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REVIEW ARTICLE

Honeybees and colony collapse disorder: understanding key drivers and economic implications

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Abstract

Biodiversity, including the diversity of pollinators such as honeybees, is crucial for ecosystem stability and sustainable development. This review highlights the complex factors contributing to Colony Collapse Disorder (CCD), focusing on inadequate bee management practices, pesticide exposure, biotic stressors, nutritional deficiencies, electromagnetic fields, and climate change. These stressors are shown to interact in ways that impair honeybee health and behavior, leading to colony declines. The paper details the biological consequences of CCD, including the absence of adult worker bees, the persistence of the queen, and the lack of dead bees within the hive. The economic impact of declining honeybee populations is significant, with losses affecting crop yields, food prices, and global trade. This decline threatens agriculture, particularly in regions dependent on pollination services. The review emphasizes the interconnectedness of honeybee health with broader ecological and economic systems, calling for urgent conservation measures, improved management practices, and sustainable agricultural strategies to mitigate the negative effects of CCD. Key recommendations for future research focus on the need for regional studies, long-term monitoring, and public education on the importance of honeybee conservation.

Keywords Honeybees · Colony collapse disorder (CCD) · Pollinator health · Pesticides · Bee diseases

Introduction

Biodiversity encompasses the variety of life forms, both within and between species, along with the diversity of ecosystems (Kumar & Verma 2017). It's not just a matter of aesthetic beauty; it holds immense value for future generations and deserves diligent preservation. Beyond the visual appeal of diverse landscapes that offer habitats to countless species, biodiversity provides a multitude of practical benefits through ecosystem services. A striking example is insect pollination, wherein nearly 90% of flowering plants worldwide depend, at least in part, on insects and other animals for pollination. These plants are fundamental to ecosystems, supplying sustenance, homes, and resources to a wide array of other species. Insects, particularly bees, stand out as the primary animal pollinators, pollinating approximately 70% of angiosperm plants (Schoonhoven et al. 2005). The global bee population exceeds 20,000 species, with India being a notable hub of honeybee species' origin. Among the five honey-producing bee species, four (*Apis dorsata, Apis florea, Apis cerana indica*, and *Trigona irridipenis*) have been present in India since ancient times (Akhila et al. 2022). Bees play an indispensable role in pollination, a process vital to life on Earth. Simply put, without pollination, plants cannot reproduce (Bekić et al. 2014). Completion of this process is what enables plants to produce seeds, grow, and provide us with agricultural yields in the form of food. While various insects participate in pollination, bees play an exceptionally critical role. They are pivotal in pollinating both wild and cultivated plants, nurturing the sustainability of our planet's precious ecosystems. An astonishing 70 out of the top 100 food crops (which supply roughly 90% of global nutrition) rely on bee pollination (Eeraerts et al. 2019). Honeybees, belonging to the Hymenoptera order (which also includes wasps and ants), are among the most well-known insects. Extensive research highlights Hymenopterans (wasps, bees, and ants), Lepidoptera (moths and butterflies), Coleoptera (beetles), and Diptera (flies) as primary pollinators. Among these, Hymenopterans, especially bees, stand out as highly effective pollinators for approximately 70% of the world's cultivated crops (Akhila et al. 2022; Byrne & Fitzpatrick

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2009). The evolutionary expansion of bees aligned with the proliferation of flowering plants (Cappellari et al. 2013). Bees occupy a crucial ecological niche as pollinators for a diverse range of flowering plants, which underscores their vital role in the intricate ecosystems of Earth. Unfortunately, these essential creatures are facing a decline in their population, potentially impacting the future quality of life for both humans and the planet as a whole. In North America and Mexico, approximately 27% of native mason bee species and 50% of native leafcutter bee species are classified as vulnerable. Within North America, 26% of bumblebee species are considered threatened. Notably, certain species, such as the western bumble bee (Bombus occidentalis), have experienced population declines of up to 93% over the past two decades. In United Kingdom 54% of total honeybee population has been lost in the last decades (A V et al. 2023). Another study mentions that over 40% of invertebrate pollinator species are at risk of extinction (Allebone-Webb et al. 2024). This paper aims to critically review the current state of honeybee population decline, with a global perspective, examining its implications from biodiversity, ecological, and economic viewpoints. It addresses existing gaps in literature by synthesizing data on pollinator decline, highlighting its far-reaching consequences for ecosystems, agriculture, and economies.

Functional role of honeybees

Insects, with pollination as a primary ecological function (Jankielsohn 2018), play a pivotal role in ecosystem processes. Among these insects, bees provide various ecosystem services that enhance human well-being and sustain our planet's life-support systems (Gill et al. 2016; Matias et al. 2017). These ecosystem services are inherently linked to the achievement of global sustainable development (Wood et al. 2018). Despite their significance, the extent to which bees contribute to achieving the full spectrum of sustainable development goals (SDGs) remains relatively unexplored. Existing research underscores the role of insects, including natural cycle regulation, pollination, seed dispersal, biological pest control, and bio-inspiration, in the achievement of multiple SDGs (Dangles & Casas 2019; Sánchez-Bayo & Wyckhuys 2019). Notably, bee pollination directly strengthens food security (SDG2) and biodiversity (SDG15) (Dangles & Casas 2019), but their contributions extend to a broader array of SDGs. Bees and plants are in an age-old interdependent relationship. Bees rely on plants for their homage and nectar and pollen being a good source of carbohydrates and protein respectively they rely on them for their foraging as well (Siegel 2012). In turn, bees actively participate in vital plant reproduction processes, facilitating cross-pollination, diversifying genetic backgrounds, and aiding in the survival and propagation of plant species (Buchmann & Nabhan 2012). Bees, particularly honeybees, hold ecological and economic significance as pollinators, playing a pivotal role in conserving plant biodiversity and crop production. The alarming decline in insect pollinators poses a substantial amount of threat to human well-being and food production, given the substantial reliance of many crops on animal pollination for both quantity as well as quality of yield. The decline of honeybees, especially *Apis mellifera*, significantly impacts ecosystems and agriculture due to their role in pollination. Reduced bee populations lead to lower yields in crops like almonds, blueberries, and apples, affecting food supply and economic stability (Gray et al. 2024; Narciso et al. 2024; Lang et al. 2023). In natural ecosystems, this decline harms wildflower biodiversity and disrupts species reliant on bees, including birds and soil health (Gray et al. 2024; Narciso et al. 2024; Lang et al. 2023; Goras et al. 2022). Our oxygen quality, food supply, the fate of other species, and various biodiversity concerns are intricately tied to our efforts to safeguard bee populations (Akhila et al. 2022). Furthermore, bees serve as barometers of air quality, thriving in clean and healthy environments. The presence of natural bee colonies serves as a valuable indicator of environmental health, offering the potential for honeybees to detect air pollution (Akhila et al. 2022).

