

CURRENT AND FUTURE TECHNOLOGIES IN THE BEEKEEPING PRACTICE

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Abstract: Beekeeping is a vital global practice that supports environmental sustainability while providing nutrition and income to people around the world. This review delves into contemporary beekeeping practices, end attempts to address pertinent issues. Practices such as individual specialisation, mobile apiaries, routine colony inspections, contract farming, and the integration of artificial intelligence technology emerge as pivotal contributors, empowering beekeepers and researchers to navigate challenges posed by natural disasters and the ongoing pandemic. Notably, these approaches help beekeepers overcome challenges and improve resilience. While acknowledging the positive impact of current practices, it is imperative to emphasise the need for continuous research and the development of innovative products. This exploration aims to amplify the economic effects of beekeeping and contribute to the restoration of endangered species, aligning with broader conservation and sustainability objectives. Moving forward, advancing beekeeping practices is crucial for both economic growth and ecological balance.

Keywords: Modern beekeeping, mobile apiaries, colony inspection, contract farming, artificial intelligence.

Introduction

Beekeeping has a long history dating back to 13,000 BC (Ashari *et al.*, 2019) and is one of the oldest forms of food production. Ancient paintings depict beekeeping activities such as bee farming, honey extraction techniques, and beehives, underscoring its historical significance (Crane & Graham, 1985). Beyond its historical roots, beekeeping plays a crucial role in modern agriculture. Bees are the primary insect pollinators that profoundly influence crop productivity. Therefore, beekeeping is an essential component of agricultural systems. Over time, beekeeping has evolved into a thriving agroforestry sector that provides crucial employment, supplementary income, and nutritious sustenance to countless rural communities, contributing significantly to societal well-being and national economies

(Kassa Degu & Regassa Megerssa, 2020). Additionally, beekeeping is a powerful tool for poverty alleviation and conserving natural biodiversity in economically disadvantaged regions.

Beekeeping is not only a traditional practice aimed at producing honey, but it also plays a crucial role in pollination (Guler & Demir, 2005). Approximately 87.5% of flowering plants require animals for pollination and the western honeybee *Apis mellifera* is the most significant and prolific animal pollinator (Hung *et al.*, 2018; Olate-Olave *et al.*, 2021). Climate changes have had a significant impact on honeybees, affecting their behaviour, physical conditions, and overall well-being (Cressey, 2015). Changes in temperature, developmental cycles, and floral environments can disrupt colonies,

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either enhancing or diminishing their foraging capabilities and growth. The Royal Society for the Protection of Beekeeping (RSPB) identifies human activities as threats to honeybees, including herders, thieves, and deforestation (Dia *et al.*, 2015). The effects of global warming extends to individuals, populations, and ecosystems, causing shifts in geographical ranges and highlighting the significant influence of plant communities on wild bee populations compared with habitat disruptions and species (Kasote, 2017). As global temperatures continue to rise, honeybees may struggle to relocate to cooler areas and establish new hives amidst habitat degradation, potentially leading to colony losses.

Honeybees have the ability to adapt to temperature and humidity changes. For example, when there is a rise in temperature, the bees change their behaviour by reducing or stopping their outdoor foraging activities (Li *et al.*, 2023). This helps them to stay within the hive and regulate temperature and humidity levels to protect the larvae and the nest. However, when the temperature is too high, bees are not able to fly properly. High humidity levels are also linked to an increase in the prevalence of diseases within the hive. Additionally, some bee species are responding to global climate changes by reducing their body size. For example, Dutch honeybees have decreased their size by approximately 10% in the past decade (Oliveira *et al.*, 2016). Changes in the bees' food sources due to climate change may also be contributing to the decline in the global bee population.

The usage of pesticides is another concerning issue affecting honeybees worldwide (Abay *et al.*, 2023). Honeybees are crucial for crop production and global food security. However, the elevated mortality rates and colony losses experienced by honeybees create a societal problem, mainly due to the harmful effects of neonicotinoids, a class of pesticides known to harm bees (Harwood & Dolezal, 2020). In light of these complex challenges, this comprehensive review aims to provide an in-depth analysis of modern beekeeping practices reported in scientific literature from 2010 to

2024. By offering insights into the current state of beekeeping, its limitations, and prospects, this review seeks to provide a comprehensive analysis that brings new perspectives to the forefront of beekeeping practices.

Literature Review

Beekeeping Practice

Beekeeping is a practice that involves various techniques worldwide, these methods include the traditional, urban, translational, modern and organic beekeeping (Eroglu, 2020; Barrientos *et al.*, 2021).

