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A review on electromagnetic fields as an emerging ecological stressor for insects

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Abstract

Anthropogenic electromagnetic fields (EMFs) generated by power transmission systems, wireless communication networks, and electronic infrastructure have become pervasive across natural and managed ecosystems. While potential health effects of EMFs on humans and vertebrate models have been extensively debated, their ecological consequences remain poorly integrated into biodiversity science. Insects underpin ecosystem functioning through pollination, nutrient cycling, and trophic regulation, yet are undergoing rapid global declines driven by interacting stressors. Here, we synthesize experimental, physiological, and ecological evidence demonstrating that EMFs disrupt insect biology across organizational levels, from oxidative stress and neurophysiological impairment to altered behaviour, reduced reproduction, and compromised genetic integrity. We argue that EMFs function as a chronic, sublethal environmental stressor capable of interacting synergistically with pesticides, climate change, and habitat modification. Recognizing insects as sensitive sentinels of electromagnetic pollution is essential for developing ecologically relevant risk-assessment frameworks in an increasingly electrified world.

Keywords: Electromagnetic fields (EMFs), insect ecology, oxidative stress, behavioural disruption, reproductive impairment, electromagnetic pollution, population dynamics, environmental risk assessment

Introduction

Insects underpin terrestrial ecosystems by sustaining pollination, nutrient cycling, decomposition, and trophic regulation. However, widespread declines in insect biomass, diversity, and abundance have been documented globally, raising concerns about ecosystem stability and resilience (Hallmann *et al*., 2017; Sanchez-Bayo & Wyckhuys, 2019; Wagner *et al*., 2021) [7, 22, 30]. While habitat loss, climate change, pesticides, and light pollution are recognised drivers of these declines, the potential ecological role of anthropogenic electromagnetic fields (EMFs) remains poorly integrated into biodiversity research (Balmori, 2022) [3].

EMFs generated by power transmission systems, wireless communication infrastructure, and electronic devices now constitute a persistent and expanding component of modern environments. Unlike chemical pollutants, EMFs are invisible, continuous, and spatially diffuse, complicating ecological assessment. Although EMF research has largely focused on human health and vertebrate models, growing experimental evidence indicates that insects may be particularly vulnerable due to their small body size, high metabolic rates, and reliance on finely regulated neurophysiological and redox processes (Saliev *et al*., 2019; Yakymenko *et al*., 2016) [21, 31]. Importantly, insect fitness is tightly linked to behaviours such as locomotion, courtship, foraging, and orientation, providing ecologically meaningful endpoints for detecting sublethal stress.

Across diverse insect taxa, EMF exposure has been associated with increased reactive oxygen species production, depletion of antioxidant defences, and oxidative damage to lipids, proteins, and DNA (Yakymenko *et al*., 2016; Luukkonen *et al*., 2017) [13, 31]. These molecular disruptions are frequently accompanied by neurophysiological alterations that manifest as impaired locomotion, disrupted courtship, altered aggression, and compromised orientation (Margaritis *et al*., 2014; Shepherd *et al*., 2018; Treder *et al*., 2023) [14, 24, 28]. Even modest behavioural and reproductive impairments can translate into reduced population growth rates, particularly when EMFs act synergistically with other anthropogenic stressors such as pesticides and climate change (Goulson *et al*., 2015; Lupi *et al*., 2021) [6, 12].

In this Review, we synthesise current evidence on EMF effects in insects across molecular, behavioural, and ecological levels. We argue that EMFs function as a chronic, sublethal environmental stressor capable of influencing insect population stability and community structure, and that insects should be incorporated into ecologically relevant EMF risk-assessment frameworks.

Insects in an electrified biosphere

Electromagnetic fields now constitute an almost continuous background component of modern environments. Unlike classical pollutants, EMFs are invisible, spatially diffuse, and persistent, complicating their detection and ecological evaluation. At the same time, insect's key drivers of ecosystem services are declining globally at unprecedented rates (Hallmann *et al*., 2017; Sanchez-Bayo & Wyckhuys, 2019; Wagner *et al*., 2021) [7, 22, 30]. Although habitat loss, climate change, and agrochemicals are widely recognized contributors, emerging evidence suggests that electromagnetic pollution represents an overlooked but biologically consequential stressor (Balmori, 2022) [3].