Factors affecting pollinator health

Pollinator health is a multifaceted issue, drawing attention from researchers who have sought to unravel its complexities. Drought, monocultural farming, unscientific farming methods, unsanitary hive conditions, and sudden changes in climate are some of the many things that are being looked at (Fig. 1) (Table 1) (Mall & Kumar, 2014; Watson & Stallins 2016). The insufficiency of nourishment, driven by vanishing foraging spaces and heightened reliance on supplementary diets, adds another layer to the problem, potentially suppressing bees' immune systems due to various stressors or combinations thereof. Furthermore, genetic uniformity poses a significant concern. Chandrasekaran et al. (2011) highlighted a global decline in pollinator populations and diversity, attributing it to several key factors. Habitat degradation, coupled with the gradual loss of nectar and pollen sources, emerges as a primary culprit (Najib & Hassan 2021). Changes in land use, stemming from deforestation, urban expansion, and industrial growth, also factor into the equation. The shift toward monoculture-dominated agriculture, once characterized by crop diversity that sustained natural pollinators throughout the year, has been supplanted by modern agricultural practices, marked by chemical fertilizers and pesticides. Unfortunately, mono-cropping forces farmers to use more pesticides, which makes the problem

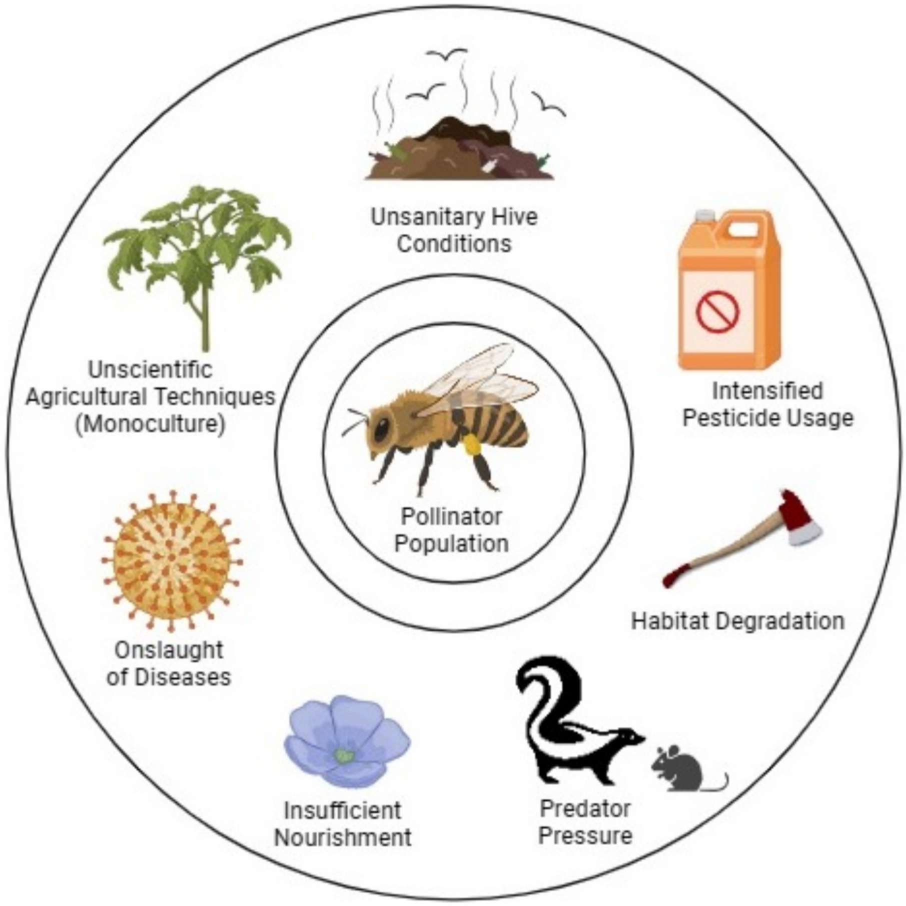

Fig. 1 Factors affecting the pollinator population: Various factors negatively influence the pollinator population, like unsanitary hive conditions, intensified pesticide usage, habitat degradation, predator pressure, insufficient nutrition, diseases, and unscientific agricultural techniques

even worse and leads to the deaths of many pollinators. Even the careless disposal of everyday items like paper cups can unwittingly ensnare bees in a sticky demise. Finally, diseases and animals that eat pollinators are always coming after them, which makes things even harder for their health. When these things work together, they paint a complicated picture of the dangers these important insects face, and they need our immediate attention and action.

Colony collapse disorder (CCD)

Colony Collapse Disorder (CCD) is a strange event in the world of beekeeping. It happens when worker bees suddenly leave hives that are doing well. This abandonment leaves a hapless queen, a handful of nurse bees, and developing bees stranded without access to the essential sustenance of nectar and pollen. To simplify, CCD can be described as the mass exodus of worker bees from a colony, leaving behind a well-fed queen, a scant number of nurse bees, and the burgeoning young bees under their care. There are only a few dead bees near the hive, but the colony still has a lot of honey and pollen. It's a quick and strange disappearance. Unfortunately, these reserves don't help the hive when there aren't any hard-working worker bees around. This intricate sequence of events, culminating in the heartbreaking loss of a bee colony, bears the ominous label of "Colony Collapse Disorder." The significance of honeybees (*Apis mellifera L.)* cannot be overstated, given their pivotal role as pollinators for numerous crops on a global scale. The abrupt decline in both the abundance and diversity of pollinators not only poses a conservation quandary but also poses a genuine threat to the critical process of crop pollination (Wyszkowska et al. 2019). A survey conducted in the U.S. from fall 2007 to spring 2008 revealed a total loss of 35.8% of honeybee colonies (VanEngelsdorp et al. 2008), significantly higher than previous years. Operations reporting CCD symptoms experienced even higher losses (40.8%), compared to 17.1% in those without symptoms (VanEngelsdorp et al. 2008). Another study reported winter mortality rates of 32%, 36%, and 29% over three consecutive years (2006–2009) in the U.S., with 10% of losses exhibiting CCD-like symptoms (Williams et al. 2010). A later survey reported annual colony losses of 25.3%