Traditional beekeeping is one of the oldest and most vital human practices that has been practiced for thousands of years. This method relies on minimal technology, with beekeepers using manual management and natural systems to care for the colonies. Despite its long history, traditional beekeeping continues to be practiced around the world, supporting millions of honeybees (Ismail, 2016). It can be classified into two main categories: Forest and domestic beekeeping. In traditional forest beekeeping, hives are set up on tall trees in forests to attract swarms. An example of forest beekeeping involves the collection of Tualang Honey in Malaysia. This technique is commonly used in areas where honeybee populations are abundant. Forest beekeeping offers several advantages such as keeping bees away from domestic animals and humans while providing access to a diverse range of food plants in their natural habitats (Harianja *et al.*, 2023). However, this method has some drawbacks. It has limited monitoring and there is a potential risk of harming honeybee colonies when hives are dropped during honey harvesting. Moreover, it can be dangerous for beekeepers to climb tall trees and many use traditional tools.

On the other hand, traditional backyard or domestic beekeeping is typically done in homesteads within a controlled environment for honeybees (Gupta *et al.*, 2014). This approach often involves constructing grass hives by weaving dry grass into cylinder or basket

shapes. These hives have access ports at both ends and are sometimes positioned close to the ground. Traditional backyard beekeeping only requires a little specialised equipment or skilled labour. Traditional backyard beekeeping has some disadvantages, internal inspections and feeding can be inconvenient and small hive sizes often result in swarming (Gupta *et al.*, 2014). Furthermore, traditional backyard beekeeping is prone to other issues including limited sparing possibilities and the absence of partitions to separate the brood chamber from the honey chamber.

Urban beekeeping refers to the practice of keeping bee colonies in urban areas. It is also called backyard or hobby beekeeping (Kulhanek *et al.*, 2021). Urban beekeeping has numerous societal benefits, from food production to environmental awareness. However, the concentration of honeybees in urban settings can raise conservation concerns that may affect urban wild insect pollinators and their crucial ecological services (Fraser, 1985; Egerer & Kowarik, 2020). The risk and benefit factors associated with urban beekeeping are illustrated in Figure 1.

Transitional beekeeping refers to the practice of combining traditional methods with modern advancements, bridging the gap between

historical and contemporary approaches to bee colony management (Hailu *et al.*, 2022). This method incorporates modern technologies and equipment while retaining key traditional practices, allowing beekeepers to enhance their operations without completely abandoning established techniques. Examples of transitional beekeeping includes the Kenya Top Bar Hive (KTBH) and Tanzania Top Bar Hive (TTBH), which are often constructed using locally available materials such as wood or mud. These hives typically consist of between 27 and 30 top bars, with each bar measuring 3.2 cm in width and 48.3 cm in length (Kassa Degu & Regassa Megerssa, 2020).

One of the key advantages of transitional beekeeping is that bees can easily build parallel combs along the top bars, allowing honeycombs to be harvested without disturbing the brood combs (Mulatu *et al.*, 2021). Additionally, the hives can be suspended using wires or ropes for weather protection. However, while top-bar hives are generally more affordable than some modern hives, they are also more prone to issues such as detachment of the honeycombs, which can complicate the harvesting process. Despite these challenges, transitional beekeeping provides an effective blend of traditional and modern beekeeping practices.

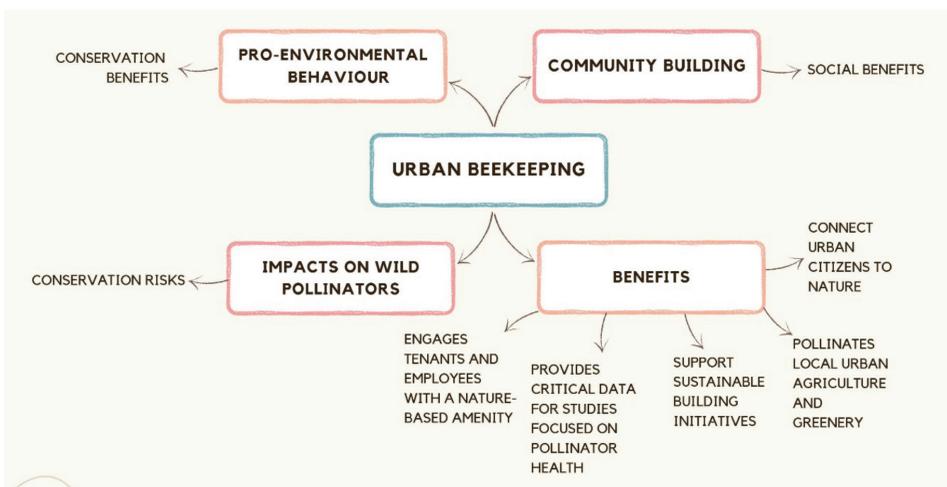


Figure 1: Urban beekeeping practice is known as backyard beekeeping offers benefits and risk factors (created using Canva)

