A Comprehensive Review of Sustainable Technologies for Managing *Varroa destructor* in Honey Bee Colonies

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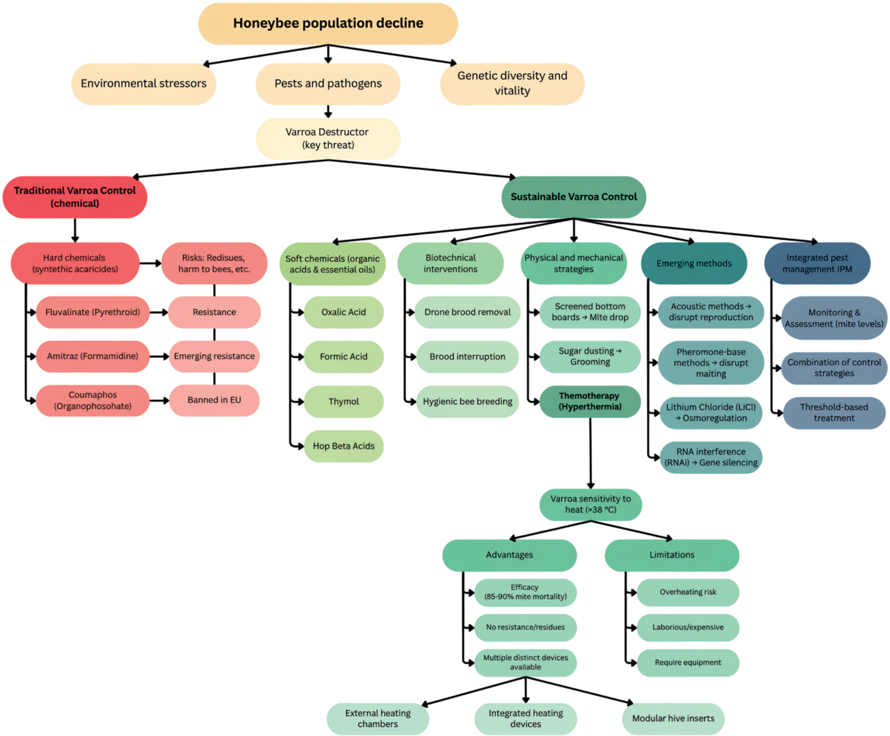
Abstract: Honeybees (*Apis mellifera*) play a key role in sustaining both global biodiversity and agricultural productivity. However, escalating declines in bee populations — largely driven by multifactorial stressors such as climate change, habitat loss, and notably, infestations by the parasitic mite *Varroa destructor* — pose significant threats to food security and rural economies. Traditional chemical treatments, despite their initial efficacy, have become increasingly problematic due to the emergence of chemical resistance, residue contamination, and adverse environmental impacts. This comprehensive review critically examines the current state of sustainable Varroa management, with a particular focus on the potential of thermotherapy. Thermotherapy, utilising controlled heat exposure, demonstrates high levels of mite mortality without compromising colony health, while complementary methods such as drone brood removal and organic acid applications further enhance the resilience of bee populations. By evaluating diverse technologies and their scalability, this paper advocates for a multidisciplinary approach that integrates advanced monitoring systems and innovative control mechanisms, and integrated pest management (IPM) strategies. Ultimately, the adoption of eco-friendly technologies is imperative to secure the long-term viability of apiculture and the essential ecosystem services it provides.



Graphic abstract

Keywords: Honey bee, Varroa destructor, Thermotherapy, Integrated Pest Management, Sustainable Apiculture

1 Introduction

The ecological and economic significance of honeybees (*Apis mellifera*) is unparalleled. Honeybees, comprising 28 recognised subspecies (Engel, 1999), are crucial pollinators for numerous crops, contributing directly to global food security. Approximately 70% of the world's major crops depend on pollinators, primarily honeybees, for reproduction (TAPHA, 2018). In the European Union alone, 84% of agricultural crops rely on pollination, with *A. mellifera* playing a central role due to its floral fidelity—pollinating single plant species per foraging trip (Knapton, 2015; Thebees.info, 2010). Beyond pollination, honeybees support the production of honey, wax, and other products that sustain rural economies globally.

However, honeybee populations are confronting critical threats. Factors such as climate change, pesticide use, habitat destruction, and monoculture farming have led to significant declines in bee health and colony numbers. In the United Kingdom, managed colonies plummeted from 250,000 in the 1950s to under 100,000 by 2015 (Potts *et al.*, 2010), a trend mirrored globally. Among these stressors, the parasitic mite *Varroa destructor* stands out as the most devastating biological threat to honeybees worldwide. This mite not only weakens individual bees by feeding on their fat body tissues but also spreads harmful viruses, such as the Deformed Wing Virus (DWV), which significantly reduces bee lifespan (Wilfert *et al.*, 2016; Rosenkranz *et al.*, 2010).

Traditional methods for controlling *Varroa destructor* have relied heavily on chemical treatments. While effective, these methods pose risks of chemical residues in honey and wax, resistance development in mites, and potential harm to bees themselves (National Bee Unit, 2018; Goulson *et al.*, 2015). Consequently, there is an urgent need to develop and adopt sustainable, non-chemical methods that are both effective and environmentally friendly.

In recent years, thermotherapy has emerged as a promising approach to controlling *Varroa destructor*. This method involves the application of controlled heat to the hive, exploiting the mite's vulnerability to temperatures above 38°C while preserving bee health. Thermotherapy is a green technology that avoids chemical residues and aligns with the growing global demand for sustainable apiculture (Bičík *et al.*, 2016; Linhart, 2015).

This paper aims to provide a comprehensive review of the current state of sustainable technologies, particularly thermotherapy, for managing *Varroa destructor*. By evaluating existing devices, their efficacy, and their scalability, we seek to highlight the potential of these technologies to revolutionise the management of Varroa mites while promoting sustainable beekeeping practices.

1.1 Ecological and Agricultural Significance of Honeybees

Honeybees (*Apis mellifera*) play a fundamental role in maintaining ecological balance and supporting agricultural productivity worldwide. Their primary ecological function is pollination, a process that enables the reproduction of many flowering plants and crops. As central-place foragers, honeybees exhibit remarkable adaptability, colonising diverse ecosystems across all continents except Antarctica through subspecies differentiation (e.g., *A. m. ligustica*, *A. m. scutellata*) and behavioural plasticity, such as migratory swarming in temperate climates (Engel, 1999; Mortensen *et al.*, 2013; Al-Ghamdi *et al.*, 2013).

The species' haplodiploid reproductive system—where fertilised eggs yield female workers or queens, and unfertilised eggs produce male drones—ensures efficient colony dynamics. Worker bees, though non-reproductive, are anatomically specialised for pollen and nectar collection, with barbed stingers that eviscerate their abdomens upon use. Queens, distinguished by elongated abdomens and smooth stingers, sustain colony reproduction, while drones facilitate genetic diversity (Mortensen *et al.*, 2013; Craig, 2017). This caste system underpins their ecological dominance, with queens achieving lifespans of up to three years under optimal conditions (Mortensen *et al.*, 2013).

