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Pulse Electromagnetic Field Generator (PEMF) Pest Control System: Laboratory-Level Assessment and Preliminary Findings

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Abstract

The overreliance on chemical pesticides in Sri Lanka poses significant risks to human health, environmental sustainability, and long-term agricultural productivity, highlighting the urgent need for innovative non-chemical pest control strategies. This study reports the design, fabrication, theoretical modeling, and laboratory-level evaluation of a pulse electromagnetic field (PEMF) generator-based pest control system. The device integrates a programmable microcontroller, MOSFET-based power amplification, dual air-core induction coils, and real-time calibration to generate controlled electromagnetic fields. The theoretical framework, derived from Maxwell's equations and the principles of Faraday's electromagnetic induction, was validated through finite element modeling and experimental measurements, confirming the uniformity and linearity of the generated electromagnetic fields.

Laboratory experiments were conducted to evaluate the efficacy of PEMF exposure against several major agricultural pests, including *Spodoptera mauritia* (paddy swarming armyworm), *Spodoptera frugiperda* (fall armyworm), *Callosobruchus maculatus* (cowpea beetle), *Tribolium castaneum* (red flour beetle), and *Aphis fabae* (cowpea aphid). Larval and pupal stages of *S. mauritia*, *C. maculatus*, and *T. castaneum* were exposed to electromagnetic field frequencies of 4, 6, and 8 Hz for 20 minutes. To assess stage-specific susceptibility, different developmental stages of *C. maculatus* and *T. castaneum* were exposed to the electromagnetic field in four time intervals (1–5, 6–10, 11–15, and 16–20 days after the initiation of the experiment). In addition, *A. fabae* and *S. frugiperda* larvae were subjected to magnetic field intensities ranging from 1.1×10^{-6} T to 5.3×10^{-6} T.

The results demonstrated clear frequency- and intensity-dependent effects on insect survival and development. Notably, higher frequencies (8 Hz) and maximum EMF intensities (5.3×10^{-6} T) significantly reduced larval survival, adult emergence, and F_1 progeny production, whereas lower EMF levels produced negligible effects. These findings indicate that PEMF exposure can effectively disrupt key physiological and developmental processes in insect pests without the use of chemical pesticides. Overall, this study establishes PEMF technology as a promising, environmentally benign, non-chemical tool for integrated pest management and provides a scalable platform for further research and potential field application in sustainable agriculture.

Key words: Environmentally benign tool, Frequency, Pest Control, Pulse Electromagnetic Field

Introduction

Sri Lanka is an agriculturally dependent country for income generation, which is one of the major sectors, whereas agriculture contributes around 7.9% to the National Gross Domestic Production in Sri Lanka (Jayasinghe *et al.*, 2024). Both in fields and during post-harvest periods, several pests cause damage and create detrimental economic effects. Farmers use various pest control measures such as cultural control methods (e.g., adjusting planting dates, intercropping, using resistant planting materials, mulching), agroecological control measures, biological control methods (including the use of predators, parasitoids, and entomopathogens), chemical control, mechanical control, and integrated pest management to control pests (Sivapalan and Delucchi, 1974; Nugaliyadde *et al.*, 1997; Widanapathirana and Dassanayake, 2013).

Even though the majority of Sri Lankan farmers depend on chemical pesticides due to their easily accessible and immediate results in a short-term manner, they cause harmful consequences such as being toxic to humans and other non-target organisms, polluting water and the ecosystem, accumulating heavy metals, causing soil infertility, developing chronic diseases, and promoting the development of pest resistance in a long-term manner (Sumudumali *et al.*, 2021). Overreliance on chemical-based pest control approaches is detrimental to sustainable agriculture and human health. Excessive dependence on these pesticides poses risks to human health, the environment, and contributes to the emergence of resistance in non-target species. Therefore, the creation of innovative non-chemical pest control technologies is imperative. In response to this issue, the Sri Lankan government implemented a statewide ban on the use and import of chemical pesticides in April 2021. In view of this, nowadays the current trend has changed and instead of chemical pesticides, people are seeking various alternative eco-friendly pest control approaches in order to combat the issues caused by chemical pesticides.