Insects are uniquely informative models for evaluating EMF impacts. Their small body size, high surface area to volume ratio, rapid metabolism, and reliance on finely regulated neural and redox processes render them sensitive to weak environmental perturbations. Moreover, insect fitness is tightly coupled to behavioural performance locomotion, courtship, foraging, and orientation providing direct functional links between physiological disruption and ecological outcomes.

Mechanistic foundations: oxidative stress and neurophysiological disruption

A convergent mechanistic signal across insect EMF studies is oxidative stress. Exposure to low frequency and radiofrequency EMFs has been shown to elevate reactive oxygen species (ROS) production, overwhelming enzymatic and non-enzymatic antioxidant defences (Yakymenko *et al*., 2016; Saliev *et al*., 2019) [21, 31]**.** This redox imbalance promotes lipid peroxidation, protein oxidation, and damage to nucleic acids, compromising cellular integrity and metabolic efficiency.

Oxidative stress is closely linked to neurophysiological vulnerability. Insect nervous systems depend on precise ion channel kinetics and neurotransmitter regulation, particularly cholinergic signalling. EMF induced alterations in membrane properties and calcium dynamics can impair neuromuscular coordination and sensory processing **(**Pall, 2013; Romanenko *et al*., 2014) [16, 20]. These effects are frequently non-thermal and occur at exposure levels below current human-centred safety limits.

At the molecular level, prolonged EMF exposure has been associated with reduced DNA integrity and increased fragmentation (Panagopoulos *et al*., 2002; Luukkonen *et al*., 2017) [13, 18]. Such genotoxic stress raises concerns about heritable effects in insects, whose short generation times may facilitate the rapid propagation of EMF induced damage across generations.

Behavioural disruption as an ecological bottleneck

Behaviour represents the most immediate interface between physiology and ecology, and behavioural endpoints provide some of the strongest evidence for ecological relevance of EMF exposure. Across multiple insect taxa, EMFs have been shown to reduce locomotor activity, impair climbing ability, alter aggression, and disrupt courtship sequences (Margaritis *et al*., 2014; Shepherd *et al*., 2018) [14, 24]. These effects directly compromise dispersal, predator avoidance, and mating success.

Orientation and temporal regulation appear particularly sensitive. Many insects rely on geomagnetic cues for navigation and spatial memory, and EMF interference with magnetoreception has been linked to impaired homing and orientation (Favre, 2011; Treder *et al*., 2023) [5, 28]. Additionally, circadian disruption caused by EMFs can desynchronise feeding, mating, and emergence from environmental cycles, eroding fitness without causing immediate mortality. Such sublethal behavioural effects are hallmarks of chronic ecological stressors with population-level consequences.

Reproductive and developmental consequences

Reproduction integrates energetic status, endocrine regulation, and gamete integrity, making it a sensitive indicator of environmental stress. EMF exposure has been associated with reduced fecundity, delayed development, and decreased offspring viability in diverse insect models (Kesari *et al*., 2012; Sharma & Kumar, 2010) [10, 23]. These effects likely arise from combined oxidative damage to reproductive tissues, metabolic exhaustion, and disrupted neuroendocrine signalling.

Even modest reductions in reproductive output can have disproportionate demographic consequences for insects, whose population dynamics depend on high fecundity and rapid turnover. Chronic EMF exposure may therefore function as a demographic stressor, subtly reducing population growth rates and resilience, particularly when interacting with other pressures such as pesticides, pathogens, and thermal extremes (Goulson *et al*., 2015; Lupi *et al*., 2021) [6, 12].

Differential sensitivity and community restructuring

Insect responses to EMFs are not uniform. Species differ in antioxidant capacity, neural robustness, and DNA repair efficiency, resulting in variable susceptibility to electromagnetic exposure. Such heterogeneity implies that EMFs may act as a selective environmental filter, favouring more resilient taxa while suppressing sensitive ones.

At the community level, this raises concerns about altered pollinator assemblages, weakened decomposition processes, and disrupted trophic interactions. Over time, EMF driven selection could contribute to shifts in species composition with cascading ecosystem effects, analogous to those observed under other pervasive anthropogenic stressors such as light pollution and chemical contamination (Holker *et al.*, 2010; Brook *et al*., 2008) [4, 8].

