony collapse, reduced foraging efficiency, impaired navigation, and weakened immune systems in bees. Sublethal pesticide exposure can reduce brood survival and compromise the resilience of colonies, ultimately reducing both honey production and pollination services. This issue is compounded by the lack of awareness among farmers who may apply chemicals indiscriminately during flowering periods when bees are most active [51-52].

Habitat degradation further undermines apiculture sustainability

Urban expansion, deforestation, and the replacement of diverse ecosystems with monocultures have drastically reduced the availability of natural forage and nesting sites for pollinators [53]. Habitat fragmentation not only limits floral diversity but also shortens the foraging season, forcing bees to rely on artificial feeding or migrate long distances. This reduces the ecological resilience of colonies and increases management costs for beekeepers. Equally concerning are disease outbreaks and pest infestations, which threaten colony survival. Pathogens such as *Nosema spp*., viruses like Deformed Wing Virus (DWV), and parasites such as the Varroa destructor mite are among the most devastating threats to honey bee health worldwide [54]. The spread of these diseases is accelerated by globalization and the movement of colonies across regions for migratory beekeeping. Managing these biological threats requires constant vigilance, timely diagnosis, and the adoption of integrated pest and disease management strategies. Beyond biological and ecological challenges, fluctuating market conditions also affect the profitability of apiculture. Prices of honey and other bee products are highly volatile due to global trade dynamics, adulteration scandals, and competition from low-quality imports. Small-scale beekeepers often lack access to stable markets, value addition technologies, and certification systems that could enhance profitability [55]. As a result, economic instability discourages new entrants into beekeeping and threatens the long-term viability of the sector.

To overcome these challenges, multi-pronged interventions are essential

Scientific innovation such as the development of disease-resistant bee strains, improved hive designs, biopesticides, and precision beekeeping technologies (e.g., sensors, digital monitoring, and AI-based decision tools)—can enhance colony health and productivity [56]. Policy support is equally important; governments can provide subsidies for equipment, regulate pesticide use, promote pollinator-friendly landscapes, and facilitate market access through cooperatives and certification schemes. Improved management practices at the beekeeper level, including diversified forage planting, integrated pest management, seasonal migration planning, and hygienic hive maintenance, are also critical for resilience. While apiculture holds immense promise as a sustainable and profitable enterprise, its future depends on proactive responses to emerging threats [57]. By combining scientific research, supportive policies, and practical innovations, beekeeping can be safeguarded against current challenges and positioned as a cornerstone of sustainable agriculture, biodiversity conservation, and rural development [58-60].

Historical and global perspective of beekeeping

Origin and evolution of apiculture

The practice of beekeeping dates back thousands of years and is one of the earliest forms of animal husbandry known to humankind. Archaeological evidence from cave paintings in Spain (dating to around 9,000 years ago) depicts humans harvesting honey from wild bee colonies, highlighting the ancient cultural and nutritional value of honey. Ancient civilizations, including the Egyptians, Greeks, Romans, and

Mayans, practiced forms of beekeeping, often using primitive clay pots, straw skeps, or hollowed tree trunks as hives [61]. Honey was not only a source of food and medicine but also played symbolic and religious roles. The Egyptians valued honey for embalming and ritual purposes, while in Vedic and Greek traditions, honey was considered "the food of the gods." Early apiculture was largely extractive, often destroying bee colonies to harvest honey and wax. The evolution of apiculture took a significant turn with the invention of the movable-frame hive by Lorenzo Langstroth in 1851, which allowed honey extraction without killing the bees. This innovation revolutionized beekeeping by enabling sustainable hive management, selective breeding, and large-scale honey production. Since then, apiculture has advanced into a scientifically managed agricultural enterprise, integrating modern technologies and practices to enhance productivity, bee health, and pollination services [62].

Traditional vs. Modern beekeeping practices

Traditional beekeeping practices vary across cultures and regions, often relying on fixed-comb hives such as clay pots, log hives, bamboo tubes, or mud structures. These systems are low-cost and locally adapted but limit colony management, disease control, and honey yield. Harvesting in traditional systems often involves destroying the colony, which is neither sustainable nor economically efficient. In contrast, modern beekeeping employs movable-frame hives (Langstroth, Dadant, Top-bar hives, etc.), which allow regular inspection, pest management, queen rearing, and honey extraction without harming the colony [63]. Techniques such as migratory beekeeping, artificial feeding, integrated pest management (IPM), and selective breeding of queens have further improved colony survival and productivity. Additionally, modern apiculture incorporates precision technologies such as hive monitoring sensors, AI-based colony health diagnostics, and climate adaptation strategies. The transition from traditional to modern practices reflects the shift from honey hunting and subsistence beekeeping toward commercialized, sustainable, and pollination-focused apiculture, aligning with global food security and biodiversity goals [64-65].

Trends, growth dynamics, and economic implications of honey production in India (2012–2024)

Over the past decade, honey production in India has exhibited a consistent upward trajectory, rising from 72.30 thousand MTs in 2012–13 to 155.65 thousand MTs in 2023–24, reflecting an overall increase of more than 115% and nearly doubling production. Growth rates, however, have shown variability: while the early years (2012–15) recorded moderate growth of 5–6% annually, a sharp spike was observed in 2015–16 (10.39%), likely due to improved beekeeping practices, policy support, and heightened awareness. The period from 2017–18 to 2020–21 marked a particularly dynamic phase, with double-digit growth culminating at 15% in 2020–21 the highest in the series after which growth stabilized at around 4–5% (2021–24), suggesting market consolidation, seasonal constraints, or production saturation. Parallel to production, the estimated economic value rose from ₹1027 Cr in 2012–13 to ₹2211 Cr in 2023–24, an increase of nearly 115%, reflecting stable pricing, consistent demand, and potential benefits from organic and medicinal honey markets as well as exports. This trajectory underscores the dual benefits of honey production: it not only supports food security and nutritional diversification but also strengthens rural livelihoods and export competitiveness, while sustaining pollinator populations vital for ecosystem health. In summary, although India's honey sector has achieved substantial growth, sustaining momentum will require technological interventions, product diversification, and stronger market linkages to avoid stagnation and to ensure long-term sustainability.