This chapter presents the comprehensive design, fabrication, theoretical modeling, and experimental validation of a PEMF generator-based pest control system developed as a sustainable alternative to chemical pesticide application. It also describes its preliminary laboratory-level application against the swarming armyworm (*Spodoptera mauritia*), a severe seasonal pest of paddy; the fall armyworm (*Spodoptera frugiperda*), a major pest of maize; the cowpea beetle (*Callosobruchus maculatus*), a major pest of stored cowpea seeds; the red flour beetle (*Tribolium castaneum*), a significant pest of stored flour; and aphids (*Aphis fabae*), a polyphagous plant sap sucking pests.

The system integrates a programmable microcontroller-based pulse generator, a high-speed MOSFET switching and amplification stage, dual air-core induction coils, and real-time calibration instrumentation. The theoretical framework is derived from Maxwell's equations under quasi-static approximation, solenoidal magnetic field theory, Faraday induction principles, and bioelectromagnetic interaction models. Mathematical formulations describing magnetic flux density, induced electric fields, impedance-frequency coupling, and exposure dosimetry are developed and experimentally validated. Finite element modeling confirms spatial field distribution and system linearity. Environmental control conditions, safety compliance with ICNIRP exposure limits, and reproducibility metrics are incorporated to ensure scientific robustness. The integrated framework establishes a scalable, environmentally benign electromagnetic intervention platform for precision agricultural pest management. The objective

of the study is to develop a PEMF generator and evaluate its application against selected pests, as well as to determine the optimum application rate under laboratory conditions.

Materials and Methods

Experimental location and duration

All experiments were conducted at the Department of Agricultural Biology, Faculty of Agriculture, Eastern University, Sri Lanka, under laboratory conditions (Temperature: 30 ± 5 °C; RH: $85 \pm 5\%$) from May 2023 to December 2025.

Selected insect species

Spodoptera mauritia, *Spodoptera frugiperda*, *Callosobruchus maculatus*, *Tribolium castaneum*, and *Aphis fabae* were selected for the study, and their cultures were maintained under laboratory conditions.

Description about PEMF generator

System architecture and fabrication

The developed PEMF system consists of a regulated DC power supply module, a programmable timer control unit, an ESP32-based master pulse generation circuit, a MOSFET-driven switching and power amplification stage, and dual air-core electromagnetic coils serving as the field-emitting elements. A stabilized 19 V DC power adapter provides continuous voltage to the timer module, microcontroller, and amplification circuitry. Voltage stability is essential to maintain waveform reproducibility and consistent magnetic flux density output.

The master control system is implemented using an ESP32 microcontroller equipped with a precision 16–40 MHz crystal oscillator. The firmware enables programmable waveform generation with frequency tunability from 1 Hz to 100 kHz, pulse width adjustment between 10 μ s and 5000 μ s, and duty cycle variation from 1% to 90%. Pulse Width Modulation (PWM) governs the temporal characteristics of current delivery. The duty cycle is defined as $D = T_{ON}/T$, and the average output voltage follows $V_{avg} = D \cdot V_{supply}$. The high timing resolution (± 0.1 μ s) allows precise control over the current slope, which directly influences induced electric field strength.

High-current modulation is achieved using an IRFZ44N N-channel MOSFET configured as a high-speed electronic switch. The MOSFET gate receives PWM signals from the microcontroller, enabling rapid switching of coil current. The inductive behavior of the coil follows $V_L = L \frac{dI}{dt}$, and a flyback diode is incorporated to suppress reverse electromotive force during rapid current collapse. A dual-channel 2×50 W amplifier increases signal current amplitude to achieve biologically effective magnetic field intensities. The magnetic field strength scales linearly with coil turns and current, expressed as $B \propto N \cdot I$.

The induction coils are fabricated using oxygen-free copper wire wound into cylindrical air-core solenoids consisting of 500 turns with a diameter of 12 cm. The air-core configuration eliminates

ferromagnetic hysteresis distortion and ensures linear magnetic response. For a long solenoid, the magnetic flux density is described by $B(t) = \mu_0 \frac{N}{L} I(t)$, where μ_0 represents the permeability of free space. The time-varying current waveform directly determines magnetic field amplitude and temporal dynamics.

Electromagnetic theoretical framework

The device operation is fundamentally governed by Maxwell's equations. Under low-frequency conditions (1 Hz–100 kHz), the quasi-static approximation applies, and displacement currents are negligible relative to conduction currents. The governing relationship simplifies to $\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$, establishing that induced electric fields arise from temporal magnetic field variation.