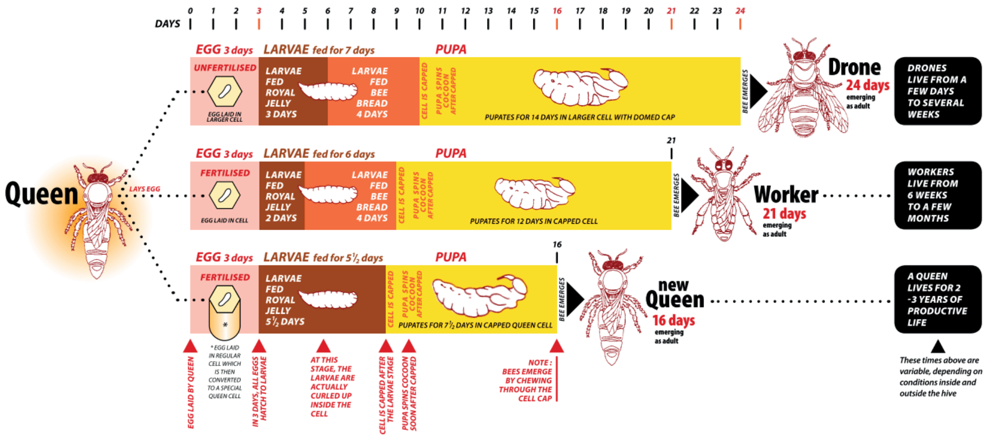


Figure 1: Figure Bee life cycle (Craig, 2017)

Economically, honeybees are indispensable. The National Audit Office estimated the value of their pollination services in the UK at £200 million annually, with the broader retail value of pollinator-dependent crops exceeding £1 billion (Holland, 2009). Specific crops, such as strawberries (*Fragaria × ananassa*) and apples (*Malus domestica*), rely on honeybees for 45% and 85% of their production, respectively (Knapton, 2015). Globally, commodities like coffee (*Coffea arabica*), cocoa (*Theobroma cacao*), and sunflower oil depend entirely on bee-mediated pollination. Paradoxically, while agroindustry increasingly cultivates pollinator-dependent crops, *A. mellifera* populations face precipitous declines, threatening food security and biodiversity (Goulson *et al.*, 2015).

1.2 Multifactorial Threats to Honeybee Health

Honeybee populations confront a multitude of anthropogenic and environmental stressors:

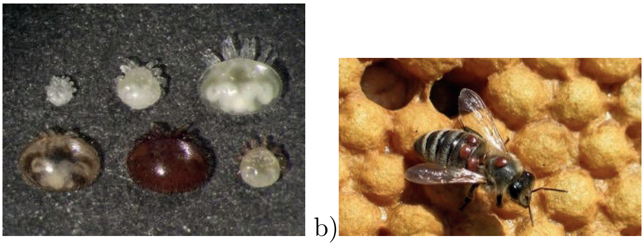
1. Industrial Agriculture: Monoculture expansion and agrochemical use—notably neonicotinoids—compromise nesting habitats, reduce floral diversity, and impair bee immunocompetence. Sublethal exposure to neonicotinoids disrupts olfactory learning and navigation, exacerbating susceptibility to pathogens (Tirado *et al.*, 2013; Jeschke *et al.*, 2010; USDA ARS, 2023).
2. Climate Change: Rising temperatures alter floral phenology, creating mismatches between bloom periods and bee emergence. Extreme heat (>40°C) forces colonies to abandon thermoregulation efforts within 3–4 days, triggering swarming (De Almeida, 2008; Kridi *et al.*, 2016). Latitudinal range contractions—up to 200 miles in Europe and North America—further imperil pollinator resilience (Kerr *et al.*, 2015; Worland, 2015).
3. Parasitism: The ectoparasitic mite *Varroa destructor* remains the most pervasive threat, vectoring virulent pathogens like Deformed Wing Virus (DWV) while feeding on fat body tissues critical for metamorphosis (Ramsey *et al.*, 2019). Heavy infestations (>3 mites per 100 bees) induce symptoms such as

scattered brood patterns, crippled bees, and colony collapse within 1–3 years (Bee Aware, n.d.; Jack & Ellis, 2021).

These synergistic stressors drive phenomena such as Colony Collapse Disorder (CCD), where worker bees abandon hives en masse, leaving behind queens and immature brood (USDA ARS, 2023). In Australia, where *Varroa destructor* was detected in 2022, authorities have shifted from eradication to management strategies, highlighting the mite's inexorable spread (The Guardian, 2024).

2 The Threat of *Varroa destructor*

Honeybees (*Apis mellifera*) face significant biological challenges that threaten their survival, with the parasitic mite *Varroa destructor* (formerly *Varroa jacobsoni*) being the most severe. This section explores the lifecycle of the mite, its impact on honeybee colonies, and the reasons behind its rapid global spread.



a) b)

Figure 2: (a) Composition of a "Varroa family" within a honeybee worker brood cell (Rosenkranz et.al, 2010) (b) A worker bee with four Varroa mites. (Rothamsted Research Ltd, 2016)

2.1 Lifecycle of *Varroa destructor*

Varroa destructor is an obligate ectoparasite that primarily targets honeybees, feeding on their haemolymph through perforations made in the host's cuticle using specialised mouthparts (TAPHA, 2018). Originally a parasite of the Asian honeybee (*Apis cerana*), it has adapted to infest *A. mellifera*, which lacks natural defences against this novel parasite (Rosenkranz *et al.*, 2010).

The reproductive cycle begins when a gravid female mite enters a brood cell shortly before capping. Concealed within larval food reserves, the mite initiates oviposition 1–2 days after cell sealing, laying up to seven eggs (National Bee Unit, 2018). Of these, only 2–3 progeny—typically one male and several females—reach adulthood. The developing mites feed on the pupa's haemolymph, with maturation synchronised to coincide with the host's emergence (Figure 2a). Post-emergence, adult female mites attach to adult bees, using them as vectors to disperse to new brood cells (National Bee Unit, 2018). Male mites, smaller and pale-yellow, remain confined to brood cells and die after mating (TAPHA, 2018).

This lifecycle exploits the colony's reproductive cycle, with drone brood preferred due to its longer development period, allowing higher mite fecundity (Rosenkranz *et al.*, 2010).

2.2 Impact on Honeybee Colonies

Varroa destructor infestation, termed *varroosis*, induces systemic colony degradation. Direct damage arises from haemolymph depletion, which weakens individual bees and reduces worker weight by up to 25% (Ramsey *et al.*, 2019). Indirectly, the mite vectors viral pathogens, including Deformed Wing Virus (DWV), which causes crippled wings, atrophied abdomens, and premature mortality (Wilfert *et al.*, 2016).