Modern beekeeping refers to practices that integrate advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT) devices, and automated systems, to efficiently manage and monitor beehives (Andrijević *et al.*, 2022). These techniques focus on maximising honey production while ensuring the well-being of the bees. In contemporary movable-frame hives, rectangular box hives are stacked in tiers, with the number of boxes adjusted based on the size of the bee colony. Modern beekeeping has been adapted to smaller-scale operations such as with *Apis cerana* and is often influenced by the Langstroth hive model (Gaga *et al.*, 2016). The development of modern hives, along with changes in social and environmental factors has also reshaped the ethnobotanical knowledge and practices related to beekeeping.

One example of implementing IoT in Meliponiculture is a system developed by a group of scientists at the Standards and Industrial Research Institute of Malaysia (SIRIM) in collaboration with Universiti Malaysia Terengganu (UMT) and Malaysian Genome and Vaccine Institute (MGVI) to monitor stingless beehives based on temperature, humidity, and the quality of produced honey. The system is known

as Kelulut Integrated Information System (KIIS) (KIIS, 2017).

A subset of modern beekeeping, organic beekeeping is a practice that prioritises environmental sustainability and the well-being of bee colonies by avoiding the use of synthetic pesticides, insecticides, and other harmful chemicals (Figure 2). It emphasises the use of eco-friendly methods to manage beehives, focusing on natural processes and ensuring that bees have access to organic nectar and pollen sources. Organic beekeepers aim to align their practices with the natural cycles of bees, promoting their health and productivity without compromising environmental integrity. This method adheres to specific regulations such as European standards and often requires certification. Apiaries must undergo annual third-party inspections to verify compliance with organic standards, ensuring that the production of honey and other bee products is carried out in a sustainable, ethical manner (Devkota, 2020).

Beehives

Beekeeping equipment includes the beehive, which must be constructed while considering the three social hierarchies of bees: The queen,

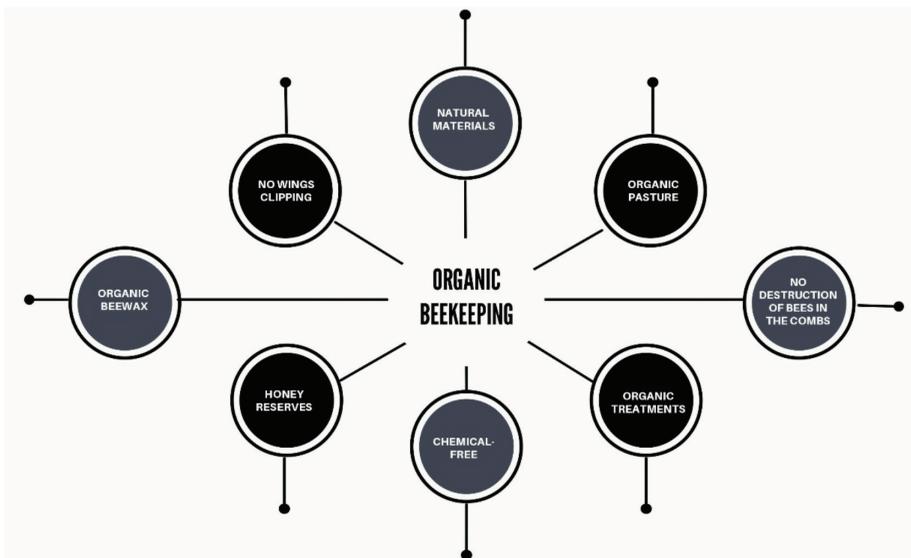


Figure 2: Organic beekeeping practice (created using Canva)

which can live up to three years and produce more than 500,000 larvae; worker bees are female bees, numbering between 30,000 and 50,000 bees in a hive; and male bees, also known as drones, which mate with the queen (Crane, 2009). The hive design is influenced by the number of bees and seasonal changes. When the old queen and young bees leave the hive during swarming, the beekeeper must collect the swarm and place it in a new hive to establish a new colony. Beekeepers can expand their apiary by splitting a beehive's colony in half.