Regulatory blind spots and research priorities

Current international EMF exposure guidelines are overwhelmingly human-centric and focus primarily on thermal thresholds (ICNIRP, 2020). Insects, however, may experience biologically meaningful disruption at exposure levels far below these limits. This discrepancy highlights a major regulatory blind spot the absence of insect inclusive and ecologically relevant EMF risk assessment frameworks.

Future research must prioritise standardized exposure protocols, ecologically realistic field conditions, and multi-generational designs that link molecular damage to population dynamics. Integrating EMFs into biodiversity risk assessments would align electromagnetic pollution with other recognised drivers of ecological change and strengthen conservation policy in increasingly electrified landscapes.

Multiscale mechanistic cascade linking electromagnetic field exposure to insect fitness and population stability.

Anthropogenic electromagnetic fields (EMFs) induce oxidative stress through increased reactive oxygen species (ROS) production, overwhelming antioxidant defenses and leading to lipid, protein, and DNA damage. These molecular disruptions impair neurophysiological and metabolic processes, manifesting as altered behaviour including reduced locomotion, disrupted courtship, and impaired orientation. Behavioral and physiological dysfunctions translate into reduced reproductive output and survival, ultimately increasing the risk of population instability. The figure highlights how sublethal EMF exposure can propagate across organizational levels, from cells to ecosystems.

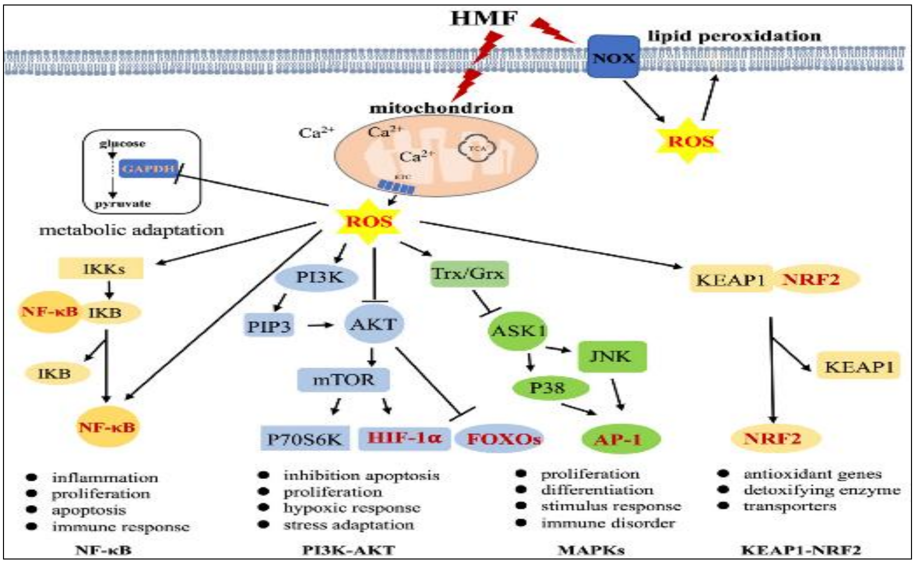

Fig 1: Proposed molecular mechanisms linking electromagnetic field (EMF) exposure to oxidative stress and downstream cellular signalling pathways

Electromagnetic field (EMF) exposure induces mitochondrial dysfunction and membrane-associated NADPH oxidase (NOX) activation, leading to excessive production of reactive oxygen species (ROS). Elevated ROS trigger lipid peroxidation and activate multiple redox-sensitive signalling pathways, including PI3K/AKT/mTOR, MAPK (p38, JNK), NF-κB, HIF-1α, FOXO, and AP-1, influencing cell survival, proliferation, apoptosis, inflammation, and metabolic adaptation. Concurrently, ROS mediated modulation of the KEAP1 - NRF2 pathway regulates antioxidant and detoxification gene expression. Collectively, these interconnected pathways illustrate how EMF induced oxidative stress can disrupt cellular homeostasis and drive physiological, behavioural, and fitness-related impairments in insects.