Table 1 Year-wise details of honey production for last 10 years (2016-17 to 2020-21)

S. No.	Year	Production (Metric Tonns)	Growth (%)	Estimated value (Rs. Cr)
1	2012-13	72.30	5.00	1027
2	2013-14	76.15	5.33	1082
3	2014-15	80.53	5.75	1144
4	2015-16	88.90	10.39	1263
5	2017-18	94.50	6.30	1342
6	2018-19	105.00	11.11	1491
7	2019-20	117.60	12.00	1669
8	2020-21	135.24	15.00	1920
9	2021-22	141.10	4.34	2003
10	2022-23	148.50	5.25	2110
11	2023-24	155.65	4.81	2211

Table 2 Major exporters and importers of natural honey

Rank	Exporters	Value (US$M)	Rank	Importers	Value (US$M)
1	China	235.31	1	United States	430.08
2	New Zealand	228.77	2	Germany	249.61
3	Argentina	146.70	3	Japan	144.52
4	Germany	131.49	4	United Kingdom	139.39
5	Ukraine	113.04	5	China	111.15
6	India	100.87	6	Italy	84.90
	World Total	1,990.5		World Total	2,012.4

The global trade in natural honey reflects both strong production and rising consumption trends, with notable asymmetry between major exporters and importers. In 2020, the total world exports of honey were valued at US$1,990.5

million, while imports slightly exceeded this at US$2,012.4 million, highlighting persistent international demand. China emerged as the largest exporter, contributing US$235.31 million, followed closely by New Zealand (US$228.77 million) and Argentina (US$146.70 million), indicating the dominance of Asia-Pacific and South America in honey supply. Germany (US$131.49 million), Ukraine (US$113.04 million), and India (US$100.87 million) also featured prominently, reflecting Europe's and South Asia's significant roles in the global honey market. On the import side, the United States was the single largest consumer with US$430.08 million worth of imports, followed by Germany (US$249.61 million), Japan (US$144.52 million), and the United Kingdom (US$139.39 million), underscoring the high demand in developed economies. China (US$111.15 million) and Italy (US$84.90 million) also ranked among the top importers, suggesting that even key producers like China maintain substantial import volumes to meet domestic needs or diversify honey varieties. Collectively, this pattern illustrates the globalization of the honey trade, where surplus-producing nations in Asia-Pacific and South America supply to high-demand regions in North America and Europe, while emerging exporters like India consolidate their position in international markets.

Global honey production and trade statistics

Honey is one of the most widely traded natural products globally. According to FAO statistics (2022–2023):

- Global honey production is estimated at 1.8–1.9 million metric tonnes annually.
- Top producers include China (28–30% of world production), followed by Turkey, Iran, India, Argentina, and Ukraine.
- The United States, European Union, and Middle East are among the largest importers, driven by rising domestic consumption and limited local production.
- Beyond honey, hive products such as beeswax, royal jelly, propolis, and bee venom also contribute significantly to international trade, with applications in food, cosmetics, and pharmaceuticals.

A major issue in global honey trade is quality assurance and adulteration control. The influx of adulterated or sugar-syrup blended honey has led to stricter testing and certification requirements in importing countries. Consequently, the market for organic, fair-trade, and certified honey is expanding, offering premium opportunities for producers adhering to quality and sustainability standards [66-67].

Regional significance of beekeeping

Asia

Asia, led by China and India, dominates global honey production. Traditional practices remain widespread, especially in South and Southeast Asia, where indigenous species such as *Apis cerana* and *Apis dorsata* are managed alongside *Apis mellifera*. In addition to honey, Asian countries emphasize pollination services for crops such as apples, mustard, and oilseeds, as well as the medicinal use of hive products in Ayurveda and Traditional Chinese Medicine [68].

Africa

Beekeeping in Africa is deeply rooted in cultural traditions, often involving log hives and honey hunting. Countries like Ethiopia, Tanzania, and Kenya are emerging as major producers of organic honey and beeswax, benefiting from relatively pesticide-free environments. Apiculture contributes significantly to rural income diversification, women's empowerment, and export trade, particularly in niche organic markets [69].

Europe

Europe has a long history of scientific apiculture, with countries like Germany, Spain, and Ukraine being leading honey producers. The European Union is a major honey importer as demand often exceeds production. EU policies emphasize pollinator protection, habitat conservation, and pesticide regulation, making beekeeping a key component of environmental policy. Additionally, apitherapy and high-value hive products enjoy strong market demand in Europe [70].

Americas

North and South America are vital players in global honey production and trade. The United States is one of the largest honey importers, while Argentina, Brazil, and Mexico are significant exporters. Migratory beekeeping is widely practiced in the U.S., especially for almond pollination in California, which represents the largest managed pollination event in the world. In South America, organic honey from forest ecosystems has strong global market appeal [71]. However, the Americas also face challenges from colony collapse disorder (CCD), pesticide exposure, and habitat loss.

The historical and global perspective of beekeeping reflects its evolution from ancient subsistence activity to a modern, commercialized, and globally significant enterprise. Its role has expanded beyond honey production to encompass pollination services, biodiversity conservation, and sustainable livelihoods. While each region contributes uniquely to global apiculture, shared challenges such as climate change, diseases, market volatility, and pollinator decline demand global collaboration, innovation, and policy support. By integrating traditional knowledge with modern practices, and aligning apiculture with sustainability goals, beekeeping is poised to remain a cornerstone of agricultural and ecological resilience worldwide [72].

Ecological aspects of beekeeping

Beekeeping is not only an economic activity but also a vital ecological practice that sustains natural ecosystems, agriculture, and human well-being. Honey bees (*Apis* spp.), being among the most effective pollinators, provide critical ecosystem services that extend far beyond the production of honey and other hive products. Their contribution to pollination, biodiversity conservation, food security, and ecosystem stability positions apiculture as an essential component of sustainable agriculture [73].

Pollination as an Ecosystem Service

Environmental pollination service is a vital ecosystem function sustained by honey bees, wild bees, and other pollinators, as they secure the reproduction of flowering plants, underpin biodiversity, and enhance agricultural productivity. To quantify the role of managed honey bees in this service, two indicators A14 (total pollinated area) and A15 (proportion of pollinated land uses) have been developed. Indicator A14 captures the overall spatial extent of land within a 3 km radius around apiaries that could benefit from pollination, reflecting the quantitative scale of influence, as larger numbers of colonies cover wider areas, including both crop fields and natural vegetation [74-75]. Complementing this, A15 emphasizes the qualitative dimension by identifying the share of pollinator-dependent land uses within the same buffer, such as farmland, urban green spaces, forests (excluding coniferous types), and

semi-natural habitats, thereby focusing on areas where pollination is most ecologically and economically relevant. The 3 km buffer is based on established scientific evidence of honey bee foraging ranges, ensuring ecological accuracy in measuring services [76]. Together, A14 and A15 provide an integrated picture: A14 highlights how much area is potentially pollinated, while A15 clarifies the significance of that land for pollination-dependent productivity. Beyond measurement, these indicators underscore the dual importance of pollinators—supporting agricultural outputs like fruits, nuts, and seeds, and conserving wild plant populations that form the backbone of terrestrial ecosystems. Their application extends to sustainable agriculture, informed beekeeping management, and evidence-based policy, offering a structured framework to recognize pollination as both an ecological necessity and an economic pillar of food security and biodiversity conservation [77].