Heavy infestations (>3 mites per 100 bees) manifest as:

- Scattered brood patterns due to pupal mortality.
- Parasitic Mite Syndrome: Emergence of deformed, flightless workers (Figure 2b).
- Colony Collapse: Untreated colonies collapse within 2–3 years in temperate climates, as winter bees—critical for thermoregulation—succumb to viral loads (National Bee Unit, 2018; Jack & Ellis, 2021).

The mite's role in DWV transmission is exacerbated by anthropogenic activities, such as the global trade of infected colonies, which facilitates viral recombination and spread (Wilfert *et al.*, 2016).

2.3 Global Spread and Resistance

Varroa destructor has achieved near-global distribution, absent only in Australia until its 2022 detection (The Guardian, 2024). First reported in the UK in 1992 (Devon), its spread reflects human-mediated dispersal through hive translocations and equipment sharing (National Bee Unit, 2018). Five factors amplify its threat:

1. Novel Host-Parasite Dynamic. *Apis mellifera* lacks the co-evolved defences exhibited by its Asian counterpart (*Apis cerana*), which grooms intensively to dislodge mites and selectively removes infested brood. Genetic studies reveal that *A. mellifera* has not yet undergone significant selection for resistance traits, leaving colonies vulnerable to unchecked mite reproduction (Mondet *et al.*, 2021). This evolutionary mismatch explains why *Varroa*-induced colony losses in Europe and North America are 3–5 times higher than in regions where *A. cerana* is native (Traynor *et al.*, 2020).
2. Economic Burden. *Varroa* management costs beekeepers an estimated 70–120 USD per hive annually in miticides, monitoring devices, and labour (Steinhauer *et al.*, 2018). In the U.S. alone, annual losses attributed to *Varroa* exceed 300 million USD, driven by colony replacements, reduced honey yields, and pollination service deficits (USDA, 2022). Residues from synthetic miticides (e.g., fluvalinate) also render honey unsellable in EU markets, where maximum residue limits (MRLs) are strictly enforced (Calatayud-Vernich *et al.*, 2018).
3. Rapid Colony Collapse. Untreated colonies in temperate climates collapse within 2–3 years, as *Varroa* infestation reduces winter bee

lifespans by 50% (Döke *et al.*, 2015). A 2023 meta-analysis found that colonies with >3 mites per 100 bees in autumn had a 92% probability of dying before spring (van Dooremalen *et al.*, 2012). This rapid collapse destabilises pollination-dependent sectors, with apple and blueberry yields declining by 12–18% in high-infestation regions (Smith *et al.*, 2022).

4. Viral Synergy. *Varroa*'s role as a viral vector exacerbates colony mortality. The mite not only transmits DWV but also amplifies viral loads by 1,000 times within infected bees (Nazzi *et al.*, 2012). Recombinant DWV strains, such as DWV-B, exhibit heightened virulence, causing 70% pupal mortality in *Varroa*-infested colonies *versus* 10% in mite-free hives (Gisder *et al.*, 2018). Climate change further intensifies this synergy, as warmer winters enhance mite reproduction and viral replication (Le Conte *et al.*, 2008).
5. Chemical Resistance. Resistance to pyrethroids (e.g., fluvalinate) and organophosphates (e.g., coumaphos) is now reported in 85% of Varroa populations globally (Hernández-Rodríguez *et al.*, 2021). A 2021 study documented mites surviving doses of amitraz 15 times higher than the lethal threshold, linked to mutations in the *-adrenergic-like octopamine receptor* gene (Hernández-Rodríguez *et al.*, 2022). This resistance has spurred reliance on stopgap treatments like oxalic acid, which lack long-term efficacy (Kanelis *et al.*, 2023).

In Europe, Varroa-driven colony losses have reduced pollinator services by 30–50%, exacerbating declines in wild bee populations (De la Rúa *et al.*, 2009). Australia's recent shift from eradication to management underscores the mite's tenacity and the urgency of sustainable solutions (The Guardian, 2024).

3 Overview of Varroa Control Methods

Effective management of *Varroa destructor* necessitates a multifaceted approach, combining chemical and non-chemical strategies. This section categorises methods into soft chemicals (low residual toxicity, organic compounds) and hard chemicals (synthetic acaricides), followed by alternative sustainable approaches. Each method is evaluated for efficacy, practicality, and ecological impact, integrating novel insights from recent research and practical beekeeping resources.

3.1 Chemical Methods

Chemical control, or the use of miticides, has been one of the most common strategies for managing *Varroa destructor*. These substances are applied directly to the hive to kill mites on adult bees and within the brood.

3.1.1 Soft Chemicals

Soft chemicals, derived from natural sources, offer reduced environmental persistence and lower resistance risk. Their application requires precision to balance efficacy and hive safety.

Organic Acids

- Oxalic Acid (OA): A cornerstone of organic beekeeping, OA disrupts mite cuticle integrity and metabolic pathways. Applied *via* dribbling (3–4% solution) or vaporisation (2.5g sublimated), it achieves 90–95% efficacy during broodless periods. However, OA cannot penetrate capped brood, necessitating timed applications (Rademacher & Harz, 2006; Apisave, 2024).
- Formic Acid (FA): Unique for its brood-penetrating vapours, FA is delivered *via* gel pads (e.g., MiteGone®, MAQS™, Formic Pro) or liquid dispensers. At 65–85% concentration, it eliminates 80–90% of mites but risks queen mortality above 30° C (Stainton & Ponting, 2020).

Essential Oils

- Thymol: Extracted from thyme (*Thymus vulgaris*), thymol disrupts mite respiration. Products like Apiguard® (gel) or ApiLife VAR® (tablets) yield 70–80% efficacy in moderate climates (20–25°C), though efficacy plummets in cooler conditions (Imdorf *et al.*, 1995; Wood, 2024).
- Hop Beta Acids: A novel miticide targeting mite vitellogenin synthesis, hop beta acids (Api-Bioxal®, Hop Guard 3) reduce mite populations by 60–70% with minimal bee toxicity (DeGrandi *et al.*, 2012).

Table 1: Table Soft Chemical Treatments

Compound	Mechanism	Application Method	Efficacy (%)	Limitations
Oxalic Acid	Cuticle corrosion, metabolic disruption	Dribbling, vaporisation	90–95	Brood-blind; requires precise timing
Formic Acid	Fumigation, brood penetration	Gel pads, liquid trays	80–90	Temperature-sensitive; queen mortality risk
Thymol	Respiratory inhibition	Gel, tablets	70–80	Requires 20–25°C; repellent at high doses
Hop Beta Acids	Vitellogenin inhibition	Strips	60–70	Slow-acting; limited field data

3.1.2 Hard Chemicals

Hard chemicals, synthetic acaricides, provide rapid knockdown but carry risks of resistance and contamination.

Synthetic Miticides

- Fluvalinate (Pyrethroid): A sodium channel modulator, fluvalinate (Apistan®) historically achieved 85–95% efficacy. However, *kdr*-gene mutations now confer resistance in 90% of global mite populations (Sanford, 1997; BeeKeepClub, 2023).