Table 1 Various factors leading to colony collapse disorder

Factor	Effects	References
Inadequate Bee Management Practices	Extended migratory routes induce stress and compromise immune systems Merging weakened colonies without investigating causes leads to the destruction of both colonies	(Roy et al. 2018)
Pesticide-Induced Peril	Neonicotinoids like imidacloprid, clothianidin, and thiamethoxam impair bee health Sublethal exposure to thiamethoxam affects homing abilities Clothianidin and imidacloprid suppress immune functions and promote deformed wing virus	(Blacquière et al. 2012)
Biotic Stressors of Honeybee Colonies	Varroa and Tracheal mites, bacteria (American foulbrood, European foulbrood), and viruses (Deformed Wing Virus) are significant stressors Various pathogens including ABPV, IAPV, KBV, sacbrood virus, chronic bee paralysis virus, and black queen cell virus pose threats	(Higes et al. 2013; Paxton 2010)
The Strain of Nutritional Stress	Nutritional scarcity from habitat depletion, pest/pathogen infections, and monoculture agricultural areas weakens immune systems and contributes to losses Poor nutrition is linked to increased rates of Nosema spp. infection	(Naug 2009; Branchiccela et al. 2019; Invernizzi et al. 2011)
Electromagnetic Fields and Bee Disappearance	Theory suggests EMFs may disrupt bees' navigation systems leading to CCD RF-EMFs from cell towers and wireless devices impact bee behaviour and health	(Wyszkowska et al. 2019; Sahib 2011; Favre 2017; Taye et al. 2017; Thielens et al. 2020)
Environmental Factors and Climate Change	Climate-induced changes affect flower availability and timing of plant flowering, causing nutritional deficiencies Variations in climate, including drier summers, reduce flower availability for honeybees, leading to food stress Out-of-season temperature changes, especially colder temperatures, can lead to colony deaths	(Ziska et al. 2016; Flores et al. 2019; Cho et al. 2021; Banaji 2022)

(2014–2015) (Seitz et al. 2016), indicating that the problem persists. Another study reveals a concerning trend of declining honey bee colonies in the United States, driven by various challenges such as pests (e.g., *Varroa destructor* mites), diseases (e.g., *Nosema spp.*), and management stress (Ellis et al. 2010). While colony loss was steady prior to the introduction of Varroa mites, the decline accelerated after their arrival. The phenomenon of CCD emerged in 2006, with beekeepers experiencing unusually high losses, sometimes exceeding 30%. Factors like viral infections, pests, chemical use, and poor bee nutrition contribute to CCD, and its impacts are significant given the crucial role of honey bee pollination in U.S. agriculture, valued at over $14 billion annually. Although CCD-like symptoms decreased in recent years, the issue persists, prompting extensive research to uncover the causes and mitigate losses (Ellis et al. 2010).

Possible causes of colony collapse disorder (CCD)

CCD is a multifactorial phenomenon. A study identified the queen's weakness (relative weight: 0.144), malnutrition (0.138), and the use of acaricides in the hive (0.135) as the most significant factors contributing to the CCD phenomenon (Mohammadian et al. 2024). Although there are other key contributors such as pesticides, parasites, climate change, and habitat loss. However, these causes rarely act in isolation—pesticides can weaken bee immunity, leaving them vulnerable to parasites, while habitat loss exacerbates nutritional stress. This section analyzes each factor and their interconnected effects.

Inadequate bee management practices

The mismanagement of bee colonies can have detrimental effects on their well-being. One common practice involves subjecting bees to extended migratory routes to support pollination services. These long journeys can induce stress in the bees due to frequent changes in their habitat and management methods, such as the transportation of colonies across vast distances to fulfil pollination demands. This practice weakens the resilience of the bee colonies, as highlighted by a study conducted by Roy et al. (2018). During these migrations, bees are often fed on sugar syrup, which may lead them to reject protein-rich food items, ultimately compromising their immune systems in exchange for the readily available but less nutritious sustenance. Inappropriate management techniques also contribute to Colony Collapse Disorder (CCD). Beekeepers sometimes combine weakened colonies with healthy ones without thoroughly investigating the underlying causes of the colony's decline. This ill-advised merging often destroys both colonies, further exacerbating the issue (Roy et al. 2018).

Pesticide-induced peril

The exposure of bees to pesticides has emerged as a significant threat to their survival. Pesticides are commonly employed in crop protection and hive insect or mite control, but their use has rendered bees more susceptible to viral diseases. Neonicotinoid insecticides, fungicides, and weed killers are particularly implicated in this crisis. Notable neonicotinoids like imidacloprid, clothianidin, and thiamethoxam have been identified as culprits. Sublethal thiamethoxam exposure has been shown to impair the homing abilities of bees, with dire consequences for colony survival. Additionally, clothianidin and imidacloprid can suppress immune functions and promote the proliferation of the deformed wing virus among infected honeybees. Organochlorine pesticides (OCPs) are another menacing group of chemicals. They are persistent organic pollutants notorious for their extreme toxicity to both humans and bees. OCPs can cause neurotoxicity, immunotoxicity, mutations, cancer, and even death. In honeybees, the activation of immune pathways is crucial for combating various threats, including xenobiotics and pathogens (Ek-Huchim et al. 2022). However, honeybees possess a limited number of genes involved in detoxifying enzymes. While the connection between neonicotinoid insecticides and honeybee decline is a topic of ongoing debate, it is increasingly evident that CCD results from a complex interplay of factors rather than a direct association with neonicotinoid use (Blacquière et al. 2012). Concerns have also been raised about glyphosate, which is another widely used herbicide that may have similar effects on bee health and function (Paul 2019a, b). Different insecticides and acaricides were found in beeswax samples from a study in France, which shows widespread exposure. Taufluvalinate, coumaphos, and endosulfan were the most common residues (Chauzat & Faucon 2007). Another study discovered that North American apiaries have a lot of pesticides and miticides. In fact, almost 60% of wax and pollen samples had at least one systemic pesticide in them (Mullin et al. 2010). This shows how common pesticides are in the environment where bees live, even though the direct link between them and CCD is still unclear and needs more research. It's also important to note that while pesticides directly harm bees, their sublethal effects also reduce resilience against pathogens such as Nosema and mites. Furthermore, pesticide exposure is amplified by poor nutrition when bees forage in monocultures.

Biotic stressors of honeybee colonies

Honeybee colonies face a multitude of biotic stressors, ranging from microorganisms to certain insects and mites, that can act as both parasites as well as vectors of pathogenic viral diseases (Fig. 2) (Table 2). These biotic stressors include mites like Varroa and Tracheal mites, bacteria such as European foulbrood and American foulbrood, and viruses like the Deformed Wing Virus. Synergistic effects of multiple viruses, including ABPV (Acute Bee Paralysis Virus), KBV (Kashmir Bee Virus), IAPV (Israeli Acute Paralysis Virus), sacbrood virus, black queen cell virus, and chronic bee paralysis virus, pose significant threats (Peña-Chora et al. 2023). Fungi also play a role, with *Nosema ceranae, Nosema apis*, and Chalkbrood disease causing issues. Insects like Small hive beetles, Greater wax moths, and Lesser wax moths can further exacerbate colony problems (Peña-Chora et al. 2023). Even mammals, such as bears, can disrupt honeybee colonies. Among these pathogens, the *Varroa destructor* (Lamas et al. 2024), RNA viruses (Dainat et al. 2012), and the microsporidia *Nosema ceranae* are the most significant contributors to colony losses (Higes et al. 2013; Paxton 2010). Pathogens implicated in CCD include *Ascosphaera apis* (causing chalkbrood disease), acute bee paralysis virus, chronic bee paralysis virus, black queen cell virus, deformed wing virus, invertebrate iridescent virus, Kashmir bee virus, Israeli acute paralysis virus, *Nosema* species, *Paenibacillus larvae* (responsible for American foulbrood), as well as sacbrood virus. A study in Mexico found a 100% prevalence of Nosema spp. in bee samples, and a high prevalence of the Varroa mite (82.6% and 79.2% in two consecutive years) (Vargas-Valero et al. 2021). The synergistic effect of pesticides and pathogens is also suggested, indicating that the combined stress may significantly impact