Neural disruption as a mechanistic link between electromagnetic fields and insect behaviour

The insect nervous system is highly distributed, comprising the brain, suboesophageal and segmental ganglia, and paired ventral nerve cords that coordinate sensory processing and motor output across the body. This organization depends on precisely regulated membrane potentials, ion-channel activity, and neurotransmitter signalling, rendering neural function particularly sensitive to physical perturbations. Electromagnetic fields may disrupt insect neurophysiology by modulating voltage-gated ion channels, altering membrane properties, and increasing intracellular calcium fluxes, thereby affecting neuronal excitability and synaptic transmission. In parallel, EMF-induced oxidative stress can damage neuronal membranes and synaptic proteins, compounding disruptions in neural signalling. Because these neural effects can propagate along the ventral nerve cord and across interconnected ganglia, even subtle perturbations may result in widespread neuromuscular dysfunction. At the organismal level, such neurophysiological disruption manifests as impaired locomotion, altered orientation, disrupted courtship, and changes in aggression, behaviour that directly determine fitness. Consequently, the structural and functional characteristics of the insect nervous system make it a plausible and sensitive target of electromagnetic field exposure, linking EMF induced neurophysiological stress to ecological and population-level consequences.

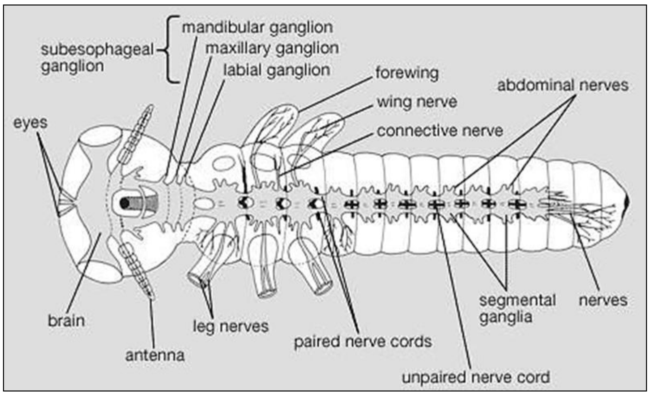

Fig 2: Insect nervous system architecture as a potential target of electromagnetic field (EMF) exposure

Schematic representation of the insect central and peripheral nervous system, including the brain, suboesophageal and segmental ganglia, paired ventral nerve cords, and peripheral nerves innervating the antennae, legs, wings, and abdomen. This distributed and highly interconnected neural organization relies on precise ion channel activity, neurotransmitter signalling, and membrane potential regulation. Such features render the insect nervous system particularly susceptible to electromagnetic field induced perturbations, which may alter neural excitability, synaptic transmission, and sensory processing, ultimately manifesting as impaired locomotion, orientation, courtship, and other ecologically relevant behaviour

Behavioral disruption as a key mediator of electromagnetic field effects on insect fitness.

Insects rely on finely coordinated behaviour including locomotion, courtship, foraging, aggression, and orientation to maintain fitness and ecological function. Electromagnetic field exposure disrupts neural signaling, redox balance, and circadian regulation, converging on behavioral impairment as a central bottleneck. Because behaviour directly links physiology to ecological performance, even sublethal EMF induced changes can disproportionately reduce dispersal ability, mating success, and survival, amplifying population-level consequences.

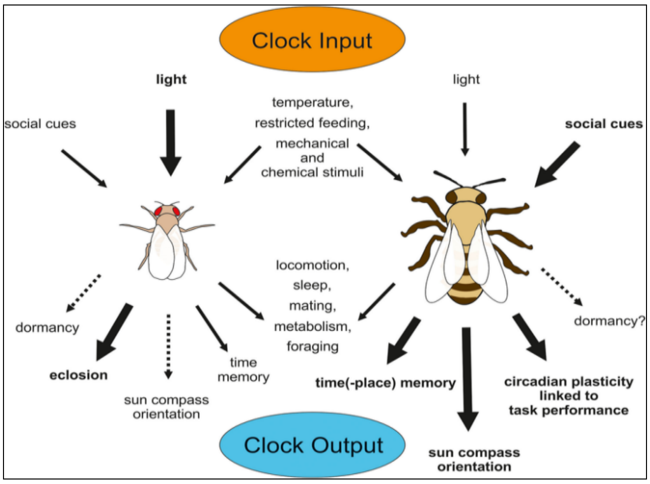

Fig 3: Circadian clock inputs and outputs regulating insect behaviour and physiology

The insect circadian clock functions as an internal timekeeping system that synchronises behaviour and physiology with daily environmental cycles. Light is the primary zeitgeber, entraining the clock through visual and extraretinal photoreceptive pathways, while additional environmental factors such as temperature fluctuations, feeding schedules, and mechanical or chemical stimuli fine tune circadian timing. Social cues, including interactions within populations or colonies, also contribute to clock entrainment, particularly in social insects. These diverse inputs converge on central and peripheral clocks, enabling insects to maintain temporal order even under variable environmental conditions.