- Amitraz (Formamidine): Binds octopamine receptors, inducing mite hyperexcitation. Apivar® strips deliver 95–98% mortality in non-resistant strains, but target-site mutations (e.g., -adrenergic receptor SNPs) are rising (Tabafunda *et al.*, 2023; Takata *et al.*, 2020).

- Coumaphos (Organophosphate): An acetylcholinesterase inhibitor banned in the EU since 2017 due to honey contamination risks. Efficacy has dwindled to 70–80% amid esterase-based resistance (PANI, 2021; ApiSave, 2024).

Table 2: Hard Chemical Treatments

Compound	**Mechanism**	**Application Method**	**Efficacy (%)**	**Limitations**
Fluvalinate	Sodium channel activation	Plastic strips	85–95*	High resistance (kdr mutations)
Amitraz	Octopamine receptor agonist	Cardboard strips	95–98*	Emerging resistance; hive residues
Coumaphos	Acetylcholinesterase inhibition	Strips	70–80	Banned in EU; honey contamination

*Efficacy in non-resistant populations

3.2 Alternative Sustainable Methods

Sustainable strategies for managing *Varroa destructor* focus on disrupting the mite's lifecycle while preserving colony health and product integrity. These approaches leverage biological, physical, and behavioural vulnerabilities of the parasite, offering scalable solutions with minimal ecological footprint.

3.2.1 Biotechnical Interventions

- Drone Brood Removal: Exploits the mite's preference for drone cells, which provide a longer developmental period (24 days vs. 21 for workers). By introducing removable drone frames, beekeepers trap reproducing mites, which are subsequently eliminated through freezing or destruction. This method reduces mite populations by 50–93% per cycle but demands precise timing to prevent mite emergence (Gordon, 2024; Hunt, n.d.).
- Brood Interruption: Achieved by caging the queen for 9–12 days, this creates a broodless window, forcing mites onto adult bees where they become susceptible to treatments like oxalic acid. When combined, these methods achieve >90% efficacy (Büchler *et al.*, 2020).

3.2.2 Biological Controls

- Entomopathogenic Fungi: Notably *Metarhizium anisopliae*, offer a natural solution. Fungal spores adhere to mites, penetrate their exoskeletons, and induce lethal infections. Efficacy reaches 60–70% under humid conditions (>70% RH), though sporulation requires consistent moisture (Dietemann, 2012).
- Hygienic bee breeding, particularly through Varroa-Sensitive Hygiene (VSH) strains, enhances colonies' innate ability to detect and remove infested brood, reducing mite loads by 30–50% (Spivak & Reuter, 2001).

3.2.3 Physical and Mechanical strategies

- Screened Bottom Boards: Provide passive control by allowing dislodged mites to exit the hive, reducing reattachment rates by 11–14%. While insufficient as a standalone solution, they complement chemical-free regimens (Jack & Ellis, 2021).
- Thermotherapy: Involving controlled hive heating to 40–42°C for 2–3 hours, exploits the mite's thermal sensitivity, achieving 85–90% mortality in brood and phoretic mites. Precision is critical to avoid bee stress or brood damage (Bičík *et al.*, 2016).

3.2.4 Homemade Solutions

- Sugar Dusting: Powdered sugar applied to bees stimulates grooming behaviour in bees, dislodging 30–40% of mites, which then fall through screened bottom boards. Though labour-intensive, it serves as a non-toxic adjunct to other methods (BeeKeepClub, 2023).
- Mineral Oil Fogging: Using food-grade oil mixed with wintergreen oil, coats mites and disrupts their attachment to bees. With 70–85% efficacy, it is safe during honey flow but requires repeated applications (BeeKeepClub, 2023).

3.2.5 Emerging Innovations

- Acoustic methods: Utilise high-frequency sound waves (14,000–15,000 Hz at 90 dB) to disrupt mite feeding and reproduction. Exposure to this acoustic stress induces mortality within 10–20 days without affecting bee behaviour (Krüger, 2017).
- Pheromone-based strategies: Deploy synthetic compounds to interfere with mite mating cycles. By mimicking or blocking natural pheromones, these treatments cause mismatched reproductive timing, leading to Varroa population collapse (Frenkie, 2014).
- Lithium Chloride (LiCl): A novel agent with systemic and contact action. Repeated trickling (500 mM LiCl) yields 97% efficacy by disrupting mite osmoregulation. Residues remain below toxic thresholds (Kolics *et al.*, 2022).
- RNA Interference (RNAi): Double-stranded RNA targeting genes critical for mite reproduction (e.g., *vitellogenin*) or metabolism. CRISPR technology could suppress populations through genetic silencing. Early laboratory trials show promise, with potential for species-specificity and long-term efficacy, reducing reproduction by 80% in experimental hives. However, ethical concerns, regulatory barriers, and technical challenges—such as delivery mechanisms—remain significant hurdles (GreenLight Biosciences, n.d.; Chen *et al.*, 2012).

Table 3: Alternative Methods Comparison

Method	Mechanism	Efficacy (%)	Advantages	Limitations
Drone Brood Removal	Traps mites in drone cells via removable frames	50–93	Chemical-free; targets reproductive mites	Labour-intensive; requires precise timing
Thermotherapy	Heat exposure (40–42°C) kills mites	85–90	No residues; effective on brood and phoretic mites	Equipment-dependent; risk of overheating bees
Entomopathogenic Fungi	Metarhizium spores infect and kill mites	60–70	Eco-friendly; self-replicating	Requires high humidity (>70%); slow-acting
Lithium Chloride (LiCl)	Disrupts mite osmoregulation via trickling	97 (repeated)	Safe for honey; penetrates capped brood	Requires precise dosing; residue monitoring needed
Acoustic Methods	High-frequency sound waves (14,000–15,000 Hz)	60–80	Non-invasive; no chemical residues	Experimental; requires uniform sound distribution
Pheromone Disruption	Synthetic pheromones disrupt mite mating	50–70	Species-specific; no hive contamination	Requires repeated application; limited field data
RNAi/CRISPR Gene Editing	Silences critical mite genes (e.g., reproduction)	$\sim$ 80 (theoretical)	Long-term suppression; high specificity	Ethical concerns; early R&D stage
Sugar Dusting	Powdered sugar induces grooming behaviour	30–40	Non-toxic; immediate application	Low standalone efficacy; labour-intensive
Screened Bottom Boards	Passive mite drop through mesh floors	11–14	Low-cost; complements other methods	Minimal standalone impact

4 Thermotherapy/Hyperthermia Devices

It has been established that *Varroa destructor* exhibits a high sensitivity to elevated temperatures, being incapable of reproducing in environments where the temperature is raised slightly above its optimal range (Linhart, 2015). According to Bičík (2016), the enzymes responsible for protein biosynthesis are likely to be the first to be affected by thermal stress in mites. Consequently, *Varroa destructor* perishes at temperatures exceeding 40°C and sustains severe physiological damage at 38° C (Linhart, 2015). However, temperatures exceeding 49–50°C have been observed to induce detrimental effects in honeybees (*Apis mellifera*), causing regurgitation, extreme lethargy, and clustering. If clustering occurs at a critical stage during heat treatment, it may lead to excessive overheating, thereby compromising both treatment efficacy and bee health (Cunningham, 1997).