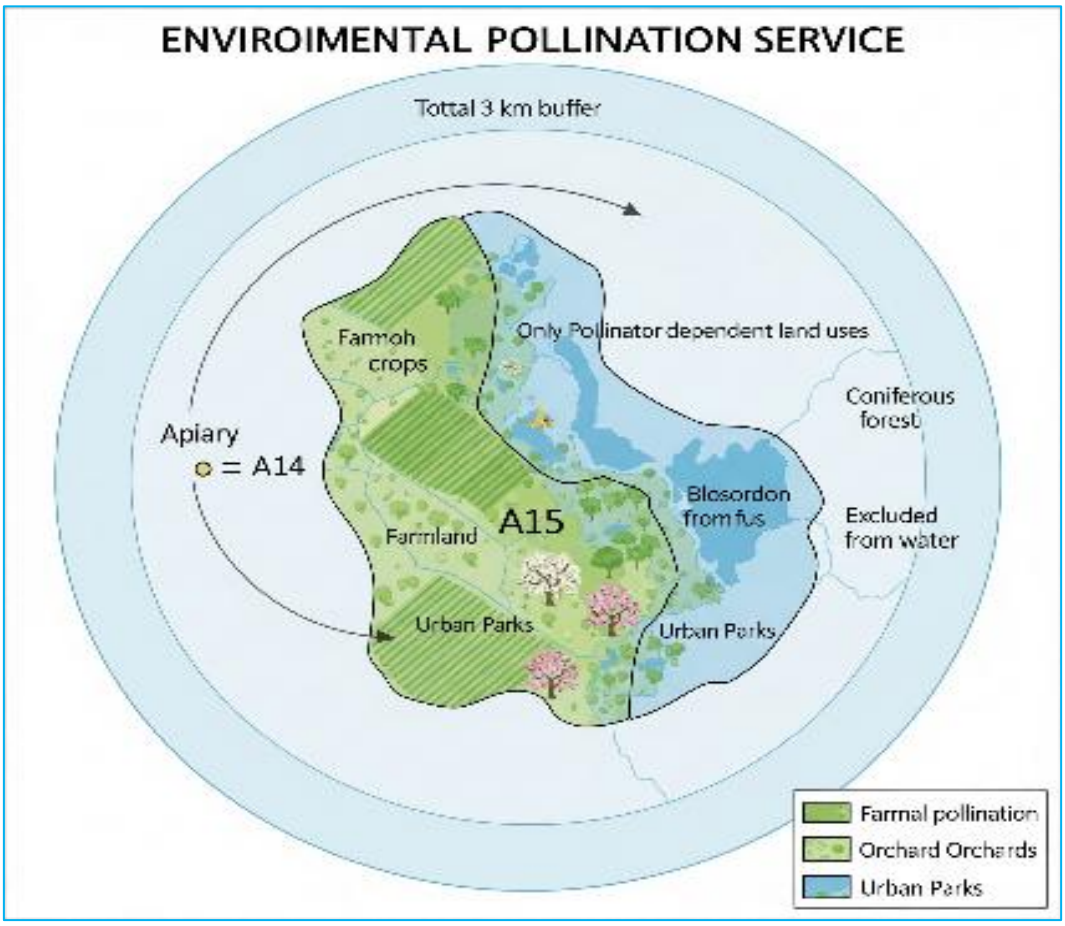

Fig 2 Diagram illustrating the environmental pollination service

Role of bees in pollination and biodiversity conservation

Pollination is a cornerstone ecological process, and honey bees are among its most efficient agents. By transferring pollen from one flower to another, bees facilitate fertilization, ensuring the reproduction of plants and the genetic diversity of species [78]. It is estimated that around 75% of global food crops and 85% of wild flowering plants depend to some degree on animal pollinators, with honey bees playing the dominant role [79]. Through this service, bees help sustain biodiversity within natural and managed ecosystems. Their activity supports wild plant populations that serve as habitats and food sources for birds, insects, and other wildlife, thereby strengthening ecological networks [80]. Beekeeping, therefore, indirectly contributes to the maintenance of ecosystem balance, preventing the decline of pollinator populations and fostering resilient landscapes.

Impact on crop productivity and food security

The integration of bees into farming systems has a direct and measurable effect on crop productivity. Pollination by honey bees not only increases yields but also improves the quality of produce in terms of size, shape, taste, and nutritional content [81]. For example, apple orchards, mustard fields, sunflower crops, cucurbits, and almonds show significant yield gains when pollination services are enhanced through managed beekeeping. This pollination-driven productivity has profound implications for food security. By ensuring a higher output and better quality of diverse food crops, honey bees contribute to the availability, accessibility, and nutritional diversity of diets. In regions where food insecurity is prevalent, promoting beekeeping can serve as a low-cost intervention to enhance agricultural output and income while simultaneously improving ecological sustainability [82].

Integration of beekeeping with agroforestry, horticulture, and organic farming

Beekeeping integrates seamlessly with multiple farming systems, making it a synergistic enterprise that complements other land-use practices:

Agroforestry: Trees and shrubs in agroforestry systems provide nectar and pollen resources for bees, while bee pollination enhances fruit and seed set in timber and fruit tree species. This mutual benefit increases the productivity and regeneration capacity of agroforestry landscapes [83].

Horticulture: Horticultural crops such as fruits (apple, mango, citrus), vegetables (cucurbits, tomatoes), and plantation

crops (coffee, cocoa) benefit significantly from bee pollination. Managed beekeeping ensures uniform flowering and fruiting, enhancing marketable yields and farmer profits [84].

Organic farming: Since organic systems avoid synthetic pesticides and chemicals, they provide safer environments for bees. In turn, bees support organic farming by providing a natural pollination service, boosting biodiversity, and helping maintain soil fertility through enhanced crop rotations and cover crops. Thus, beekeeping fits naturally within the principles of organic and sustainable agriculture [85].