Clock outputs represent the downstream behavioural and physiological processes governed by circadian timing. These include locomotor activity rhythms, sleep wake cycles, mating behaviour, metabolic regulation, foraging efficiency, and orientation using sun compass navigation. Circadian control further extends to developmental and seasonal processes such as eclosion timing, dormancy, and circadian plasticity linked to task performance and time place memory. Disruption of clock inputs through environmental stressors such as electromagnetic fields, artificial light, or altered thermal regimes may therefore desynchronise circadian outputs, leading to impaired behavioural performance and reduced fitness. This integrative framework highlights the circadian system as a critical pathway through which environmental perturbations can influence insect ecology and population stability.

Table 1: The List of Reviews Which Focused on The Effect of EMF Exposure on Insect

Species	**Order**	**EMF /Frequency**	**Experimental Endpoints**	**Major Findings**	**Reference**
Drosophila melanogaster	Diptera	RF-EMF (900 MHz)	Oogenesis, apoptosis	Increased apoptotic cell death	Panagopoulos *et al*., 2002 [18]
D. melanogaster	Diptera	RF-EMF (900 - 1800 MHz)	DNA integrity	DNA damage, fragmentation	Margaritis *et al*., 2014 [14]
D. melanogaster	Diptera	RF-EMF	Development	Delayed development	Panagopoulos *et al*., 2007 [19]
D. simulans	Diptera	ELF-EMF (50 Hz)	Longevity	Reduced lifespan	Sharma and Kumar, 2010 [23]
D. virilis	Diptera	RF-EMF	Larval survival	Reduced survival	Agarwal *et al*., 2009 [1]
Apis mellifera	Hymenoptera	RF-EMF (900–2450 MHz)	Homing behaviour	Impaired homing ability	Treder *et al*., 2023 [28]
A. mellifera	Hymenoptera	ELF-EMF (50 Hz)	Learning, memory	Reduced associative learning	Shepherd *et al*., 2018 [24]
A. mellifera	Hymenoptera	RF-EMF (mobile phone)	Communication	Worker piping behaviour	Favre, 2011 [5]
A. mellifera	Hymenoptera	ELF-EMF	Aggression	Increased aggression	Shepherd *et al*., 2019
A. mellifera (queen pupae)	Hymenoptera	RF-EMF	Development	Altered queen development	Odemer and Odemer, 2019 [15]
Bombus terrestris	Hymenoptera	RF-EMF	Foraging	Reduced foraging efficiency	Balmori, 2015 [2]
Bombus impatiens	Hymenoptera	RF-EMF	Colony growth	Reduced colony growth	Lupi *et al*., 2021 [12]
Formica rufa	Hymenoptera	RF-EMF	Orientation	Disrupted nest orientation	Balmori, 2021
Camponotus compressus	Hymenoptera	ELF-EMF	Activity rhythm	Altered circadian activity	Sharma and Kumar, 2010 [23]
Solenopsis invicta	Hymenoptera	ELF-EMF	Social behaviour	Altered colony activity	Lupi *et al*., 2021 [12]
Nasonia vitripennis	Hymenoptera	RF-EMF	Reproduction	Reduced parasitism success	Panagopoulos, 2019 [17]
Osmia bicornis	Hymenoptera	RF-EMF	Nesting behaviour	Reduced nesting success	Lupi *et al*., 2021 [12]
Megachile rotundata	Hymenoptera	RF-EMF	Brood success	Reduced brood emergence	Balmori, 2015 [2]
Tenebrio molitor	Coleoptera	ELF-EMF	Growth, survival	Delayed development	Vilic *et al*., 2017 [29]
Tribolium castaneum	Coleoptera	ELF-EMF	Reproduction	Reduced fecundity	Kesari *et al*., 2015 [11]
Sitophilus oryzae	Coleoptera	ELF-EMF	Mortality	Increased mortality	Kesari *et al*., 2015 [11]