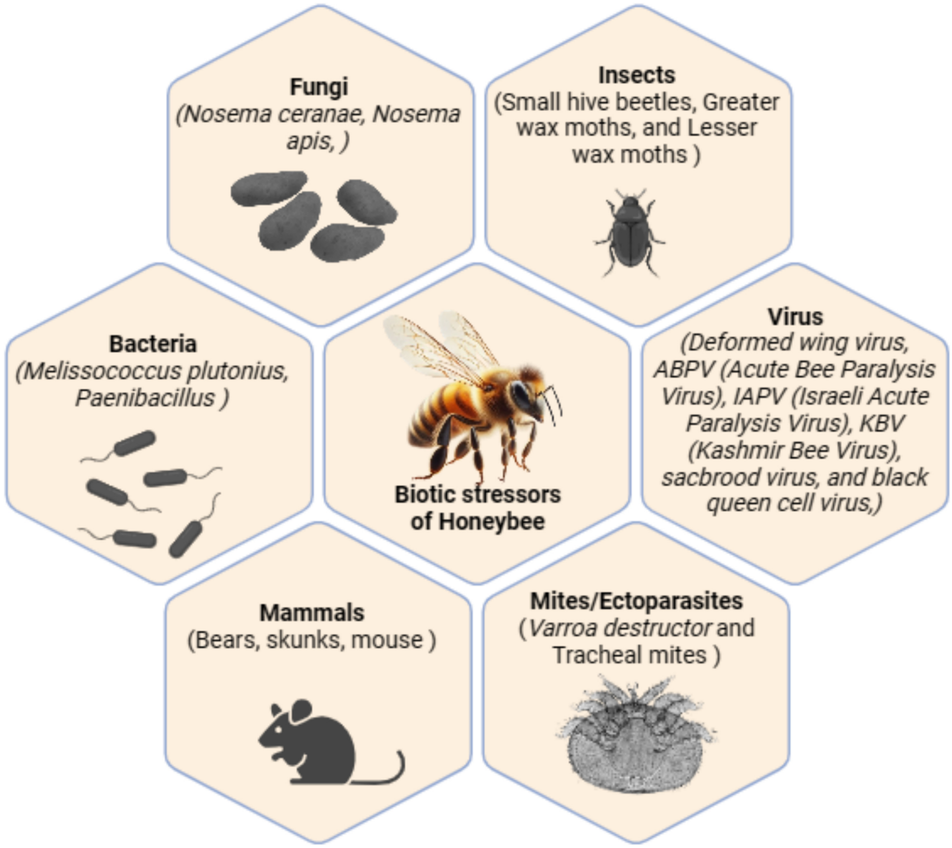

Fig. 2 Biotic stressors of Honeybee: The diagram illustrates the diverse enemies of honeybees, from microscopic bacteria and fungi to hungry insects, deadly viruses, and even curious mammals, all circling the vulnerable honeycomb at the core

bee health (Vargas-Valero et al. 2021). Another study highlights *Varroa destructor* as a primary factor in colony loss, with baseline losses of 10–20% in overwintering colonies, and losses as high as 50–100% in some areas (Watanabe 2007). The spillover of pathogens from commercially reared bumblebees to wild populations is another concerning factor, with models predicting significant infection rates (Otterstatter & Thomson 2008). Studies have confirmed this spillover is occurring, and that it has allowed *Crithidia bombi* to invade several wild bumble bee species near greenhouses (Otterstatter & Thomson 2008).

The strain of nutritional stress

Nutritional stress has become a major concern for honeybee colonies, driven by habitat depletion, pest and pathogen infections, and pesticide exposure. The stress is closely connected to the intensification of land use and the expansion of monoculture agricultural regions, where bees struggle to find diverse sources of polyfloral pollen to meet their nutritional needs (Naug 2009; Branchiccela et al. 2019). The nutritional quality of pollen significantly impacts bee lifespan, immunocompetence, resistance to pathogen infections, and behavioural patterns (Alaux et al. 2010; Ament et al. 2010; Di Pasquale et al. 2013; Basualdo et al. 2014). Poor nutrition has also been linked to increased rates of *Nosema* spp. infection (Invernizzi et al. 2011), adversely affecting colony health and contributing to depopulation and losses. Nutritional scarcity can result from various factors, including the lack of suitable vegetation, the availability of low-nutritional-value crops, over-reliance on a single crop, frequent colony migrations, and overcrowding of bee colonies (Ziska et al. 2016). These factors collectively weaken bees' immune systems, leading to colony losses attributed to CCD.

Electromagnetic fields and bee disappearance

One intriguing theory posits that the proliferation of telecommunications technology and the increasing prevalence of electromagnetic fields (EMFs) may play a role in CCD (Fig. 3) (Wyszkowska et al. 2019; Sahib 2011; Hill & Bartomeus 2016). Adult honeybees possess a magnetoreception sense akin to other animals, including birds, microbes, fishes, whales, dolphins, and insects. Like other organisms such as birds, microbes, fishes, whales, dolphins, and insects, adult honeybees are equipped with an impressive magnetoreception sense. This sense aids in navigation during migrations and long-distance travel (Ferrari 2014). It is postulated that magnetic fields, electromagnetic field fluctuations, and geomagnetic disturbances disrupt bees' navigation

Table 2 Various biotic stressors of honeybees, leading to colony collapse disorder

Pathogen	Correlation with CCD	References
Israeli acute paralysis virus of bees	Strongly correlated with colony collapse disorder (CCD). It was observed that irradiated combs from affected colonies can be repopulated with naive bees suggesting that infection may contribute to CCD	(Cox-Foster et al. 2007)
Invertebrate iridescent virus 6 (IIV-6)	A study identified IIV-6 in collapsing honeybee colonies and demonstrated that honeybees are very susceptible to the virus. In the cytoplasm of honeybee brood that had been previously exposed to IIV-6, viral inclusion bodies were noted. Electron microscopy showed a significant abundance of viral particles within cells three days after inoculation	(McInnis et al. 2020)
Varroa destructor	Known to infest honeybee colonies and weaken the bees by sucking their fat bodies. This infestation can lead to the spread of various viruses, ultimately contributing to colony collapse disorder	(Lamas et al. 2024; Roy et al. 2018)
Nosema apis	A microsporidian pathogen found in collapsing honeybee colonies. Its presence in bee samples from collapsing hives has been documented in previous studies	(McInnis et al. 2020)
Nosema ceranae	Another microsporidian pathogen found in collapsing honeybee colonies. Its presence in bee samples from collapsing hives has been documented in previous studies	(McInnis et al. 2020)
Parasitic phorid fly	Considered as a potential factor in colony collapse disorder. Its role in contributing to the decline of honeybee colonies has been studied and is a subject of ongoing research	(Roy et al. 2018)
Neonicotinoid group of pesticides	Suspected to weaken honeybee colonies and make them more susceptible to pathogens and other stressors, potentially contributing to colony collapse disorder	(Roy et al. 2018)
Honeybee tracheal mite	Known to infest the tracheae of honeybees, leading to health issues and potentially contributing to colony collapse disorder	(Roy et al. 2018)