Contribution to ecosystem services

Beyond pollination, beekeeping contributes to multiple ecosystem services that sustain both agriculture and the environment:

Provisioning services

Honey, beeswax, propolis, pollen, royal jelly, and bee venom are valuable natural products with nutritional, medicinal, and industrial uses. Provisioning services are the tangible products derived from ecosystems that directly contribute to human well-being and livelihoods. In the context of apiculture, honey bees provide a diverse range of natural products honey, beeswax, propolis, pollen, royal jelly, and bee venom which hold significant nutritional, medicinal, and industrial value [86]. Honey is the most recognized bee product, serving as a natural sweetener rich in bioactive compounds, antioxidants, vitamins, and minerals. Beyond nutrition, honey exhibits antimicrobial and wound-healing properties, making it widely used in traditional and modern medicine, as well as in cosmetics and functional foods [87]. Beeswax, secreted by worker bees, is valued in industries ranging from candle-making and food preservation to pharmaceuticals and cosmetics due to its emollient, stabilizing, and protective properties [88]. Propolis, a resinous substance collected by bees from tree buds and mixed with wax, has strong antimicrobial, antiviral, and anti-inflammatory properties, making it a key ingredient in natural medicines, dietary supplements, and health products [89]. Bee pollen, often referred to as a "superfood," is a rich source of proteins, amino acids, vitamins, and enzymes, consumed as a dietary supplement for boosting immunity, energy, and overall health [90]. Royal jelly, the exclusive food for queen bees, is renowned for its unique composition of proteins (major royal jelly proteins), fatty acids, and bioactive compounds, which have been linked to enhanced vitality, fertility, and potential therapeutic benefits in humans [91]. Lastly, bee venom, though less common in everyday use, is increasingly recognized in apitherapy for its anti-inflammatory, analgesic, and immune-modulating properties, applied in treating conditions such as arthritis and certain skin disorders [92]. Collectively, these products represent the provisioning services of bees, not only contributing to food security and health but also supporting rural livelihoods, global trade, and sustainable industries. Their wide-ranging applications highlight the essential role of apiculture in linking biodiversity conservation with economic and human well-being [93].

Regulating services

Bees contribute to regulating ecosystem processes by enhancing plant reproduction, stabilizing vegetation cover, and indirectly reducing soil erosion and carbon loss. Regulating services are ecosystem functions that maintain environmental balance and resilience, ensuring the sustainability of natural and human systems. Bees, as vital pollinators, play a central role in regulating ecosystem processes by enhancing plant reproduction, stabilizing vegetation cover, and indirectly mitigating soil erosion and carbon loss. Through pollination, bees facilitate the sexual reproduction of flowering plants, ensuring genetic diversity, seed set, and fruit development. This reproductive success not only sustains agricultural productivity but also maintains wild plant populations, which are essential for ecological stability. By promoting continuous plant regeneration, bees contribute to stable vegetation cover, which acts as a protective layer against land degradation [94]. Dense vegetation supported by pollination enhances soil structure, reduces exposure to erosive forces like wind and water, and improves water infiltration and retention. Consequently, the indirect effects of bee activity help in reducing soil erosion and maintaining soil fertility both of which are critical for sustainable agriculture and ecosystem health [95].

Moreover, bees play a significant role in carbon regulation. By sustaining diverse plant communities, they contribute to increased biomass and carbon sequestration, as plants absorb and store atmospheric carbon dioxide during photosynthesis [96]. Healthy vegetation cover supported by pollination thus reduces carbon loss and strengthens ecosystem resilience against climate change. In agricultural systems, pollination enhances crop yields and quality, reducing the need for land-use expansion and preventing further deforestation, which is a major source of carbon emissions. Additionally, stable ecosystems supported by bee pollination provide habitats for other species, reinforcing biodiversity and the ecological interactions necessary for regulating nutrient cycles and hydrological balance. In essence, bees act as natural regulators of ecosystem services, linking pollination with soil conservation, carbon sequestration, and climate stability. Their role extends far beyond food production, highlighting their ecological significance in maintaining healthy landscapes and mitigating environmental degradation [97]. Protecting bee populations, therefore, is not only vital for agriculture but also for ensuring broader regulating services that underpin global sustainability.

Supporting services

By maintaining biodiversity and genetic diversity among plants, bees strengthen ecological resilience, enabling ecosystems to adapt to environmental changes and climate stress. Supporting services are the foundational ecological processes that sustain life, upon which all other ecosystem services—provisioning, regulating, and cultural depend. Bees play a critical role in supporting services by maintaining biodiversity and genetic diversity among plants, which in turn strengthens ecological resilience [98]. Through their pollination activities, bees facilitate cross-pollination, ensuring gene flow between plant populations. This genetic exchange enhances the adaptability of plant species, allowing them to evolve traits that improve survival under changing environmental conditions such as drought, temperature extremes, pests, and diseases. A genetically diverse plant community is more robust and capable of withstanding stress, thereby reducing the risk of ecosystem collapse [99]. By maintaining a wide array of plant species, bees indirectly sustain the habitats and food sources of countless other organisms, from soil microbes to herbivores and higher trophic levels. This biodiversity support creates a stable ecological web in which interdependent species can thrive. For example, pollinator-supported flowering plants provide nectar and fruits that feed insects, birds, and mammals, while also contributing to soil fertility and nutrient cycling through organic matter. Such interconnectedness builds ecological resilience, allowing ecosystems to recover more quickly from disturbances like wildfires, floods, or human land-use changes [100].

Furthermore, bees contribute to climate adaptation by enabling the persistence of diverse and well-adapted vegetation. Plant species pollinated by bees form the basis of natural regeneration in forests, grasslands, and agricultural landscapes, ensuring that these ecosystems can adapt to shifting climates and provide long-term services such as carbon storage, water regulation, and soil conservation. Without adequate pollination, many plant species would decline, leading to reduced biodiversity, genetic bottlenecks, and weakened ecological networks [101]. Bees act as keystone species in supporting services, underpinning biodiversity and genetic diversity that are crucial for ecosystem resilience. Their role ensures the stability, adaptability, and productivity of ecosystems in the face of climate stress and environmental change. Protecting bees, therefore, is equivalent to safeguarding the ecological foundation upon which human societies and natural systems depend [102].

Cultural services

Beekeeping is embedded in traditional knowledge, rituals, and livelihoods in many cultures. Moreover, the presence of bees in landscapes fosters environmental awareness and conservation ethics among communities. Cultural services refer to the non-material benefits people derive from ecosystems, encompassing spiritual, educational, recreational, and heritage values. Bees and beekeeping embody profound cultural services that extend beyond their ecological and economic roles [103]. In many societies, beekeeping is deeply embedded in traditional knowledge systems, where practices for hive management, honey harvesting, and medicinal use of bee products are passed down across generations [104]. These practices often form part of local identity, rituals, and folklore, symbolizing harmony with nature and respect for biodiversity. For instance, in several indigenous cultures, honey and beeswax are used in ceremonies, healing traditions, and offerings, reflecting the spiritual and cultural significance of bees [105].