In India, beekeepers traditionally kept stingless bees in baskets, wooden logs, subterranean beehives, and clay pots. However, the introduction of the Langstroth bee space, Johannes comb foundation, and Frang von Hruschka's honey extraction techniques have significantly impacted beekeeping in India. As a result, there has been a shift, with beekeepers throughout the Indian subcontinent encouraged to migrate to mobile frames (Kishen *et al.*, 2017). Meanwhile, Malaysia identified seven critical factors influencing the adoption of modern hive technology. These factors encompass the role of extension agents, production and harvesting processes, technological enhancements, knowledge from extension services, perceived benefits of modern technology, and the availability of information resources (Musa *et al.*, 2019; Soh *et al.*, 2021).

Furthermore, a recent study highlights the potential of stingless beekeeping as a reliable source of income for communities in Kapuas Hulu Regency in Indonesia. The success of this endeavour depends on various factors such as the selection of suitable locations for bee cultivation, the development of strategies for relocating and distributing bee colonies from the forest, and meticulous care and maintenance of these colonies after relocation. The evolution of beehive design and beekeeping practices reflects the continuous development in the field, catering to the diverse needs of beekeepers and bee colonies alike (Ashari *et al.*, 2019). Generally, there are three main type of beehives used today for *Apis species* bees: Langstroth (Crane, 2009), Warre, and Top Bar (Crowder & Harrell, 2012).

The Langstroth Hive

A Langstroth hive is a beehive with frames that hang vertically. The hive has a bee entrance on the bottom board, containing boxes for brood and honey frames. The lowest box is for the queen to lay eggs while the boxes above are for storing honey. The hive also has a weatherproof inner cover and top cap. Bees in a Langstroth hive construct honeycombs into frames that can be easily moved around. Unlike other hive designs, the honeycomb cannot be attached to the hive's walls or neighbouring frames. This is because the frames are designed to prevent bees from attaching combs that are unnecessary. This design allows beekeepers to manage their hives in ways that were once unimaginable (Crane, 2009).

The Warre Hive

The Warre hive can maintain a stable temperature and environment throughout the year, except for brief periods during honey harvesting or formal inspection, which happens just once or twice a year. The hive manages to keep the bee nests at a temperature similar to that of human beings, this is no small feat considering bees cannot thermoregulate body heat on their own and are classed as cold-blooded animals. Bees create natural honeycombs within the hive on eight top bars arranged one by one on the top of Warre hives (Heaf, 2016; Hung *et al.*, 2018). They fill the hollow space with combs without frames, attaching them to the sidewalls naturally. This results in inverted pockets of warm air where young bees can be raised. On the other hand, frames create drafty spaces around comb edges, allowing heat to escape. Bees must work harder to maintain their optimal temperature, which leads to physiological stress, increased susceptibility to diseases, and higher consumption of honey.

The Top Bar Hive

Top bar hives are suitable for beekeepers who keep bees at home. These hives do not have frames, but wooden bars hang from the top of the inside of the box. Bees use the bars to construct combs. Typically, a hive has between 20 and 28

bars, meaning bees can create that many combs. The top of the box is wider than the bottom, which helps the comb to stick less to the inside walls of the boxes. When harvested regularly, especially during peak nectar flow seasons, the top-bar beehive may yield as much honey as a Langstroth hive (Crowder & Harrell, 2012).

Number of Major World Beekeeping Practice

The number of beehives is often used to measure the extent of beekeeping practices worldwide. According to a 2019 report (Table 1), India leads with approximately 12.25 million beehives, followed by China with just over nine million hives (Ranz, 2020). Beehive populations have seen significant growth in recent decades, particularly in Asia, reflecting a rising interest in beekeeping and the increasing demand for pollination services. In contrast, many other regions have experienced only modest changes in the number of beehives over the past decade, suggesting that beekeeping practices in these areas have either stabilised or are dealing with challenges that hamper growth.

Table 1 shows the number of beehives in selected countries, offering insights into beekeeping trends across various regions. The substantial number of beehives in India and China indicates that beekeeping is not only widespread but also thriving in these regions. This growth is likely tied to the increasing awareness of pollination and its importance

for agriculture and food production. In contrast, countries like the United States and Mexico show lower figures, which may reflect challenges such as colony loss, environmental issues, or less widespread adoption of modern beekeeping practices.

Issues with Beekeeping

Honey collection poses a significant challenge as it puts bee colonies at risk. Honey serves as a farm product and a food reserve for the colony’s survival. Beekeepers must choose between a riskier harvest that boosts productivity or a less risky one that ensures the colony’s security. Additionally, the cost and need for disinfection are also drawbacks. Several other issues also affect beekeeping (Soh et al., 2021).