systems, preventing their return to their hives (Ferrari 2014). In CCD the vanished bees never recover but are believed to die individually, far from their hives (Sahib 2011). Honeybees are known to detect Earth's magnetic field, possibly using organized magnetic nanoparticles within their bodies (Liang et al. 2016; Lambinet et al. 2017). Thielens et al. conducted a study on the effects of radio-frequency electromagnetic fields (RF-EMFs) on Western honeybees (Thielens et al. 2020). Their study suggested that a modest transition in environmental incident power density, moving from frequencies below 3 GHz to higher frequencies, resulted in a notable rise in absorbed power. Active mobile phone handsets were found to have a profound impact on bee behaviour, inducing worker piping signals. Subsequent experiments confirmed these initial observations with controlled RF-EMF signal enhancements (Favre 2017). Mall and Kumar (2014) reported that radiofrequency and electromagnetic radiations can negatively impact biomolecular cells, ultimately impairing the biological structure and functions of organisms. Honeybees possess magnetic crystals in their fat bodies, and the effect of cell phone tower electromagnetic radiation on the foraging behaviour of Asiatic honeybees was observed (Taye et al. 2017). Observations included changes in returning ability, flight activity, and pollen foraging efficiency. Results revealed that colonies close to mobile phone towers were most affected, with flight activity and returning ability decreasing as proximity to the towers increased. RF-EMF from wireless devices and cell towers can cause changes in neurotransmitter functions, blood–brain barrier, morphology, calcium efflux, electrophysiology, cellular metabolism, and gene and protein expression in certain types of cells, even at low intensities (Sivani & Sudarsanam 2012). Exposure to mobile phone radiation has been shown to cause decay and damage to the internal plasma membranes of honeybee stomach cells, which in turn affect the levels of Mg, Ca, Zn, and Fe elements in the cells (Mahmoud & Gabarty 2021). Mobile phone radiation has been found to significantly reduce the hatching ratio of honeybee queens, but it did not adversely affect mating success. However, surviving queens were not negatively impacted after the exposure (Odemer & Odemer 2019).

Microwave radiation from mobile phones has been shown to cause adverse effects on different cell functions, including histological alterations in various visceral organs and changes in blood parameters in mice models (Yousif Al-Fatlawi 2022). Although Pollen foraging behavior did not show any significant difference, these findings underscore the potential harm of cell phone radiation on honeybee populations, which could have far-reaching consequences for ecosystems.

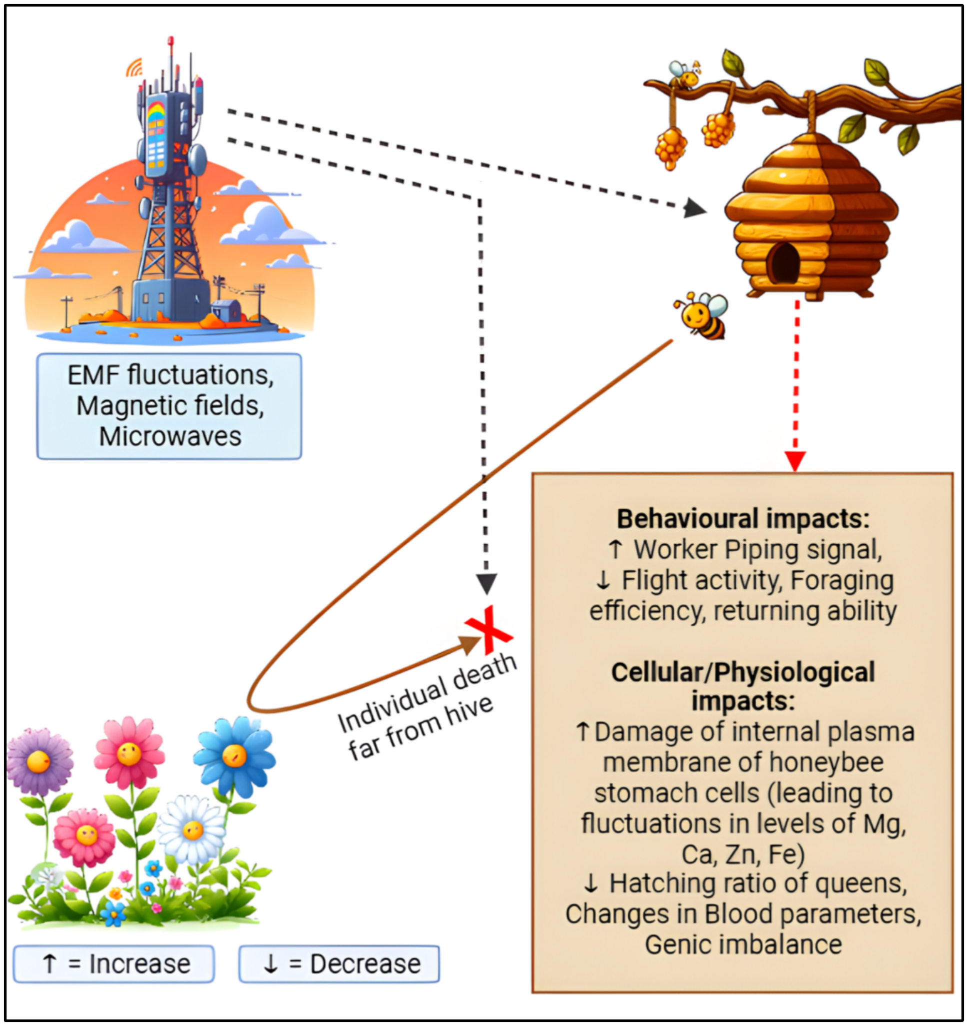

Fig. 3 Effects of electromagnetic fields on Honeybee health: EMF exposure is proposed to induce both behavioural changes (reduced foraging, increased distress signals, and impaired navigation) and cellular/physiological effects (membrane damage, mineral imbalances, reproductive impairment, stress markers, and genic imbalances). These changes can lead to individual bee death and potentially disrupt colony dynamics and survival, which can ultimately boost the process of colony collapse disorder