Beekeeping also supports livelihoods and cultural heritage, particularly in rural areas where smallholder farmers integrate apiculture into their farming systems. Beyond income generation, the craft of beekeeping represents a cultural legacy of sustainable resource use and community resilience. Local honey markets, festivals, and traditions tied to honey harvesting strengthen social bonds and foster cultural continuity. Additionally, the artistic and literary symbolism of bees as emblems of hard work, cooperation, and environmental harmony illustrates their pervasive influence in human culture [106].

Moreover, the presence of bees in landscapes fosters environmental awareness and conservation ethics. Communities engaged in beekeeping or exposed to the ecological importance of pollinators often develop stronger conservation values, recognizing the interdependence between humans and ecosystems. Educational initiatives and eco-tourism projects centered around bees and apiaries also contribute to spreading awareness of biodiversity protection, climate resilience, and sustainable farming [107]. In urban areas, rooftop beekeeping and pollinator gardens are not only innovative livelihoods but also cultural movements that reconnect people with nature. In essence, the cultural services provided by bees highlight their role as bridges between ecology and society, reinforcing traditional wisdom, promoting conservation ethics, and nurturing human-nature relationships. By sustaining cultural heritage and inspiring environmental stewardship, bees contribute to intangible yet powerful aspects of human well-being that are as vital as their provisioning and regulating services [108].

The ecological aspects of beekeeping extend far beyond hive products; they lie at the heart of sustainable agriculture, biodiversity conservation, and ecosystem health. Honey bees play a critical role in pollination, directly influencing crop productivity and food security, while their integration with agroforestry, horticulture, and organic farming strengthens farm resilience. Additionally, the multiple ecosystem services supported by bees underscore their importance as keystone species in natural and managed landscapes. Promoting beekeeping, therefore, is not only an economic strategy but also an ecological necessity, ensuring that agriculture and ecosystems remain productive, diverse, and sustainable for future generations [109].

Beekeeping as a sustainable enterprise

Beekeeping, or apiculture, is increasingly recognized as a model of sustainable livelihood and ecological enterprise. Unlike many resource-intensive agricultural practices, it is characterized by its low-input requirements, ecological compatibility, and wide adaptability across geographical and social contexts [110]. By simultaneously generating income, supporting biodiversity, and enhancing agricultural productivity, beekeeping offers a unique convergence of economic, environmental, and social sustainability.

Low-input and eco-friendly nature of apiculture

One of the defining features of beekeeping is its low-resource demand compared to conventional farming. Honey bees require no direct feed or cultivation inputs, as they forage naturally on nectar and pollen. The land requirement is minimal colonies can be kept in small spaces, making beekeeping possible even without farmland. Beekeeping is inherently eco-friendly because it does not deplete soil nutrients, consume irrigation water, or rely heavily on synthetic fertilizers and pesticides [111]. On the contrary, bees actively contribute to environmental enrichment by supporting pollination and biodiversity. Compared with intensive farming systems that often degrade ecosystems, beekeeping operates in harmony with natural cycles, making it one of the most sustainable agricultural enterprises [112].

Suitability in rural, peri-urban, and urban systems

Apiculture is highly versatile and can be practiced in diverse settings:

Rural areas: Beekeeping is an accessible income-generating activity for smallholder farmers, providing honey, wax, and other products while simultaneously increasing crop yields through pollination. It integrates easily with existing farming systems, enhancing agricultural productivity without competing for land [113].

Peri-urban areas: In areas surrounding cities, beekeeping provides opportunities for market-oriented production. Peri-urban landscapes with gardens, orchards, and horticultural farms offer abundant forage, and proximity to urban markets facilitates honey sales and value addition [114].

Urban areas: Growing environmental consciousness has popularized urban beekeeping on rooftops, balconies, and community gardens. Besides producing honey, urban beekeeping enhances urban biodiversity, pollinates green spaces, and fosters public awareness of environmental conservation. Cities such as London, Paris, and New York have embraced rooftop beekeeping as part of their sustainable urban development initiatives [115]. This adaptability across rural,

peri-urban, and urban systems makes beekeeping one of the most scalable and inclusive enterprises globally.

Opportunities for marginalized communities (women, landless farmers, youth)

Beekeeping is an enterprise that promotes social equity and inclusion.

Women empowerment: Beekeeping is less physically demanding than many agricultural activities, making it accessible for women. Women's involvement in honey production, processing, and marketing enhances household incomes and strengthens their role in decision-making [116].

Landless farmers: Since beekeeping does not require land ownership, it is particularly suitable for landless rural populations. Colonies can be maintained in backyards, near forests, or on leased spaces, providing income without competing for scarce land resources [117].

Youth engagement: With rising unemployment, particularly among rural youth, beekeeping presents an attractive opportunity due to its low entry costs, quick returns, and entrepreneurial scope. Value addition, branding, and digital marketing of honey and bee products further expand employment opportunities for young people. By creating inclusive livelihood options, beekeeping supports poverty reduction, gender equity, and youth empowerment, aligning with multiple sustainable development goals (SDGs) [118].

Climate resilience and environmental compatibility

Beekeeping is inherently climate-resilient, making it a strategic livelihood under changing environmental conditions. Honey bees adapt to diverse ecological zones from tropical forests and savannas to temperate orchards and arid landscapes due to their flexible foraging behavior. Moreover, by promoting pollination, beekeeping enhances the resilience of agricultural ecosystems [119]. Pollinator-dependent crops exhibit improved yields and genetic diversity, which are crucial for adapting to environmental stress. Beekeeping also encourages habitat preservation, as farmers and communities are motivated to maintain flowering plants, forests, and agroforestry systems that support bees [120]. Environmentally, beekeeping is compatible with agroecological principles. It reduces reliance on chemical inputs, fosters biodiversity, and complements sustainable farming systems such as agroforestry, organic agriculture, and permaculture [121]. In this way, beekeeping aligns with global strategies for climate adaptation, biodiversity conservation, and ecosystem restoration. Beekeeping exemplifies a sustainable enterprise that integrates economic viability with ecological stewardship and social inclusiveness. Its low-input nature makes it accessible even to resource-poor farmers, while its adaptability across rural, peri-urban, and urban settings ensures scalability [122]. By empowering women, landless farmers, and youth, beekeeping strengthens livelihoods and supports equitable development. Furthermore, its ecological compatibility and role in climate resilience highlight its contribution to sustainable agriculture and environmental conservation. As global concerns about food security, biodiversity loss, and rural poverty intensify, promoting beekeeping represents a win–win solution, bridging the gap between economic development and environmental sustainability [123].