Environmental Climate

Honeybees maintain their hives at temperatures that range between 32°C and 36°C (89.6°F–96.8°F), which is essential for the development of larvae and pupae. Outside this temperature range, the bees’ offspring cannot develop and may perish. When external temperatures drop, worker bees cluster together on the hive’s exterior to form an insulating shell that traps heat, protecting the colony. Because of this, climate change presents a significant challenge to honeybees, including increased temperature fluctuations, altered weather patterns, and an increased exposure

Table 1: List of countries and number of beehives (Rodet, 2019)

Country	Number of Beehives
India	1,224,733
China	90,884
Türkiye	8,128
Iran	7,516
Ethiopia	6,220
Russian Federation	3,093
Argentina	2,985
United Republic of Tanzania	2,984
United States of America	2,812
Mexico	2,157

to diseases, parasites, and pesticides (Daisley *et al.*, 2020). These changes impact honeybee behaviour, physiology, and distribution, as well as the availability of food resources critical to colony survival and growth (Brodschneider & Crailsheim, 2010).

To address these challenges, digital tools such as remote sensing technologies and IoT devices can help beekeepers monitor hive conditions in real time. These technologies enable the tracking of internal hive temperature and humidity levels, allowing beekeepers to detect any deviations from optimal conditions that may arise due to external climate changes (Hamza *et al.*, 2023). Additionally, machine learning algorithms can analyse data from these sensors to predict potential risks such as heat stress or pest infestations, providing beekeepers with timely alerts (Zaman & Dorin, 2023).

By integrating climate data and weather forecasts, the digital systems can also help anticipate extreme weather events, enabling beekeepers to take proactive steps to protect the colonies and improve its ability to deal with climate-related challenges.

Transhumance

Transhumance, the practice of relocating bee colonies to resource-rich areas is a key strategy in modern beekeeping (Vercelli *et al.*, 2021). Beekeepers move hives either to boost honey production or to prevent food shortages by ensuring access to abundant forage. While transhumance offers significant benefits, it also presents several challenges. The physical relocation can cause stress to the colonies, disrupting their natural behaviours and lead to a temporary decline in productivity as they adjust to the new environment. Additionally, this practice increases the risk of spreading diseases and pests such as Nosema or Varroa mites, between regions, potentially devastating local bee populations (Martínez-López *et al.*, 2022).

Furthermore, relocating colonies may disrupt ecosystems, as non-native bees could outcompete or displace local pollinators,

threatening biodiversity. Legal restrictions also complicate transhumance, as many areas impose strict regulations to prevent the spread of pests, which can result in fines or quarantine measures if not followed. Financially, the costs of transporting hives and acquiring necessary equipment can be burdensome for small-scale beekeepers. Climate and weather uncertainties at the destination can also pose a risk, as adverse conditions may lead to food shortages for the bees. Thus, while transhumance is a valuable tool for beekeepers, it requires careful management to mitigate these risks and ensure the health and sustainability of bee colonies (Zacepins *et al.*, 2016).

Beekeeping and Bee Health During the COVID-19 Pandemic

The global spread of COVID-19 caused widespread disruptions to production across the world, but beekeeping remained largely unaffected during the pandemic (Sivakumar *et al.*, 2023). This resilience can be attributed to the fact that honeybees primarily rely on nectar, honeydew, and pollen collected within a 3 km radius of their hives, so, food shortages are not a significant issue (Van Der Sluijs & Vaage, 2016). More surprisingly, the lockdown imposed in many regions provided bees with several unintended benefits.

As countries enforced restrictions, air pollution levels dropped significantly, leading to notable improvements in air quality. For instance, in major cities such as New York, air pollution decreased by 50%, and in China, emissions were reduced by 25% (Ficetola & Rubolini, 2020). Similarly, the United Kingdom, Spain, and Italy also observed reductions in nitrogen dioxide (NO₂) emissions. The reduction in pollutants, including NO₂, carbon monoxide (CO), sulphur dioxide (SO₂), and particulate matter (PM), contributed to these reductions, which contributed to an overall improvement in air quality, which had a positive impact on bee populations (Saha *et al.*, 2022). In many megacities, the concentration of air pollutants like NO₂ and PM decreased by over 60%

during the lockdown period, which significantly improved environmental conditions for wildlife, including bees (Pal *et al.*, 2022).

For bees, the cleaner air and reduced human activity resulted in a more favourable environment for foraging. Car exhaust pollution is known to interfere with a bee's ability to detect floral scents by altering the chemical composition of these scents (Attia *et al.*, 2020). The decrease in traffic and pollutants allowed bees to forage more effectively, with fewer disturbances affecting their natural behaviours.