Environmental factors and climate change

Climate change poses a substantial threat to honeybee colonies, disrupting crucial processes like pollination. Variations in climate, including drier summers, reduce the availability of flowers for honeybees, leading to food stress. Moreover, climate-induced changes alter the timing of plant flowering, affecting pollination and causing nutritional deficiencies among bees. The lack of adequate nutrition can result in Colony Collapse Disorder (CCD) (Flores et al. 2019). Climate shifts also impact atmospheric CO_2 (carbon dioxide levels), affecting the concentration of proteins in pollen, a vital component of the honeybee diet (Ziska et al. 2016). Environmental problems and their effects on honeybees in the context of sustainability have been a subject of research (Varol & Yücel 2019). The conversion of grassland to agricultural fields can negatively affect bee diversity and abundance (McNally 2015). The loss of habitat and reduction in floral diversity directly impacts the nutritional resources available to bees, weakening their immune systems and making them more vulnerable to diseases and parasites. Studies suggest that bees have a limited capacity to adapt to temperature fluctuations, making them vulnerable to overheating, especially during foraging trips. Sudden, out-of-season temperature changes, particularly colder temperatures, can lead to colony deaths. Bees have a relatively short lifespan, and during winter, queens spend their time decomposing ground leaf litter, increasing their susceptibility to temperature fluctuations. Poor air quality episodes also extend foraging trip durations for honeybees (Cho et al. 2021; Banaji 2022).

Biological consequences of CCD on honeybees

Colony Collapse Disorder (CCD) manifests as a perplexing array of symptoms, with the most prominent being the startling absence of adult honeybees within the hive, juxtaposed with a queen that still lives, and an eerie lack of deceased honeybee bodies in and around the hive (Higes et al. 2013).

This sudden disappearance of adult worker bees is a hallmark of CCD, accompanied by a disconcerting disinterest in tending to the brood and a noticeable decline in the overall vigour of the colony (Fig. 4) (Ellis 2016). Intriguingly, there are no discernible signs of pathological infection, defying the usual indicators of disease (Mockel et al. 2011). Equally baffling is the absence of dead bees, both inside and outside the beehive, a phenomenon that further deepens the enigma (Naug 2009). Instead, one often encounters a hive populated solely by developing bees or even entirely devoid of adult worker bees, with only immature, nascent bees (brood) present (Kumar 2018; vanEngelsdorp et al. 2017). These cryptic manifestations underscore the intricate and elusive nature of CCD, demanding continued research and vigilance to unravel its mysteries.

The enigma of Colony Collapse Disorder (CCD) is linked with the complex changes that take place as honeybees age, bearing implications for honeybee pathophysiology (vanEngelsdorp et al. 2017). The decline of colonies is caused by many interconnected factors, such as poor nutrition, increasing pressure from endo and ectoparasites, rising bacterial and viral loads, and the complex interaction of pesticides (Francis et al. 2013; Staveley et al. 2014). Colony-induced stress plays a central role in propelling CCD, dismantling the robust defences of bees and rendering colonies vulnerable to insidious diseases. This stress arises from myriad sources, including the scarcity of nectar and pollen-rich plants, the deployment of honeybees for pollinating crops bereft of nutritional value, and the overcrowding of honeybee colonies (Johnson et al. 2010; Rennich et al. 2012). The nomadic existence imposed upon colonies, subjected to arduous long-distance journeys for pollination or honey production, further compounds their stress. Bees are already in a bad situation, but being exposed to pesticides and parasitic invaders makes it even worse. As a result, there is a strong belief that actions aimed at improving the health of honeybees could help ease the burden of colony stress. Innovations in nutritional supplements stand poised to fortify honeybee health during periods of nectar and pollen scarcity or adverse weather conditions. Several extensive migratory operations have undertaken periodic monitoring, seeking early warning signals of impending colony health crises that may precipitate or exacerbate CCD. There are many suggestions for beekeepers, such as giving antibiotics to stop Nosema infections, choosing genetic strains that are resistant to mites, and only using fumigants like formic acid or thymol-based products when there are varroa mite infestations. Furthermore, a prudent measure involves refraining from reusing equipment previously exposed to colonies that succumbed to the enigmatic clutches of CCD.

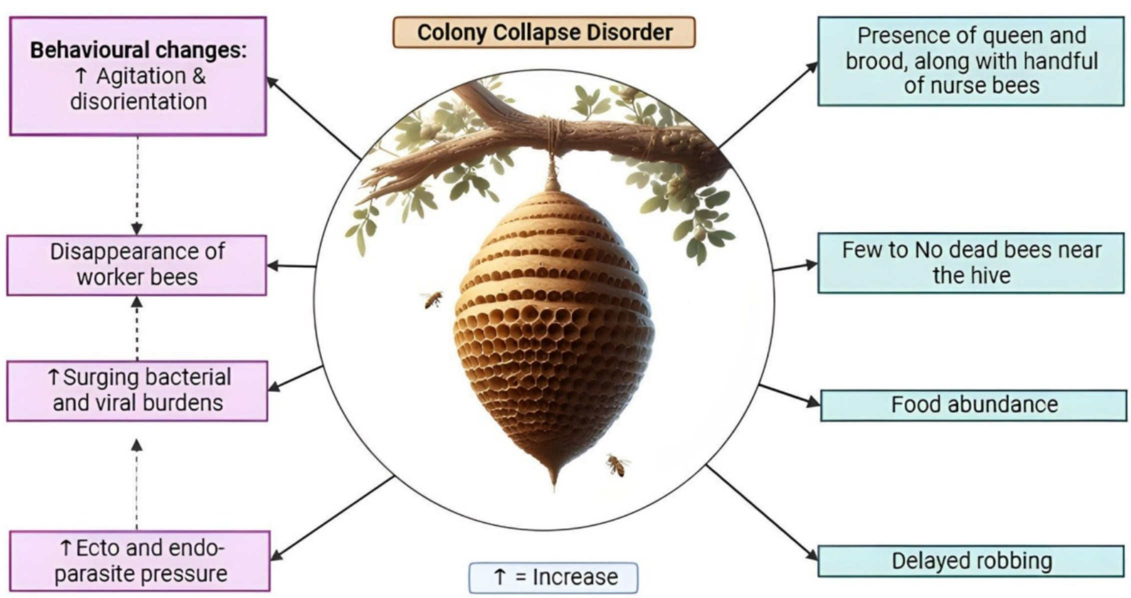

Fig. 4 Attributes of Colony collapse disorder (CCD): CCD occurs when most of the worker bees in a hive disappear, leaving behind the queen, the brood, and a few nurse bees. The hive has plenty of food and few or no dead bees near it. The causes of this disorder are not fully understood, but some factors and/or symptoms that may attributed to it are increased agitation and disorientation of the bees, higher levels of bacterial and viral infections, and more pressure from parasites. These factors can affect the bees' health, behaviour, and ability to navigate and communicate. As a result, the hive becomes weak and vulnerable to robbing and collapse

Lose of bee diversity and impact on the economy

Pollinators, particularly bees, play a crucial role in maintaining genetic diversity and ensuring food security through crop pollination. The decline in bee diversity poses significant threats to both ecosystems and economies (Paxton 2010; Aizen & Harder 2009). Notably, the global stock of domesticated honeybees is struggling to keep up with the increasing demand for pollination services in agriculture (Aizen & Harder 2009). Insect pollinators, with a spotlight on bees, contribute significantly to biodiversity, supporting wild plants, human diets, and global agricultural production (Klein et al. 2007; Kline & Joshi 2020). Their impact not only include ecological consequences but influence the global economy as well. Pollination services are pivotal for human welfare, benefiting agriculture and indirectly contributing to landscape aesthetics and wildlife support. However, environmental changes, such as climate warming and urbanization, can disrupt essential plant-pollinator interactions (Freimuth et al. 2022). These disruptions have far-reaching consequences, leading to reduced plant reproduction and diminished pollination services.