Bee products and their economic potential

Beekeeping is not only valued for its role in pollination and ecosystem services but also for the diverse range of bio-products derived from honey bees. These products have significant nutritional, medicinal, industrial, and commercial applications, making apiculture a highly profitable enterprise when managed effectively. Beyond honey, which is the most widely known, products such as beeswax, royal jelly, pollen, propolis, and bee venom constitute a lucrative segment of global markets, particularly in health, pharmaceuticals, cosmetics, and nutraceutical industries [124]. The following discussion highlights the diversity and potential of bee products.

Honey: Varieties, nutritional, and medicinal values

Honey is the primary product of apiculture, and its economic potential lies in its nutritional, therapeutic, and cultural significance.

Varieties: Honey can be classified based on botanical source (e.g., clover honey, acacia honey, eucalyptus honey, sunflower honey) or geographical origin (e.g., Manuka honey from New Zealand, Sidr honey from Yemen, Kashmir honey from India). Each variety differs in flavor, color, aroma, and bioactive composition. Specialty honeys, such as organic or monofloral honey, command premium prices in international markets [125].

Nutritional value: Honey contains natural sugars (fructose and glucose), enzymes, amino acids, vitamins (B-complex, C), and minerals (calcium, potassium, magnesium). Unlike refined sugar, honey provides both energy and essential micronutrients [126].

Medicinal value: Honey is well-documented for its antimicrobial, antioxidant, anti-inflammatory, and wound-healing properties. It is widely used in traditional medicine systems such as Ayurveda, Unani, and Chinese medicine. In modern medicine, medical-grade honey (e.g., Manuka honey) is applied in wound dressings, burns, and post-surgical healing due to its antibacterial activity. Its growing reputation as a functional food strengthens its global demand [127].

Beeswax and its industrial applications

Beeswax is a natural secretion of honey bees, used to build honeycombs, but it also has extensive industrial applications.

Industrial uses: Beeswax is a key raw material in the cosmetics industry (lip balms, moisturizers, creams, lotions), pharmaceuticals (ointments, capsules, drug coatings), food processing (as a glazing and coating agent), and candle making (premium smokeless candles). It is also used in polishes, waterproofing, and art materials such as encaustic painting [128].

Economic potential: The demand for natural and eco-friendly alternatives to synthetic waxes has expanded the market for beeswax. High-quality beeswax fetches premium prices in both domestic and export markets, especially when sourced organically [129].

Royal jelly, pollen, propolis, and bee venom as high-value bio-products

These secondary bee products are often more profitable per unit weight than honey, as they cater to specialized health and cosmetic markets [130].

Royal jelly: A milky secretion produced by worker bees, royal jelly is consumed by the queen bee and is associated with vitality and longevity. Rich in proteins, fatty acids, and vitamins, it is marketed as a dietary supplement for boosting immunity, fertility, and anti-aging. It is highly valued in nutraceuticals, traditional medicine, and cosmetics [131].

Bee pollen: Collected from flowers by bees, pollen is rich in proteins, amino acids, vitamins, and minerals. It is sold as a superfood supplement, promoting energy, stamina, and improved metabolism. Health-conscious consumers drive its global demand, particularly in urban and developed markets [132].

Propolis: A resin-like substance collected by bees from plant exudates, propolis has antibacterial, antifungal, antiviral, and anti-inflammatory properties. It is widely used in herbal medicine, throat sprays, lozenges, tinctures, and skin-care products. Propolis is sometimes referred to as "nature's antibiotic," making it a promising product in natural health markets [133].

Bee venom: Though produced in small quantities, bee venom is highly valued in apitherapy for treating arthritis, multiple sclerosis, chronic pain, and inflammatory conditions. It is also used in cosmetics as a natural anti-aging ingredient, often called "nature's Botox." Because of its rarity and high medicinal demand, bee venom commands extremely high prices in niche pharmaceutical and cosmetic markets [134].

Value addition and niche markets (organic, medicinal, cosmetic industries)

The true economic potential of bee products lies not only in raw sales but in value addition and niche marketing.

Value addition: Processing raw honey into creamed honey, infused honey (with herbs, spices), honey-based beverages, and confectioneries increases profitability. Similarly, beeswax can be turned into high-value candles, cosmetics, and ointments [135].

Niche markets

Organic honey and products: Growing consumer demand for pesticide-free, environmentally safe products has created a thriving organic honey and beeswax market [136].

Organic honey and bee products: Market trends and sustainability

The global demand for organic and environmentally safe products has surged in recent years, driven by increased consumer awareness of food safety, environmental sustainability, and health benefits. Honey and other bee products, when produced organically, align perfectly with these consumer expectations, leading to the development of a rapidly expanding organic apiculture sector [137].

Organic honey and bee products are emerging as a significant and fast-growing niche within the global apiculture sector, primarily fueled by rising consumer awareness about food safety, environmental sustainability, and holistic health benefits [138]. Unlike conventionally produced honey, organic honey is sourced from bee colonies that forage in landscapes free from synthetic pesticides, herbicides, fertilizers, and genetically modified crops, with beekeeping practices strictly following certified organic standards that emphasize hive health, natural foraging, and minimal chemical intervention. Similarly, other bee-derived products such as beeswax, royal jelly, propolis, and pollen must undergo organic production and processing methods that preserve their natural integrity and prevent contamination, ensuring their nutritional, medicinal, and ecological value is maintained. Certification frameworks administered by recognized international bodies such as USDA Organic in the United States, EU Organic in Europe, JAS in Japan, and NPOP in India not only ensure credibility and standardization but also open access to lucrative global markets were consumer trust hinges on certified authenticity [139]. With the increasing global shift toward sustainable consumption patterns, organic apiculture offers a dual advantage: it provides beekeepers with higher income potential through premium pricing while simultaneously contributing to environmental stewardship by promoting biodiversity, reducing chemical dependency, and supporting resilient ecosystems. This convergence of ecological responsibility, economic opportunity, and consumer-driven demand positions organic honey and related products as a cornerstone of sustainable agriculture and a promising pathway for the future of beekeeping worldwide [140]. The organic honey and bee products market is a rapidly expanding segment that combines economic opportunity with ecological responsibility. Growing consumer demand for pesticide-free, environmentally safe, and health-promoting products has transformed apiculture into a premium, high-value enterprise. Beyond economic benefits, organic apiculture supports pollinator health, biodiversity, and sustainable land management, making it a model for environmentally conscious and socially inclusive agricultural practices. With proper certification, quality control, and market linkages, organic honey and beeswax provide both financial returns and ecological stewardship, reinforcing the role of beekeeping as a sustainable and future-ready enterprise [141].