Alphitobius diaperinus	Coleoptera	ELF-EMF	Development	Growth retardation	Agarwal *et al*., 2009 [1]
Coccinella septempunctata	Coleoptera	ELF-EMF	Predation	Reduced predatory efficiency	Lupi *et al*., 2021 [12]
Harmonia axyridis	Coleoptera	RF-EMF	Behaviour	Altered activity	Balmori, 2015 [2]
Acheta domesticus	Orthoptera	ELF-EMF	Locomotion	Altered movement	Sharma and Kumar, 2010 [23]
Gryllus bimaculatus	Orthoptera	RF-EMF	Calling behaviour	Reduced calling activity	Balmori, 2015 [2]
Locusta migratoria	Orthoptera	ELF-EMF	Locomotion	Altered jumping	Sokolova, 2013 [26]
Schistocerca gregaria	Orthoptera	ELF-EMF	Behaviour	Reduced activity	Sokolova, 2013 [26]
Periplaneta americana	Blattodea	RF-EMF	Neural activity	Modified neuronal firing	Romanenko *et al*., 2014 [20]
Blattella germanica	Blattodea	ELF-EMF	Circadian rhythm	Altered activity cycle	Sharma and Kumar, 2010 [23]
Bombyx mori	Lepidoptera	ELF-EMF	Larval growth	Reduced growth rate	Agarwal *et al*., 2009 [1]
Bombyx mori	Lepidoptera	RF-EMF	Cocoon quality	Reduced silk quality	Yakymenko *et al*., 2016 [31]
Galleria mellonella	Lepidoptera	RF-EMF	Immunity	Suppressed immune response	Luukkonen *et al*., 2017 [13]
Helicoverpa armigera	Lepidoptera	ELF-EMF	Feeding	Reduced feeding efficiency	Agarwal *et al*., 2009 [1]
Spodoptera litura	Lepidoptera	ELF-EMF	Development	Developmental delay	Kesari *et al*., 2012 [10]
Plutella xylostella	Lepidoptera	RF-EMF	Survival	Reduced survival	Thielens *et al*., 2018 [27]
Manduca sexta	Lepidoptera	RF-EMF	Metabolism	Altered metabolic rate	Yakymenko *et al*., 2016 [31]
Aedes aegypti	Diptera	RF-EMF	Flight behaviour	Reduced flight performance	Thielens *et al*., 2018 [27]
Culex pipiens	Diptera	ELF-EMF	Larval development	Delayed larval growth	Kesari *et al*., 2012 [10]
Anopheles stephensi	Diptera	RF-EMF	Longevity	Reduced lifespan	Agarwal *et al*., 2009 [1]
Musca domestica	Diptera	ELF-EMF	Longevity	Reduced adult lifespan	Sharma and Kumar, 2010 [23]
Calliphora vicina	Diptera	RF-EMF	Orientation	Impaired navigation	Balmori, 2015 [2]
Sarcophaga bullata	Diptera	ELF-EMF	Development	Delayed pupation	Kesari *et al*., 2012 [10]
Bactrocera dorsalis	Diptera	RF-EMF	Reproduction	Reduced egg laying	Panagopoulos, 2019 [17]
Ceratitis capitata	Diptera	ELF-EMF	Development	Developmental abnormalities	Agarwal *et al*., 2009 [1]
Nilaparvata lugens	Hemiptera	ELF-EMF	Survival	Reduced survival	Agarwal *et al*., 2009 [1]
Bemisia tabaci	Hemiptera	RF-EMF	Reproduction	Reduced fecundity	Thielens *et al*., 2018 [27]
Nezara viridula	Hemiptera	ELF-EMF	Development	Developmental delay	Kesari *et al*., 2012 [10]
Aphis gossypii	Hemiptera	ELF-EMF	Reproduction	Reduced fecundity	Sharma and Kumar, 2010 [23]
Myzus persicae	Hemiptera	RF-EMF	Population growth	Reduced growth rate	Balmori, 2015 [2]
Cimex lectularius	Hemiptera	RF-EMF	Behaviour	Altered activity	Balmori, 2015 [2]
Tetranychus urticae	Acari	ELF-EMF	Reproduction	Reduced fecundity	Kesari *et al*., 2015 [11]
Ixodes ricinus	Acari	RF-EMF	Orientation	Altered host-seeking	Balmori, 2021
Argas persicus	Acari	ELF-EMF	Survival	Reduced survival	Agarwal *et al*., 2009 [1]
Panonychus citri	Acari	ELF-EMF	Reproduction	Reduced egg production	Kesari *et al*., 2015 [11]
Forficula auricularia	Dermaptera	ELF-EMF	Behaviour	Reduced activity	Sharma and Kumar, 2010 [23]
Gryllotalpa africana	Orthoptera	ELF-EMF	Burrowing behaviour	Altered burrowing	Sharma and Kumar, 2010 [23]
Oryctes rhinoceros	Coleoptera	ELF-EMF	Development	Delayed larval growth	Agarwal *et al*., 2009 [1]
Chilo partellus	Lepidoptera	ELF-EMF	Survival	Reduced survival	Kesari *et al*., 2012 [10]
Sitotroga cerealella	Lepidoptera	RF-EMF	Reproduction	Reduced fecundity	Balmori, 2015 [2]
Corcyra cephalonica	Lepidoptera	ELF-EMF	Development	Delayed emergence	Agarwal *et al*., 2009 [1]
Anisopteromalus calandrae	Hymenoptera	RF-EMF	Parasitism	Reduced parasitic efficiency	Panagopoulos, 2019 [17]
Encarsia formosa	Hymenoptera	RF-EMF	Reproduction	Reduced parasitism rate	Lupi *et al*., 2021 [12]
Trichogramma chilonis	Hymenoptera	ELF-EMF	Egg parasitism	Reduced emergence	Kesari *et al*., 2012 [10]
Trichogramma brassicae	Hymenoptera	RF-EMF	Parasitism	Reduced host-	Balmori, 2015 [2]