Economic impact and threats to agriculture

The economic impact of declining bee populations is profound, affecting crop yields, production costs, and crop diversity (Bauer & Wing 2010; Leonhardt et al. 2013; Kevan & Phillips 2001). The consequences extend globally, impacting food supply, security, and trade if pollinator abundance continues to decline. Bee losses result in reduced agricultural production, potentially leading to higher food prices for consumers. Invasive alien species, like the *Vespa velutina nigrithorax* (Yellow-legged hornet), pose both ecological and economic threats, impacting pollination services and increasing the risk of bee colony mortality (Requier et al. 2023). The economic impact of colony loss for beekeepers is substantial, given the dual role of beekeeping in honey production and providing essential pollination services to agriculture. Invasive species, like *Vespa velutina*, contribute to declining honeybee populations, crucial for pollinating both wild and cultivated plants (Leza et al. 2019). Biodiversity-friendly farming practices can enhance agricultural production by supporting wild species' ecosystem services, such as pollination and natural pest control (Scheper et al. 2023). However, integrating biodiversity-friendly management into farming systems' economic profitability is not well understood, with the costs of reduced grassland forage yields potentially outweighing the benefits garnered from enhanced pollination.

Sihag (2023) highlighted that a decline in pollinators would lead to the loss of pollination services, resulting in severe negative ecological and economic impacts, adversely affecting wild plant diversity, crop production, food security, ecosystem stability, and human welfare. Abrol (2023) explored beekeeping's potential in conjunction with agriculture for income generation, emphasizing its role in sustainable economic development in India. Moomen and Appiah (2023) investigated the impacts of mining activities on beekeeping, revealing a correlation between low Location Quotient (LQ) values in beekeeping and high LQ values in mining, providing insights for integrated rural and sustainable development.

Pătruică et al. (2023) assessed the economic efficiency of essential oils in bee colony feeding, revealing positive correlations between oils like oregano, thyme, basil, and mint, and factors such as germs, brood cell numbers, and honey yield. Mint, oregano, thyme, and basil were found to be the most profitable for honey production. Potts et al. (2016) and Garibaldi et al. (2016) underscored bees' importance in maintaining ecosystem biodiversity and contributing to agricultural income through pollination. The symbiotic relationship between melliferous plants and bees was highlighted. Popescu and Popescu (2019) reported the positive social, economic, and environmental impacts of ecological beekeeping in Romania, emphasizing benefits for beekeepers, agriculture, society, and the environment. The economic vulnerability arising from dependence on a narrow range of pollinators, especially honeybees, makes agriculture susceptible to disease, pests, and environmental changes, posing risks to food security and economic stability. A decline in bee populations impacts beekeeping and honey production industries, leading to job losses and reduced revenue. Downstream industries, such as chocolate and coffee production, are also affected due to their reliance on bee-pollinated ingredients, potentially leading to price increases and economic challenges. Bees' role in pollinating ornamental plants has implications for tourism and aesthetic value, potentially affecting industries associated with these sectors. Additionally, a decline in bee populations results in reduced honey production and hive products, affecting related industries such as cosmetics and herbal medicine. Furthermore, the loss of biodiversity due to declining bee populations has ecological and economic consequences, disrupting ecosystems and contributing to broader socio-ecological crises linked to human activity and climate change (IPCC, 2018; Schultz 2011).

Table 3 illustrates the wide range of economic losses attributed to honeybee and pollinator decline. The variation stems from several factors, including the different methodologies employed, the regional specificity of studies, and the difficulties in capturing all direct and indirect economic impacts. Several studies highlight the significant

Table 3 Quantitative insights on economic losses due to honeybee/pollinator decline

Region	Pollinator(s)	Economic Loss Estimate (USD)	Year	Methodology	References
Chengdu Plain, China	Insect pollinators (including managed bees)	$85.1 million (rapeseed) and $31.0 million (peaches)	Not specified	Economic valuation; field experiments	(Liu et al. 2019)
Costa Rica	Tropical forest pollinators (coffee)	$60,000 per year (per farm)	2000–2003	Experiments along distance gradients	(Ricketts et al. 2004)
Ethiopia	Managed honeybees	$815 million	Annual	Economic valuation	(Fikadu 2019)
Florida, USA	Honeybees (SHB infestation)	$3 million (1998)	1998	Estimate of beekeeper losses	(Pompilus et al. 2015)
Georgia, USA	Biotic pollinators (including honeybees)	$367 million	2015	Economic valuation; GIS analysis	(Barfield et al. 2015)
Global	Insect pollinators	At least $57 billion (US)	Annual	Algorithm estimation; projections of losses	(Losey & Vaughan 2006)
Global	Bees	$153 billion	Annual	Economic valuation	(Paul 2019a, b)
Great Britain	Bees and hoverflies	Net loss over 2.7 million occupied 1 km^2 grid cells across all species	1980–2013	Occupancy models	(Powney et al. 2019)
Maine, USA	Honeybees and wild bees	Not explicitly stated, but nearly 30% yield reduction in wild blueberries projected with honeybee disruption	2010–2012	Economic model; field studies	(Bushmann & Drummond 2020)
Netherlands	Managed and wild pollinators	≈$100 million	1992	Government estimate	(Ruijter 2002)
New Zealand	Honeybees	$1.96 billion	Annual	Economic valuation; pollinator exclusion experiments	(Sandhu et al. 2016)
Ouagadougou, Burkina Faso	Insect pollinators	Up to 83% reduction in household revenue (depending on crop dependency)	Not specified	Household Vulnerability Index (HVI)	(Stenchly et al. 2018)
Pakistan	Honeybees	$1.59 billion (pollination-dependent crops)	Annual	Economic valuation	(Usman et al. 2022)
South Africa (Mangoes)	Pollinators (including honeybees)	Not explicitly stated but highlights economic endangerment without effective pollination	Not specified	Flower visitor surveys, exclusion experiments	(Carvalheiro et al. 2010)
United Kingdom	Bees	£36.7 million (apples only)	Annual	Bioeconomic model; field experiments	(Garratt et al. 2014)
United States	Honeybees	$54 billion—$620 million	Various (1980–2009)	Meta-analysis of major studies; varying methodologies	(Chisel 2015)
United States	Insect-pollinated crops	$14.29 billion (1996)—$15.12 billion (2009)	1992–2009	Trend analysis of aggregate data	(Calderone 2012)