When thermotherapy, also known as hyperthermia, is applied correctly, it proves to be considerably less aggressive to bees than chemical treatments and demonstrates comparable efficacy (Linhart, 2015). Studies indicate that elevating the temperature of the brood chamber to 40–47°C for a sustained period of 2.5 hours effectively eliminates *Varroa destructor* within the sealed brood without causing harm to the bee brood (Bičík, 2016). To ensure complete eradication of mites in the sealed brood, it is critical to maintain a minimum temperature of 40°C for 150 minutes, while temperatures exceeding 47°C are discouraged. Optimal results necessitate two consecutive thermotherapy sessions, with the second application scheduled between 7 and 14 days after the initial treatment (Bičík, 2015). A one-year field trial showed that an in-hive hyperthermia treatment device effectively suppressed Varroa mite populations below damaging levels without chemicals, although it caused some brood mortality and slightly reduced honey yield as trade-offs (Sandrock, 2024).

Table 4: Key temperatures for honeybees (Apis mellifera) and Varroa mites (Varroa destructor)

Brood box temperature [°C]	**Effect on Bees/Varroa**	**Additional notes**	**Reference**
<10	Bees cannot fly	Honeybees are cold blooded.	(Hiskey 2012)
20	Brood led to higher mortality	If they are submitted for a period greater than 12 hours.	(Wang *et al.* 2016)
<27	Bees keep inside and thermoregulate the hive	This inner temperature reflects an outside temperature of 9°C.	(Hiskey 2012)
26-33	Varroa is capable of reproduction	It also needs stress less conditions.	(Bičík, *et al.* 2016)
32.5-33.4	Optimal temperature for the development of Varroa	Often found inside the brood nest.	(Arnia 2013)
32-36	Normal temperatures in the brood chambers	Bees keep the brood nest at a constant temperature.	(Burlew 2012)
>36	The reproductive capability of female mites significantly decreases	Synthesis of proteins is affected.	(Bičík, *et al.* 2016)
>38	Varroa die without engaging in reproduction.	Female mites are damaged and become infertile.	(Bičík, *et al.* 2016)
40-47	Thermal conditions for Thermotherapy	It has to last 150 minutes. starting from the moment when the temperature reached 40°C at the floor.	(Bičík, *et al.* 2016)
>40	Increased mortality in adult bees	Bees die exposed to higher temperatures for more than 48 hours.	(Bičík, *et al.* 2016)
>41	Bees start swarming	When they cannot regulate the temperature for a long period (3-4 days).	(Kridi *et al.* 2016)
43-44	Thermoregulation of bees	Bees heat their bodies to raise the temperature of the beehive. Their thorax achieves up to 44°C.	(Arnia 2013) (Hiskey 2012)
46	Bees still can fly	While their thorax is still at 45°C.	(Heinrich and Esch 1994)
>49	Wax loses its mechanical strength	During thermotherapy the structural integrity of the work remains.	(Bičík, *et al.* 2016)
49-50	Bees overheating	They get lethargic and regurgitate if the lapse is prolonged.	(Cunningham 1997)
60-62	Cooling thermoregulation of bees	During thermotherapy no signs of damage to the brood or abnormalities in oviposition by the queens have been registered.	(Bičík, *et al.* 2016)

4.1 Evolution of Thermotherapy Devices

Hanko's Thermocube (1981, Czechoslovakia)
Developed as an early prototype, the Thermocube employed a transparent acrylic chamber with a wire mesh compartment to house bees. Solar radiation passively heated the interior to 45°C over 20 minutes, achieving 70% mite mortality. While innovative for its renewable energy use, the design suffered from inconsistent heat distribution and scalability issues, limiting its application to small bee samples (Linhart, 2016).

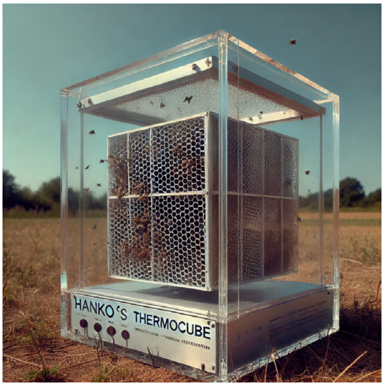


Figure 3: Figure Hanko's Thermocube (Illustration for visual reference, not a real photo)

Thermo-Bell (1983, Czechoslovakia)
This dual-layered device featured a bell-shaped outer chamber submerged in a heated water bath (45°C). Bees within the inner wire cavity were exposed to dry heat for 7 minutes, resulting in 95.7% mite mortality. Though effective for phoretic mites, the Thermo-Bell's reliance on external water heating made it impractical for brood treatment or large-scale use (Linhart, 2016).

Figure 4: Thermo-bell (Illustration for visual reference, not a real photo)

Kamler & Pastor Thermobox (1986, Czechoslovakia)
A gas-powered rotating chamber designed for brood-free colonies, the Thermobox heated bees to 46–48°C for 10 minutes. Its rotating mechanism improved heat uniformity, yielding 80–85% mite mortality. However, the exclusion of brood and dependence on gas infrastructure restricted its adoption (Linhart, 2016).

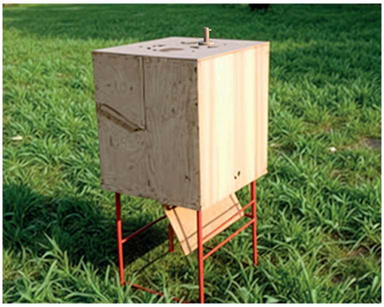


Figure 5: Kamler & Pastor Thermobox

Cunningham's Cabinet (1997, US)
This portable wooden chamber used a 1500W electric heater to force warm air through a metal mesh cylinder containing bees. Trials demonstrated 90% efficacy against phoretic mites, but the requirement to manually transfer bees and inability to treat brood rendered it labour-intensive (Cunningham, 1997).

Figure 6: Cunningham's Cabinet (Illustration for visual reference, not a real photo)

Mite Zapper (2001, US)
A frame-integrated electric resistance heater, the Mite Zapper targeted mites within capped brood cells. Installed adjacent to brood frames, it raised local temperatures to 40°C over 2 hours, achieving 75–80% efficacy. Despite its compact design, uneven heat distribution and compatibility issues with diverse hive types hindered its reliability (Imkershop, n.d.).

Figure 7: (left) Mite Zapper device and a battery; (right) System in use

Thermovar (2006, Greece)
Developed by a Greek beekeeper, Thermovar employed a thermal chamber with air ducts to circulate heated air uniformly across brood combs. An electronic controller maintained temperatures between 42°C and 45°C, achieving 88–92% mite mortality. While praised for its precision and comb-friendly design, the system's reliance on grid power and complex installation limited its adoption outside specialised apiaries (DIAS, n.d.).