Medicinal honey and apitherapy products

Beekeeping extends far beyond honey production for culinary use; it also encompasses the therapeutic applications of bee products, an area broadly termed apitherapy. Apitherapy refers to the use of honey, propolis, royal jelly, bee venom, and other hive products for preventive and curative healthcare. Among these, medicinal honey and propolis supplements have emerged as flagship products in international markets, combining the ancient wisdom of natural medicine with modern scientific validation. Their global prominence highlights both their pharmacological potential and their significant economic opportunities in nutraceutical and pharmaceutical industries [142].

Medicinal honey and propolis supplements have become central to the convergence of apiculture, healthcare, and global commerce, with products like Manuka honey setting the benchmark for therapeutic potential and market success. Manuka honey, derived from the *Leptospermum scoparium* shrub in New Zealand and parts of Australia, owes its unique antibacterial activity to methylglyoxal (MGO), making it highly effective in wound healing, burn treatment, skin infections, ulcers, and sore throats, while its authenticity is safeguarded through regulatory frameworks such as the UMF grading system, FDA approvals, and EU standards [143]. Alongside Manuka, other regional honeys like Sidr, Tualang, and Acacia have also gained recognition for their antimicrobial, antioxidant, and immune-boosting properties, increasingly marketed as functional foods with distinctive geographic branding. Propolis, often referred to as "nature's antibiotic," further strengthens this medicinal portfolio, with its flavonoid- and phenolic-rich composition providing broad-spectrum antimicrobial, antiviral, antifungal, anti-inflammatory, and immunomodulatory benefits, now utilized in diverse forms

such as capsules, tinctures, sprays, ointments, and skincare products [144]. Its traditional uses for respiratory ailments, ulcers, and infections are now scientifically validated, boosting consumer demand, especially in post-COVID health markets. Together, medicinal honey and propolis fuel the growth of apitherapy a complementary and alternative medicine practice that also incorporates bee venom, royal jelly, and pollen extracts now integrated into healthcare systems in countries like South Korea, Germany, and China [145]. Despite challenges such as adulteration, mislabeling, lack of standardization, and climate-induced threats to raw material quality, the opportunities are immense, with consumers increasingly seeking safe, natural, and sustainable remedies. Their premium market value, sometimes exceeding USD 100-300 per kg for medicinal honeys and expanding nutraceutical applications of propolis, underscores their economic potential [146]. Ultimately, these products not only enhance global health and wellness but also elevate apiculture into a sustainable, innovation-driven industry where therapeutic efficacy, ecological responsibility, and economic growth intersect.

Cosmetic industry: The incorporation of beeswax, royal jelly, and bee venom into premium beauty and skincare products has significantly expanded market opportunities [147].

Export potential: Countries such as China, Turkey, Argentina, and India are leading exporters of honey and bee products, while high-end specialty honeys and therapeutic products fetch premium prices in Europe, the USA, and the Middle East [148].

Bee products represent a diverse and expanding portfolio of high-value commodities, ranging from staple products like honey and beeswax to specialized bio-products such as royal jelly, propolis, and bee venom. Each product offers unique nutritional, medicinal, or industrial benefits, positioning apiculture as a multi-product enterprise with immense economic promise [149]. Value addition and diversification into organic, medicinal, and cosmetic niches further enhance profitability and global competitiveness. Thus, bee products not only provide sustainable livelihoods for beekeepers but also contribute to the health, wellness, and natural products industry worldwide, strengthening the role of apiculture in modern economies [150].

Bee products and their economic potential

Bee products represent a diverse portfolio of natural commodities with significant nutritional, medicinal, industrial, and economic value. Honey, the most widely known product, occurs in several varieties such as monofloral, multifloral, honeydew, comb, and creamed honey, each characterized by unique physicochemical attributes, bioactive profiles, and market differentiation; it is primarily composed of sugars, enzymes, organic acids, minerals, and phenolic compounds that impart antimicrobial, antioxidant, and therapeutic properties [151]. Beeswax, a complex mixture of esters, hydrocarbons, and fatty acids, is highly valued in pharmaceutical, cosmetic, food, and industrial applications, including ointments, lip care products, fruit coatings, and eco-friendly wraps [152]. Other hive-derived products such as royal jelly, bee pollen, propolis, and bee venom are considered high-value bioresources: royal jelly is rich in proteins and 10-hydroxy-2-decenoic acid (10-HDA), with nutraceutical and anti-aging potential; bee pollen offers proteins, amino acids, and vitamins for dietary supplements; propolis provides polyphenols and flavonoids with antimicrobial and antioxidant benefits in medical and oral care applications; and bee venom, containing melittin and apamin, is under investigation for pharmaceutical and cosmeceutical formulations [153]. Furthermore, value addition through organic certification, single-origin branding, innovative product development, and entry into niche markets such as health foods, cosmetics, and wellness industries can significantly enhance profitability [154]. Ensuring quality assurance, residue-free production, sustainable beekeeping practices, and compliance with regulatory standards remains critical for positioning bee products as globally competitive, multifunctional bioeconomy assets.

Economic efficiency of beekeeping

Beekeeping is economically efficient because it combines relatively low fixed capital and input costs with multiple revenue streams (honey, wax, pollen, propolis, royal jelly, venom) and valuable ecosystem services (pollination), producing attractive cost–benefit ratios for both smallholder and commercial operations. At the enterprise level, benefit–cost analyses from several regions show positive returns migratory operations often report higher ratios than stationary ones due to improved forage access and service contracts while small-scale apiaries frequently attain rapid payback on equipment (boxes, frames, basic extraction) when value-added products or direct marketing are used [155]. Compared with many traditional cropping systems, beekeeping offers a comparative advantage through (a) land- and labour-efficient income generation (a single hectare can support many hives without displacing crops), (b) low water and input requirements, and (c) risk diversification because pollination and product sales provide complementary revenue streams. Empirical studies and sustainability assessments highlight that beekeeping can outperform marginal cropping or fallow land use on economic and environmental metrics, especially where floral diversity and seasonal nectar flows are available [156]. Importantly, the economic value of pollination services frequently exceeds direct hive-product revenues in many intensive cropping systems: U.S. almond pollination alone generated several hundred million dollars in pollination fees in recent seasons and in some years pollination receipts have approached or surpassed honey revenues, demonstrating that renting colonies for pollination can be a principal income source for commercial beekeepers [157]. Valuation studies that combine crop dependency and production data show that national pollination services can represent a substantial share of agricultural value (for example, conservative estimates place pollination's annual value at hundreds of millions of USD in smaller countries and billions globally), which argues for policy support and compensation mechanisms when pollinator populations decline [158]. Case studies illustrate diverse models and outcomes: California's migratory-almond system demonstrates very high short-term fees and systemic vulnerability to colony losses; Nepal and other developing-country analyses show that community-scale apiculture substantially increases household income and nutritional access; and regional studies from Turkey and India reveal that scale, access to markets, and investments in quality control (residue testing, traceability, organic certification) are decisive for profitability and sustainable growth [159]. In sum, when well-managed and integrated with value addition (single-origin honey, propolis extracts, pollen capsules) or pollination service contracts, beekeeping often delivers superior economic efficiency versus many land-extensive farming options but realizing that potential requires attention to colony health, seasonal forage planning, market linkages, and policies that recognize and remunerate pollination as a critical agricultural input.