Additionally, the reduction in human activity allowed wildflowers and natural vegetation to thrive, providing more abundant food sources for bees thus encouraging better pollination. This temporary improvement in environmental conditions likely contributed to healthier bee colonies and increased pollination during the lockdown (Scivicco *et al.*, 2022). The reduction in pollution enabled bees to forage in areas that were previously impacted by human activities, which enhanced the insects' health and productivity.

Overall, the COVID-19 pandemic highlighted the significant role of environmental quality in supporting bee health and the potential for cleaner urban environments to benefit pollinators. The improvement in air quality during the lockdown period, driven by a global reduction in industrial and transportation activities, offers a clear example of how human behaviour and environmental conditions directly affect bee populations and biodiversity (Saha *et al.*, 2022).

Application of Beekeeping

Beekeeping is a type of farming that allows even those without land to participate. This migratory activity can lead to increased crop yields through cross-pollination. When bees are involved, some crops can experience yield increases of up to 200%. Bees are critical in pollinating both cultivated and wild plants, making them an indispensable part of agriculture. Farmers are often willing to invest millions of dollars

in hiring hives to fertilise their crops. Bees are responsible for pollinating over one-third of the crops humans use for food, either directly or indirectly. Remarkably, beekeeping presents a rewarding low-maintenance, high-impact opportunity for various stakeholders.

The primary products derived from apiculture are honey and wax, with the primary role being pollination (Figure 3). Bees contribute to crop pollination, resulting in increased yields, and they also support thriving honey businesses (Tutuba *et al.*, 2019). While honey production is the primary focus of beekeeping, other minor products such as royal jelly, pollen, propolis, venom, and wax hold value for buyers. They are used in various industries like cosmetics, polishing, and pharmaceuticals (Ediriweera & Premarathna, 2012). Honey, known for its medicinal properties and nutritional value, also has a host of applications in culinary preparations and therapeutic uses (Zgank, 2019; Zulkifli *et al.*, 2023; Agussalim *et al.*, 2024; Zulkifli *et al.*, 2024).

The global honey market was valued at \$9.21 billion in 2020 and is expected to grow by 8.2% (García, 2018). Honey contains essential nutrients, including calcium, minerals, vitamins, and antioxidants (Bogdanov *et al.*, 2008). It possesses various medicinal properties such as maintaining blood pressure levels, improving metabolism, reducing the risk of diabetes, and promoting wound healing (Majtan, 2014). Additionally, honey has been used to treat various conditions, including eye diseases, throat infections, bronchial asthma, tuberculosis, sleeping disorders, diabetes, and more, in addition to serving as a nutritious and easily digestible diet for the elderly (Ediriweera & Premarathna, 2012; Al-Asiri *et al.*, 2017; Zulkifli *et al.*, 2023; Agussalim *et al.*, 2024; Zulkifli *et al.*, 2024).

Cosmetics, including lip ointments, cleansing milk, moisturising creams, after-sun products, tonic lotions, shampoos, and conditioners, often feature honey as a key ingredient (Ediriweera & Premarathna, 2012; Burlando & Cornara, 2013). The increasing