Figure 8: Thermovar

Varroa Terminator (2010, Slovakia)
Featuring two 120W electric panels and evaporators, this device gradually heated brood boxes to 42°C over three hours while maintaining 60–70% relative humidity. Its gentle temperature ramp and humidity control minimised bee stress, yielding 88–92% efficacy. However, prolonged treatment durations and grid dependency limited its appeal for remote apiaries (Hivet, n.d.).

Figure 9: (left) Varroa Terminator device; (right) System in use

Rašnov Thermosolar Hive (2010, Romania)
This solar-insulated hive incorporated thermosolar panels below the roof to passively accumulate heat. By removing roof covers, beekeepers could elevate brood chamber temperatures to 40–47°C, achieving 85% mite mortality. While sustainable, the system demanded constant monitoring to prevent overheating and performed inconsistently in cloudy climates (Linhart 2015).

Figure 10: Thermosolar Hive with 2 National boxes

Varroa Controller (2011, US)

A thermally insulated chamber resembling an industrial oven, the Varroa Controller treated entire brood frames by heating them to 40–47°C. Equipped with electric heating, ventilation, and humidity sensors, it achieved 90–95% efficacy in controlled settings. However, the need to manually transfer frames and its steep cost (€2,424) relegated it to niche use in large-scale operations (ECODESIGN company GmbH, n.d).

Figure 11: Varroa Controller

The Victor (2013, US)

A roof-mounted electric resistance unit, The Victor distributed heat downward *via* fans, reaching 40°C within 90 minutes. Compatible with most commercial hives, it achieved 82–87% mite mortality but lacked humidity regulation and struggled to penetrate densely packed brood areas (Green Bee Hives, 2013).

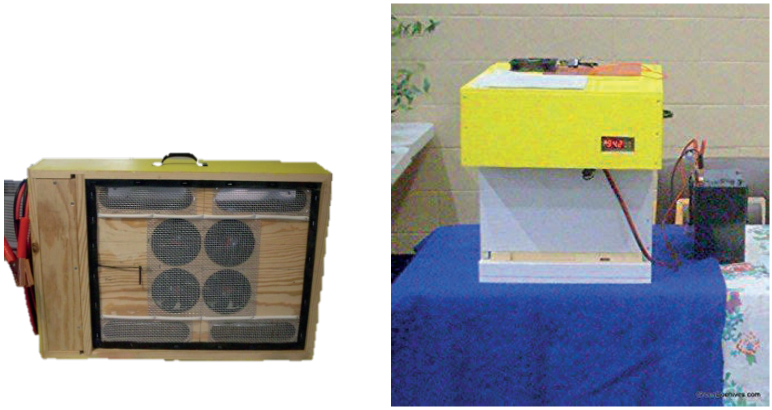


Figure 12: (left) The Victor device – bottom view; (right) System in use

Bee Ethic System (2017, Italy)
This Italian-designed hive integrated electrical resistances directly into frames, powered by solar panels or grid electricity. A digital controller regulated brood chamber temperatures to 40–42°C, achieving 80–85% mite mortality. While eco-friendly and user-friendly, its inflexible design and high cost (€550–€850) restricted compatibility with non-proprietary hive components (Bee Ethic, 2017).

Figure 13: Bee Ethic. (left) A single frame; (right) System's beehive

Mighty Mite Killer (2017, US)
This industrial-grade electric blanket, installed on hive floors, automated temperature ramps to 40°C using pre-programmed cycles. With 85–90% efficacy and minimal labour requirements, it became popular among commercial beekeepers. However, its reliance on grid power and absence of humidity sensors posed challenges in arid regions (Ordman. 2017).

Figure 14: (left) Mighty Mite Killer device; (right) System in use

Bienen-Sauna (2017, Germany)

A supplementary hive box placed below the brood chamber, the Bienen-Sauna combined resistive heating plates with fans and humidifiers to maintain 40–42°C. Pre-programmed cycles ensured 85% mite mortality while stabilising hive humidity. Despite its technical sophistication, the system's bulky design, battery dependency (limiting runtime), and high cost (€1,500) deterred widespread adoption (Bienensauna, n.d.).

Figure 15: (left) Bienen-Sauna system; (right) System in use

ThermoMite™ (2020, UK)

A portable, unit designed for small-scale operations, the ThermoMite™ gradually heated hives to 40°C, achieving 75–80% efficacy. Its lightweight design and off-grid compatibility suited hobbyists, though limited battery runtime and reduced effectiveness in high-infestation scenarios constrained broader use (PCMP, n.d.).

Figure 16: (left) ThermoMite system; (right) System in use

4.2 Classification of Thermotherapy devices

To systematise the diverse array of thermotherapy technologies, we propose a tripartite classification based on their operational integration with hive infrastructure:

1) External Heating Chambers

Standalone units *outside the hive* where bees or frames are temporarily relocated for heat treatment. These systems operate independently of the hive structure, enabling precise temperature control but requiring manual handling of bees or combs.

Advantages:

- Single device serves multiple hives (cost-effective for large apiaries).
- Precision in temperature regulation (reduces overheating risks).
- Effective for brood treatment (direct access to frames).

Limitations:

- High equipment costs
- Labour-intensive (requires bee/frame relocation).
- Stressful for colonies due to repeated handling.

2) Integrated Heating Beehives

Complete hive systems *designed with built-in heating mechanisms*, enabling thermotherapy without colony displacement. These hives serve dual purposes: standard colony housing and in situ heat treatment.

Advantages:

- Minimal colony disruption (treatment within the hive).
- Dual-purpose design labour complexity.
- Reduces long-term costs through multifunctional design.

Limitations:

- Prohibitively expensive for large apiaries (each hive requires its own system)
- Inflexible with non-proprietary hive parts.
- Limited portability (stationary infrastructure).

3) Modular Hive Inserts

Portable heating devices *inserted into standard hives* to deliver localised thermotherapy. These components augment existing hive infrastructure without structural modifications, prioritising portability and compatibility.

Advantages:

- Compatibility with commercial hive designs (e.g., Langstroth, National).

- Rapid deployment (no hive disassembly required).
- Cost-effective for small-to-medium operations (one insert can service multiple hives sequentially).

Limitations:

- Potential uneven heat distribution (hotter near heating elements).
- Limited brood penetration (surface-level efficacy).