Challenges and constraints

Beekeeping, despite its recognized ecological and economic importance, faces persistent challenges ranging from biological stressors to institutional weaknesses. Colony health is threatened by pests and pathogens such as *Varroa destructor*, *Nosema spp.*, and foulbrood, which reduce productivity and increase losses, necessitating integrated pest management and breeding of resistant stocks [160]. Pesticide exposure further compounds risks, as sub-lethal and lethal effects of agrochemicals impair foraging efficiency, contaminate hive products, and accelerate colony decline. Climate change and habitat degradation exacerbate these pressures by disrupting floral cycles, altering nectar flows, and diminishing forage resources, thereby heightening colony nutritional stress [161]. Market inefficiencies, fluctuating prices, and underdeveloped value chains restrict the profitability of hive products, while policy gaps including inadequate extension, weak pesticide regulation, and failure to formally value pollination services undermine sectoral growth. Addressing these challenges requires a systemic approach that combines scientific innovation, residue-free production, forage enhancement, and sustainable management practices with institutional reforms that integrate beekeeping into agricultural policy, strengthen certification and quality infrastructure, and expand access to credit and insurance. Such measures can enhance resilience, increase profitability, and secure apiculture's dual role as a livelihood source and a critical provider of pollination services essential for food security and biodiversity [162].

Way forward: Strategies for sustainable and profitable beekeeping

Addressing these challenges requires a multi-pronged strategy that integrates science, policy, and market development. For biological threats, integrated pest management, breeding of disease-resistant bee strains, and establishment of diagnostic centers can reduce colony losses [163]. To mitigate pesticide impacts, enforcement of bee-safe pesticide regulations, adoption of Integrated Pest and Pollinator Management, and farmer–beekeeper collaboration are vital. Habitat degradation and climate stress can be addressed through the planting of nectar- and pollen-rich flora, promotion of climate-resilient practices such as migratory beekeeping and supplementary feeding, and conservation of wild pollinator habitats [164]. Market inefficiencies call for investment in processing and certification infrastructure, promotion of cooperatives and farmer producer organizations, and diversification into high-value products such as organic honey, propolis tinctures, beeswax cosmetics, and pollen supplements [165]. At the policy level, recognizing beekeeping as a mainstream agricultural enterprise, incentivizing pollination services, providing access to credit and insurance, and strengthening research–extension–industry linkages will create an enabling environment for growth [166]. Together, these measures can transform beekeeping into a resilient and profitable enterprise that supports livelihoods, enhances agricultural productivity, and contributes to biodiversity conservation.

Opportunities and future prospects

Looking ahead, beekeeping offers immense opportunities that extend well beyond honey production. Technological innovations, including precision beekeeping tools, smart hives equipped with sensors to monitor colony health, and mobile platforms for data-driven management, are reshaping the sector by improving efficiency and reducing losses [167]. Diversification into Api-tourism and allied industries such as apiary tours, honey-tasting events, educational workshops, and wellness therapies offers new income streams while enhancing public awareness of pollinators. The growing global demand for natural and chemical-free products creates strong incentives for organic certification and export-oriented production, which can significantly increase returns for premium honey, beeswax, and propolis-based products [168]. Community-based beekeeping models and cooperatives provide small-scale beekeepers with opportunities to pool resources, access advanced technologies, strengthen bargaining power, and establish collective brands that enhance market access. Furthermore, the role of research, extension, and policy interventions will be decisive in shaping the sector's trajectory: investments in breeding resilient bee strains, climate-smart beekeeping, product standardization, and international collaboration can position apiculture as a cornerstone of sustainable agriculture and rural entrepreneurship [169].

Beekeeping today represents both an ancient practice and a modern economic frontier, with the capacity to contribute significantly to food security, rural livelihoods, and ecological sustainability. While pests, diseases, pesticides, climate change, market inefficiencies, and institutional gaps pose real challenges, the sector's adaptability and resilience provide a strong foundation for growth [170]. By embracing technological innovations, diversifying into high-value markets, building strong value chains, and integrating apiculture into agricultural policies, beekeeping can evolve into a climate-resilient, globally competitive enterprise. Its dual role providing high-value hive products and ensuring pollination services makes it not only a profitable livelihood option but also a vital component of sustainable agriculture and biodiversity conservation. With coordinated efforts from beekeepers, researchers, policymakers, and markets, the future of apiculture holds the promise of prosperity, resilience, and ecological balance.

CONCLUSION

Beekeeping has evolved from an ancient subsistence activity into a modern, globally significant enterprise that bridges economic, ecological, and social dimensions of sustainability. Historically rooted in cultural traditions and early forms of animal husbandry, apiculture today provides not only honey and hive products but also indispensable pollination services that underpin global food security and biodiversity. The comparative analysis of traditional and modern practices highlights the transition from extractive methods to scientifically managed systems that enhance productivity, colony health, and ecological compatibility. With an annual global production nearing 1.9 million metric tonnes and a rapidly expanding market for organic, medicinal, and cosmetic bee products, apiculture contributes substantially to international trade and rural livelihoods. Regional variations demonstrate its adaptability from Africa's organic honey exports and Asia's integration with traditional medicine, to Europe's policy-driven pollinator protection and the Americas' commercial pollination services making it a universally relevant agricultural practice. Ecologically, bees act as keystone species, ensuring crop productivity, ecosystem resilience, and biodiversity conservation. Economically, beekeeping remains highly efficient, combining low-input requirements with multiple revenue streams and opportunities for marginalized groups such as women, landless farmers, and youth. Yet, challenges including pests, diseases, pesticide exposure, climate change, and market inefficiencies threaten its

sustainability. The way forward lies in integrated approaches that combine technological innovations, value addition, quality assurance, and supportive policies with community-based and cooperative models. Ultimately, apiculture represents a resilient and future-ready enterprise that simultaneously advances food security, rural development, biodiversity conservation, and climate adaptation. By aligning traditional knowledge with modern science and sustainability goals, beekeeping stands as both an enduring legacy and a forward-looking solution for global agricultural and ecological resilience.

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