contribution of honeybees to agricultural productivity. For example, Usman et al. (2022) estimates that honeybees contribute over $200 billion annually to the global economy, while in Pakistan alone, pollination-dependent crops are worth $1.59 billion annually. Chisel (2015) emphasizes the significant discrepancy in economic valuations of honeybee services in the United States, ranging from tens of billions of dollars to only hundreds of millions of dollars. This highlights the need for more robust and consistent methodologies. Studies focusing on specific crops or regions provide more precise estimates. Barfield et al. (2015) estimates that the annual economic value of biotic pollinators in Georgia is $367 million, representing approximately 13% of the total production of the studied crops. Garratt et al. (2014) quantifies the economic value of insect pollination for two UK apple varieties at £36.7 million annually. Liu et al. (2019) estimates the economic value of insect pollination for rapeseed and peaches in the Chengdu Plain, China, at $85.1 million and $31.0 million, respectively. The research also highlights the vulnerability of different regions and agricultural systems to pollinator decline. Stenchly et al. (2018) uses a Household Vulnerability Index to show that household revenue in Ouagadougou, Burkina Faso, could be affected by up to 83% due to reduced pollination services, depending on the level of crop dependency. Bushmann & Drummond (2020) demonstrates that a disruption in the supply of honeybees in Maine could lead to a nearly 30% decrease in wild blueberry crop yield, although this is partially buffered by wild bees. Powney et al. (2019) shows a net loss of pollinator species across Great Britain, with implications for both crop production and biodiversity. It is critical to acknowledge the limitations of the available data. Many studies focus on direct economic losses from reduced crop yields, neglecting indirect economic impacts. The global estimate of at least $57 billion in annual losses in the United States (Losey & Vaughan 2006) represents a lower bound, as it does not fully capture all the indirect economic effects. Furthermore, the lack of standardized methodologies hinders the comparison and aggregation of findings across different studies and regions.

Multi-faceted impacts on industries and food security

The decline in pollinators, particularly honeybees, is a threat to food security, potentially causing reduced crop yields and increased production costs (Westerkamp & Gottsberger 2002; Holden 2006). Marshman et al. (2019) emphasized the vital role of pollinators in food crop pollination, with climate change amplifying the decline and urging a shift toward native bee conservation. A potential future with compromised pollination highlights the need for increased hand pollination, incurring estimated labour costs of $90 billion annually in the US alone (Atkins & Atkins 2016). This could lead to increased food prices, potentially creating food elitism. In regions threatened by nutrient deficiencies, a lack of pollination may aggravate deficiencies in iron, vitamin A, and folate, impacting areas already suffering from hidden hunger (Chaplin-Kramer et al. 2014). Pollinator-dependent plants contain essential nutrients, and a decline in pollinator populations may lead to the rise of diseases linked to nutritious diets (Potts et al. 2016; Eilers et al. 2011). Honeybees not only provide pollination services but also deposit nitrogen during foraging, benefiting plant health (Mishra et al. 2013).

Industries associated with agriculture, such as food processing, transportation, and retail, can be affected by bee losses, influencing economic benefits derived from sustainable agriculture (Paudel et al. 2015). The economic impact of bee losses has prompted interest in conservation efforts, with governments, businesses, and organizations investing in bee-friendly initiatives and habitat restoration (Sumner & Boriss 2006). Global food trade is interconnected, and bee losses can disrupt supply chains, impacting food access worldwide (Hamilton et al. 2020). The decline in bee populations has economic ramifications for beekeepers and farmers, affecting hive maintenance costs, crop yields, and expenses related to pollination services (Potts et al. 2016). Concerns about the long-term sustainability of agriculture arise from ongoing bee population declines. Bee contributions extend beyond pollination to medicine, fibre, culture, and ecosystem sustainability (IPBES 2016). Flowering plants dependent on pollinators provide not only food but also aesthetic, cultural, educational, and therapeutic values (Hanley et al. 2015; Guerry et al. 2015).

Gaps in current understanding and future perspectives

This study on the declining population of honeybees and CCD showcases certain gaps in our understanding of this complex issue that present us with future areas to focus on. There is a lack of a clear and unified mechanism for CCD which makes it difficult to develop targeted interventions (Lu et al. 2020). There is a complex interplay between various stressors such as pesticides, pathogens, environmental factors, and biotic stressors that makes it challenging to find the primary cause or culprit of CCD (Nikita et al. 2022). To develop a complete and comprehensive understanding of CCD as well as its prevention we need to take this multifactorial perspective in mind. We can utilize novel technologies like genomics, proteomics, and metabolomics to identify new biomarkers and mechanisms that underlie CCD (Lu et al. 2020). The potential impacts of electromagnetic fields from telecommunication towers and other sources need to be investigated thoroughly as current studies present us with contrasting results (Wyszkowska et al. 2019). The relationship between climate change and CCD as well as the potential for adaptation and mitigation strategies needs to be explored thoroughly (Mohammadian et al. 2019). More regional studies need to be conducted to understand specific factors that contribute to CCD in various geographical locations (Mohammadian et al. 2019). Long-term monitoring should be there to track changes in the population of the honeybee and CCD incidences that take place over time (Nikita et al. 2022). Public awareness and education about the importance of honeybees as pollinators needs to be increased among the general public (Nikita et al. 2022). They should know what kind of threats honeybees are facing as well as the role of beekeepers and consumers that can be played to safeguard honeybee populations. Addressing these gaps and future perspectives is of crucial importance for developing effective strategies to protect honeybee populations and mitigate the impacts of CCD.

Conclusion

The decline in honeybees, highlighted by phenomena like Colony Collapse Disorder, poses a significant threat to global agriculture, economy, and food security. Aligning with existing literature, it emphasizes the crucial role of honeybees as primary pollinators and the interconnectedness of factors contributing to their decline. This paper calls for collaborative efforts to bridge research gaps, revisit bee management practices, reevaluate pesticide use, and promote biodiversity-friendly farming. Mitigation strategies should prioritize the promotion of native flora to enhance forage diversity, strict regulation of pesticide use, and the adoption of sustainable beekeeping practices. Policymakers must incentivize habitat restoration and support smallholder farmers to reduce agrochemical dependency. Future research should focus on understanding the synergistic effects of stressors on honeybee health, developing disease-resistant bee strains, and monitoring long-term climate impacts on pollinator populations. Proactive, multidisciplinary approaches are critical to safeguarding pollinator ecosystems.

Data availability The data is already available in the manuscript.

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