Table 5: Summary of the Thermotherapy devices

Year	Thermotherapy device	Origin	Operating temperature	Operating time	Cost	Heat /Power source	Method of Use	Classification
1981	Hanko's thermo cube	Czechoslovakia	45°C	12 mins	N/A	Solar	Heating box exposed to direct sunlight for infested bees.	External heating chamber
1983	The thermo-bell	Czechoslovakia	>45°C	7 mins	N/A	70°C water	Dipped infested bees into a hot water bath in a hollow-bell structure.	External heating chamber
1986	Kamler & Pastor Thermobox	Czechoslovakia	46 and 48°C	10 mins	N/A	Fuel burning	Rotating cavity heated with a gas burner; infested bees are treated brood-free.	External heating chamber
1997	Cunningham's	USA	46-48°C	15 mins	N/A	Electric AC	A cabin with a heater treats removed bees; powered by 1500W electric heater.	External heating chamber
2001	Mite Zapper	USA	43-45°C	5 mins	95 EUR	Electric DC	Drone comb heats sealed brood to kill mites; powered by a portable battery.	Modular hive insert
2006	Thermovar	Greece	42°C	480 mins	N/A	Electric AC	Hot chamber heats the hive with adjustable temperature using an air circuit.	Modular hive insert
2010	Varroa terminator	Slovakia	42°C	180 mins	362 EUR	Electric AC	Two heating panels elevate hive temperature; maintains 60-70% RH during treatment.	Modular hive insert
2010	Linhart Thermosolar Hive	Romania	40-47°C	150 mins	700 EUR	Solar	Solar-heated hive warms brood combs to high temperatures for effective mite killing.	Integrated heating beehive
2011	Varroa Controller	Germany	40-47°C	120 mins	2388 EUR	Electric AC	Thermally insulated housing heats brood; adult bees are removed beforehand.	External heating chamber
2013	The Victor	USA	42°C	150 mins	240 USD	Electric DC	Device heats brood box on top; powered by a deep cycle battery for 3 hours.	Modular hive insert
2017	Bee Ethic	Italy	42°C	N/A	550 EUR	Solar and Electric DC	Thermostatic frames heat hive monthly; increases efficiency and honey production.	Integrated heating beehive
2017	Mighty Mite Killer	USA	43°C	5 mins	300 USD	Electric AC	Heater blanket placed in the brood box floor; switches off after the treatment cycle.	Modular hive insert
2017	Bienen-sauna	Germany	41°C	180 mins	1300 EUR	Electric AC	Box inserted below hive controls heat and humidity; thermotherapy applied indirectly.	Modular hive insert
2020	ThermoMite	UK	40°C	150 mins	360 GBP	Phase Change Material	Rechargeable heating pouches placed inside the hive to deliver precise thermotherapy.	Modular hive insert

5 Discussion

5.1 Comparative Analysis of sustainable Technologies

The increasing global urgency to curtail the harmful impacts of chemical acaricides in apiculture has fostered the development of numerous sustainable technologies. A comparative analysis reveals a multifaceted landscape in which alternative methods—ranging from biotechnical interventions and physical controls to advanced thermotherapy devices—each offer distinct advantages and limitations. Chemical treatments, although historically effective, are increasingly constrained by issues of residue contamination, resistance evolution, and environmental toxicity. In contrast, sustainable technologies such as thermotherapy capitalise on the thermal sensitivity of Varroa destructor, achieving high levels of mite mortality (85–90%) without leaving chemical residues. For instance, an empirical study demonstrated that modifying the powdered sugar dusting method (by confining and agitating bees) can remove about 92% of phoretic Varroa mites from colonies – a mite drop efficacy comparable to a thymol-based miticide – with no apparent harm to the bees (Carroll, 2024)

Moreover, biotechnical interventions, including drone brood removal and brood interruption, demonstrate that behavioural manipulation can significantly reduce mite populations; however, these methods often demand labour-intensive procedures and precise temporal execution. Similarly, the integration of entomopathogenic fungi and emerging approaches like RNA interference (RNAi) present promising species-specific solutions but currently suffer from scalability issues and regulatory uncertainties. Hence, while sustainable methods align with contemporary ecological imperatives, their operational efficacy varies with climatic, biological, and infrastructural contexts. The integrated use of these technologies, as opposed to a singular strategy, appears to provide the most robust and adaptable defence against Varroa infestation, ensuring both colony health and the long-term sustainability of beekeeping practices.

5.2 Integrated Pest Management (IPM)

One alternative strategy for the sustainable control of *Varroa destructor* is the Integrated Pest Management (IPM). By amalgamating cultural, biological, and physical control methods, IPM minimises mite populations while significantly reducing the reliance on chemical treatments. Its strength lies in its adaptability, enabling beekeepers to tailor interventions to the dynamic challenges posed by varroa infestations. The principles of IPM are:

1. Monitoring and Assessment: Regular monitoring of mite levels is essential for determining the severity of infestations and the timing of interventions. Methods such as alcohol washes, sugar shakes, and natural mite fall counts provide quantitative data for informed decision-making (Delaplane *et al.*, 2010).

2. Combination of Control Strategies: IPM emphasises the use of complementary strategies, such as combining drone brood removal with organic acids or thermotherapy. This multifaceted approach addresses the mite's lifecycle stages and reduces the likelihood of resistance development.

3. Threshold-Based Treatment: Treatments are applied only when mite levels exceed a predetermined economic threshold, ensuring interventions are justified and minimising unnecessary stress on colonies.

The practical benefits of IPM have been vividly demonstrated in commercial beekeeping. For example, a large-scale study conducted in North America reported that beekeepers implementing IPM strategies achieved a 50% reduction in chemical miticide usage while still maintaining effective mite control (Jack & Ellis, 2021). In this study, the integration of drone brood removal, screened bottom boards, and targeted organic acid treatments led to improved colony health and productivity, thereby exemplifying the efficacy and sustainability of the IPM framework.

5.3 Current gaps in the adoption of sustainable technologies

The adoption of sustainable Varroa management technologies, as delineated throughout this paper, is constrained by a confluence of technical, economic, and sociocultural factors. Although innovative approaches—such as thermotherapy, biotechnical interventions, and emerging molecular techniques—demonstrate considerable promise under controlled experimental conditions, their effective integration into routine apicultural practice remains limited due to several critical gaps.

Firstly, there is a marked deficiency in extensive, large-scale field trials that validate the performance of these technologies across diverse environmental conditions and heterogeneous hive architectures. This gap renders the extrapolation of laboratory efficacy to practical, on-farm scenarios uncertain, thereby impeding beekeepers' confidence in transitioning from conventional chemical treatments to sustainable alternatives.

Secondly, the high initial capital costs and operational complexities associated with advanced devices, including integrated heating beehives and modular hive inserts, represent significant economic barriers, particularly for small- and medium-scale beekeeping operations. The absence of standardised protocols and best-practice guidelines further exacerbates these challenges, as inconsistent application methods contribute to variable treatment outcomes and reduce the overall reliability of sustainable technologies.

Moreover, the integration of these sustainable methods within the framework of Integrated Pest Management (IPM) is often fragmented. Current strategies tend to rely on isolated interventions—ranging from physical methods like sugar dusting to sophisticated thermotherapy systems—without a harmonised, synergistic approach. This disjointed implementation not only limits the potential for cumulative benefits but also complicates the process of knowledge transfer and capacity building within the beekeeping community. Using survey data, Gray *et al.* (2024) found that beekeepers employing IPM had significantly higher winter colony survival rates than those using a single treatment.