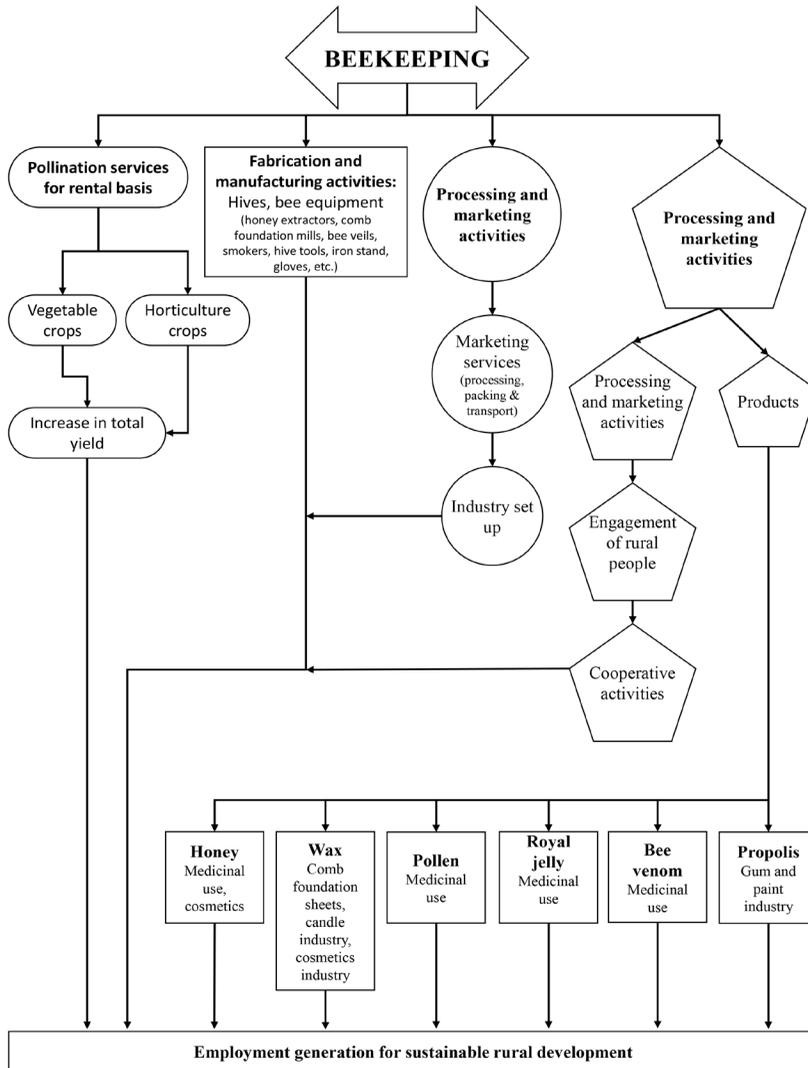


Figure 3: Various activities through beekeeping
 Soh *et al.* (2021)

demand for nutritious food items such as honey, driven by growing awareness of healthy lifestyles is a significant driver of market growth (Kasote, 2017). Beekeeping’s major benefits include providing nutritious food (all bee products) and serving as a source of industrial products (cosmetics, pharmaceuticals, etc.).

Beekeeping is a sustainable production model that holds paramount importance for biodiversity, encompassing social and economic dimensions. It has been practiced historically in

various regions, aiding in preserving ecological balance and natural biodiversity and benefiting plants and animals (Ingrao, 2021). Honeybees thrive on a diverse plant diet, serving as vital indicators of ecosystem health.

Modern Beekeeping Practice

Apiculture or beekeeping can be characterised in various ways, with one of the key aspects being integrating innovative technology, which enhances apiary efficiency (Chand *et al.*, 2021).

Individualist Specialisation

Modern beekeeping often features individual specialisation. Without queens, beekeepers can visit specialised bee nurseries where large farms are involved in queen removal and implementation. Pollen is collected and stored in specific beehives within expansive apiaries serving greenhouses, some of it is transferred to working beehives supporting greenhouse crops (Meo *et al.*, 2017).

Mobile Apiaries

The use of mobile apiaries is becoming increasingly common in modern beekeeping. This approach offers several advantages, including saving time and energy of the bees by eliminating the need for them to fly from field to hive for harvesting of nectar for honey (Sivakumar *et al.*, 2023). Hive positioning in compact spaces, easy-to-inspect frames, and the absence of the need for a smoker or protective gear for beekeepers when transporting bees are key benefits. Mobile apiaries can also enhance crop output by improving pollination efficiency.

Regular Colony Management and Inspection

Regular colony inspections to assess brood conditions, adding extra hive supers during flowering seasons, monitoring and harvesting ripe honey, adjusting hive space, providing supplemental feed during dearth periods, and detecting and controlling bee pests are all practices that enhance colony performance. These practices contribute to reduce absconding, stronger colony health, and higher hive yields.

Contract Farming

Contract farming involves a written agreement between farmers and purchasers outlining their responsibilities as trading partners. Buyers typically provide embedded services, including inputs and pre-financing of input supplies on credit. This service is particularly valuable, as amateur beekeepers in Russia own approximately a million apiaries nationwide (Kostenko, 2022).

Artificial Intelligence in Bee Farming

The role of digital farming has gained significant attention in recent years, driven by various research initiatives. Central to this evolution are platforms that integrate human-computer interfaces and IoT modules, creating interconnected systems that provide real-time data on agricultural operations (Sharma & Shivandu, 2024). In beekeeping, Information and Communication Technologies (ICT) are essential for assessing colony health, behaviour, and productivity, thus, advancing the practice of precision apiculture (KIIS, 2017; Zaman & Dorin, 2023).

A notable application of artificial intelligence in beekeeping is the use of Machine Learning (ML) techniques such as deep Graph Attention Convolutional Neural Networks (GACNN), to diagnose complex issues like chemical poisoning in honeybees (Chen *et al.*, 2024). GACNN analyses the relationship between various environmental data points, enabling it to predict potential risks like chemical exposure based on the broader context of the colony's environment. This ability to process both local and environmental data allows for more accurate predictions of threats to bee health, especially in diverse and variable conditions across regions (Chen *et al.*, 2021). Such AI-driven models are promising tools for addressing the complex and highly variable problems in beekeeping, making them crucial for advancing both research and practice (Wei *et al.*, 2012).