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Cotesia plutellae	Hymenoptera	ELF-EMF	Longevity	Reduced adult lifespan	Kesari *et al*., 2012 [10]
Microplitis demolitor	Hymenoptera	RF-EMF	Development	Reduced cocoon success	Agarwal *et al*., 2009 [1]
Chironomus riparius	Diptera	ELF-EMF	DNA damage	Increased genotoxicity	Luukkonen *et al*., 2017 [13]
Tipula paludosa	Diptera	RF-EMF	Orientation	Impaired flight orientation	Balmori, 2015 [2]
Eristalis tenax	Diptera	RF-EMF	Foraging	Reduced foraging efficiency	Lupi *et al*., 2021 [12]
Delia radicum	Diptera	ELF-EMF	Development	Delayed larval growth	Kesari *et al*., 2012 [10]
Phormia regina	Diptera	RF-EMF	Neural response	Altered sensory response	Romanenko *et al*., 2014 [20]

Conclusion

Electromagnetic fields represent an invisible yet pervasive component of the Anthropocene, embedded within modern landscapes through power transmission systems, wireless communication networks, and expanding technological infrastructure. The evidence synthesised in this Review demonstrates that EMFs can disrupt insect biology across multiple organisational levels, from oxidative stress and neurophysiological imbalance to altered behaviour, impaired reproduction, and reduced population stability. Importantly, many of these effects arise at exposure levels well below those associated with acute lethality, highlighting EMFs as a chronic, sublethal ecological stressor rather than a conventional toxic agent.

By linking molecular damage to functional outcomes, this synthesis underscores behaviour as a critical bottleneck through which EMF-induced physiological stress is translated into ecological consequences. Impairments in locomotion, courtship, orientation, and circadian regulation directly compromise fitness, dispersal, and reproductive success, thereby influencing population dynamics even in the absence of immediate mortality. Species-specific variation in sensitivity further suggests that EMFs may act as a selective environmental filter, with the potential to reshape insect community composition and associated ecosystem services over time.

Recognising insects as early warning sentinels of electromagnetic pollution reframes EMF exposure as not solely a human health issue, but a global biodiversity concern. Current exposure guidelines remain largely human-centric and thermally focused, overlooking ecologically relevant endpoints such as behaviour, reproduction, and population resilience. Integrating insects into EMF risk assessment frameworks would provide a more biologically realistic evaluation of environmental electromagnetic exposure and align electromagnetic pollution with other recognised drivers of biodiversity loss.

Addressing this emerging challenge will require interdisciplinary collaboration across physics, biology, ecology, and environmental policy. Future research should prioritise standardised exposure protocols, ecologically realistic field studies, and multi-generational approaches that link molecular mechanisms to population- and community level outcomes. As technological advancement continues to accelerate, ensuring that the expansion of electromagnetic infrastructure does not undermine the ecological foundations upon which ecosystems depend represents a critical and timely priority for environmental science and conservation policy.

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