Finally, a substantial information gap exists due to inadequate dissemination of empirical data and practical guidelines through extension services. Many beekeepers remain unaware of the full potential and operational nuances of these green methods, leading to slow adoption rates and a continued reliance on traditional, chemically based treatments.

Addressing these gaps necessitates concerted research efforts, enhanced industry collaboration, and supportive policy frameworks that together can bridge the divide between experimental innovation and practical application in sustainable apiculture.

5.4 Challenges in scaling thermotherapy and other green methods

Scaling thermotherapy from controlled experimental conditions to large-scale, field-level operations presents a series of technical and logistical challenges. One of the primary concerns is the heterogeneity inherent in commercial hive designs, which can result in uneven heat distribution and suboptimal treatment outcomes. The precision required to maintain the brood chamber within the narrow thermal window of 40–47°C—sufficient to inactivate Varroa without adversely affecting bee physiology—necessitates advanced control systems and real-time monitoring, factors that add to the complexity and cost of these devices.

In addition, energy dependency remains a significant barrier. Many thermotherapy devices are reliant on grid power or specialised energy sources, which may not be feasible in remote or resource-limited apiaries. The risk of overexposure to heat, particularly in densely populated or poorly ventilated hives, further complicates the deployment of these technologies on a larger scale. Complementary green methods, such as acoustic or pheromone-based interventions, similarly require rigorous standardisation and validation to ensure that their performance is consistent across diverse environmental conditions. Thus, while green methods offer substantial promise in mitigating Varroa infestations, their scalability is intrinsically linked to overcoming these engineering, logistical, and operational challenges.

5.5 Future directions for research and development

The future trajectory of sustainable Varroa management lies in the convergence of advanced engineering, molecular biology, and practical beekeeping insights.

Furthermore, the integration of advanced artificial intelligence (AI) technologies could revolutionise sustainable Varroa management through a multidisciplinary approach that synergises precision thermotherapy devices with AI-driven control systems. Central to this innovation is the development of smart thermotherapy units equipped with sensors that continuously monitor critical parameters—such as temperature, humidity, and bee activity—thereby enabling machine learning algorithms to dynamically adjust thermal profiles. Research should prioritise the development of multifunctional thermotherapy devices that integrate precision sensors, automated control algorithms, and Internet of Things (IoT) capabilities to facilitate real-time monitoring and adaptive temperature regulation. Such innovations would not only enhance treatment efficacy but also reduce the risk of collateral damage to the colony.

Parallel to hardware advancements, there is a pressing need to further explore the molecular mechanisms underpinning Varroa's thermal sensitivity and its interaction with bee physiology. The application of RNAi and CRISPR-based technologies, while still in its infancy, holds the potential to disrupt the reproductive cycle of the mite at a genetic level. However, future studies must rigorously address the ethical, regulatory, and biosafety concerns associated with these approaches to pave the way for their practical adoption.

Looking ahead, it is also imperative to consider complementary long-term strategies that bolster the resilience of honeybee populations against Varroa destructor. Recent research by Guzman-Novoa *et al.* (2024) has documented that certain feral and Africanized honeybee populations in Latin America possess intrinsic resistance mechanisms—such as enhanced grooming behaviour and efficient brood removal—that enable them to survive Varroa infestations without reliance on chemical treatments. These findings suggest that incorporating selective breeding programmes or integrating resilient stock into managed colonies could serve as a sustainable adjunct to physical interventions like thermotherapy.

Finally, a more holistic research paradigm is required—one that incorporates long-term field studies, cost–benefit analyses, and comprehensive environmental impact assessments. This integrative approach should aim to refine existing IPM strategies, ensuring that sustainable technologies are not only efficacious but also economically viable and ecologically sound. Collaboration among researchers, industry stakeholders, and beekeepers will be pivotal in transforming these emerging concepts into robust, scalable solutions that safeguard both the ecological and economic sustainability of global apiculture.

6 Conclusion

This paper has elucidated the imperative for sustainable *Varroa destructor* management. Traditional chemical treatments, though once effective, are now rendered increasingly unsustainable by issues such as chemical resistance and environmental contamination. In contrast, alternative strategies—including thermotherapy, biotechnical interventions, and integrated pest management—demonstrate a robust capacity to achieve high mite mortality rates while preserving the integrity and health of honeybee colonies. These findings underscore that a multifaceted, sustainable approach is not only viable but essential for the long-term resilience of apiculture.

Thermotherapy, in particular, stands out as a promising avenue due to its capacity to exploit the inherent thermal sensitivity of *Varroa destructor*. By elevating hive temperatures within a narrowly defined window, this technique achieves high levels of mite mortality without compromising the integrity of the bee colony. Alongside thermotherapy, complementary strategies—ranging from biotechnical interventions like drone brood removal to integrated pest management frameworks—offer a multifaceted approach that addresses multiple stages of the mite's lifecycle. These eco-friendly technologies not only reduce chemical reliance but also enhance the overall health and resilience of bee colonies, a prospect that fills me with both admiration and fervour for the innovative future of apiculture.

6.1 Summary of Key Findings

- Traditional chemical treatments are becoming increasingly unsustainable due to issues such as chemical resistance, residue contamination, and detrimental environmental impacts.

- Alternative sustainable strategies—including thermotherapy, biotechnical interventions, and integrated pest management—demonstrate robust efficacy in achieving high Varroa mite mortality.

- Thermotherapy stands out as a particularly promising method, exploiting the thermal sensitivity of *Varroa destructor* to inactivate mites without compromising bee colony health.

- Complementary techniques such as drone brood removal and integrated pest management address multiple stages of the mite's lifecycle, thereby reducing chemical reliance.
- A multifaceted, sustainable approach is essential for ensuring the long-term resilience and viability of apiculture, safeguarding both colony integrity and global food security.

6.2 Future Perspectives

To capitalise on the promising outcomes identified herein, future research must focus on extensive, large-scale field trials that validate the efficacy of sustainable interventions across diverse environmental conditions and hive architectures. It is crucial to refine thermotherapy devices, standardise best-practice protocols, and integrate advanced monitoring technologies—such as IoT-enabled sensors and AI-driven control systems—to optimise treatment parameters. Collaborative efforts among researchers, industry stakeholders, and beekeeping practitioners will be paramount in developing cost-effective, user-friendly solutions that can be readily implemented in both small- and large-scale operations.

In light of the escalating challenges posed by *Varroa destructor* and the pressing need to preserve global honeybee populations, it is imperative that the apicultural community, policymakers, and scientific researchers commit to the widespread adoption of sustainable mite control methods. A concerted, interdisciplinary approach is essential to drive innovation, enhance practical implementation, and ensure the continued viability of beekeeping practices worldwide. Let us embrace these eco-friendly technologies with urgency and determination, for the future of our pollinators—and by extension, our global food systems—depends upon it.

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