In parallel, Smart Apiculture Management Services (SAMS) represent a significant advancement in beekeeping technology, particularly for small-scale operations in developing countries (Wakjira *et al.*, 2021). SAMS is a three-tiered system designed to enhance bee health management and productivity through remote monitoring and ICT solutions. The project, funded by the European Union, aims to promote sustainable agriculture and the UN Sustainable Development Goals by facilitating international collaboration between Europe, Ethiopia, and Indonesia.

By implementing User-Centered Design (UCD) principles, SAMS addresses the specific needs of beekeepers in these regions, enabling them to monitor hives remotely, track colony health, and optimise productivity. This system has demonstrated positive outcomes in Ethiopia and Indonesia, where beekeepers can assess temperature, humidity, and colony behaviour in real-time. The integration of these technologies has led to improved honey yields, job creation (especially for youth and women), and increased local investment in beekeeping. Additionally, SAMS fosters knowledge exchange through international partnerships and networks, promoting sustainable practices across different regions (Wakjira *et al.*, 2021). Table 2 provides an overview of the development and responses of hives, the Decision Support System (DSS), and adapted bee management techniques.

Furthermore, ICT and remote sensing technologies play a critical role in bee pollination and the sustainable production of hive products. By enabling real-time monitoring, these tools help ensure that bees operate in optimal conditions, thereby improving overall hive productivity and ecosystem health (Sagili & Burgett, 2011; Gaga & Esaulov, 2016). One approach, known as precision apiculture, focuses on monitoring individual colonies rather than conducting general hive inspections, leading to more targeted interventions that boost bee output (Garcia, 2018).

However, despite the potential of these technologies, challenges remain, particularly in rural or underdeveloped areas. The high costs of implementing such systems can be prohibitive for small-scale beekeepers, the

technological literacy required to operate advanced tools like ML and IoT devices may be lacking (Andrijević *et al.*, 2022). These barriers can hinder the widespread adoption of digital technologies in beekeeping, making it crucial to develop affordable and accessible solutions that empower beekeepers in less-developed regions. Therefore, while the potential benefits of digital farming in beekeeping are clear, addressing these challenges is essential for ensuring that these technologies are inclusive and widely adopted (Huet *et al.*, 2022).

Quality Honey Constraints and Future Prospects

Quality honey production and the authenticity status of honey are among the major issues in beekeeping (Md Dan *et al.*, 2018; Samat *et al.*, 2018; Ismail *et al.*, 2020). Quality honey is critical from the standpoint of a buyer. If international standards are reached, the country’s honey sector might become a substantial source of foreign cash. The potential export market may be exploited by employing contemporary collecting, storage, beekeeping practices, honey processing, and bottling technology. It is crucial to consider how to encourage high-quality production while expanding the export market.

Meanwhile, fake and adulterated honey was reported to impact consumers negatively (Samat *et al.*, 2018). Realising the issues that may jeopardise the beekeeping industry, beekeepers, academics, and other apiculture stakeholders might develop networks and groups that would allow them to share information about honeybee health and their products, particularly honey. Training is one of the effective techniques for

Table 2: Development and response of hives, DSS, and adapted bee management (Garcia, 2018; Wakjira *et al.*, 2021)

Development	Response
Modern and modular hives	Bee colony behaviour, production, and health conditions are all monitored via a remote measuring system
Cloud-based Decision Support System (DSS)	Management Advisory Support Service (ASS)
Adapted bee management	Seasonal changes and ICT-data driven model for needed beekeeping actions

raising awareness about honey and promoting honeybee colony marketing. The safety of agrochemicals used in agricultural cultivation is now being tested. It also necessitates rules that govern pesticide management such as marketing, storage, and application (Wang *et al.*, 2020).

Conclusions

Beekeeping, practiced globally with a blend of traditional and modern techniques is undergoing transformative changes fuelled by innovative technologies. Examples of such advancements include smart hive monitoring systems, precision beekeeping apps utilising artificial intelligence, and automated honey extraction systems. Recognising the vital role of bees as essential pollinators in agriculture, the integration of these technologies becomes imperative. Sustainable beekeeping practices, coupled with inventive products contribute not only to the well-being of bees but also aligns with broader environmental conservation goals. This delicate balance between tradition and innovation is pivotal for the sustained success of global beekeeping efforts. By embracing the technological advancements, beekeepers can enhance their practices, ensure the health of bee colonies, and play a crucial role in preserving the ecosystems that rely on the pollination services provided by bees.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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