Applying Faraday's law to cylindrical symmetry yields $E(r, t) = -\frac{r}{2} \frac{dB(t)}{dt}$. Substituting the solenoidal magnetic field expression results in $E(r, t) = -\frac{r}{2} \mu_0 \frac{N}{L} \frac{dI(t)}{dt}$. This demonstrates that biological interaction is primarily governed by the rate of current change rather than static magnetic amplitude alone. Consequently, higher switching frequencies and sharper pulse transitions enhance induced electric field strength.

The coil behaves electrically as an RL circuit with impedance $Z(f) = \sqrt{R^2 + (2\pi fL)^2}$. As frequency increases, inductive reactance rises, reducing current amplitude. Therefore, an optimal operational frequency window exists where induced field strength and current magnitude are balanced to maximize biological coupling efficiency.

Magnetic energy density is defined as $u_B = B^2 / (2\mu_0)$, and total exposure dose over time is expressed as $D_{EM} = \int_0^T B(t)^2 dt$. These parameters provide quantitative metrics for comparing exposure regimes and optimizing treatment protocols.

Finite element modeling and field distribution

Finite element simulations were conducted by solving the magnetostatic vector potential equation $\nabla \times (1/\mu \nabla \times \mathbf{A}) = \mathbf{J}$. The modeling incorporated coil geometry, applied current, and boundary conditions representing free-space propagation. Simulation outputs included radial field decay, edge flux intensification, and spatial uniformity within the exposure zone. Experimental validation using a calibrated 3-axis Hall-effect probe demonstrated less than 5% deviation between simulated and measured magnetic flux densities, confirming model reliability.

Biological interaction mechanisms

The time-varying electromagnetic fields generated by the device induce localized electric fields within pest tissues. These induced fields may influence transmembrane potential gradients, modulate voltage-gated ion channel kinetics, and disrupt neuromuscular coordination. The cyclotron resonance condition $f_c = qB/(2\pi m)$ suggests potential frequency-specific interactions with biologically relevant ions such as Ca^{2+} , Na^+ , and K^+ . Additionally, electromagnetic exposure may interfere with radical pair reactions associated with magnetoreception pathways. The mechanism is therefore primarily electrodynamic rather than thermal.

Experimental protocol and environmental control

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All experiments were conducted under controlled laboratory conditions at $25 \pm 2^\circ\text{C}$ and relative humidity of 55–60%. The device was housed within an electrically shielded enclosure and mounted on a non-conductive platform to minimize interference. For each experimental trial, frequency, duty cycle, and current amplitude were configured via the microcontroller interface. Magnetic field intensity was verified using a Hall probe, and waveform integrity was monitored with a 100–200 MHz bandwidth oscilloscope. Exposure durations ranged from 1 to 60 minutes depending on study design. Each condition was replicated a minimum of three times to ensure statistical reliability. Post-exposure cooling intervals were implemented to maintain thermal stability.

Safety, thermal management, and compliance

Thermal rise within the coil was monitored using infrared thermometry. Joule heating followed $P = I^2R$, and coil temperature was maintained below 50°C to eliminate thermal confounding effects. Field intensities were maintained within ICNIRP (2010) occupational exposure guidelines for time-varying magnetic fields between 1 Hz and 100 kHz. System linearity testing confirmed proportionality between coil current and magnetic flux density with correlation coefficient $R^2 > 0.98$.

Optimization framework

Biological coupling efficiency can be expressed as a multivariable function $\eta = f(B, dB/dt, D, T_{exp})$, where B represents magnetic amplitude, dB/dt represents temporal gradient, D is duty cycle, and T_{exp} is exposure duration. Optimization involves identifying operational parameters that maximize biological interaction while satisfying thermal and exposure constraints. Analytical differentiation of the efficiency function enables parameter selection under constrained optimization conditions.

*Experiment – 01: Efficacy of PEMF against *Spodoptera mauritia**

Larvae of *Spodoptera mauritia* were obtained from a laboratory culture and individually introduced into glass beakers containing moistened cotton and chopped young paddy leaves as a food source. For each treatment, twenty glass beakers, each containing a single larva, were prepared. The experiment consisted of four treatments, and five replicates were arranged in a completely randomized design.

Larvae assigned to each treatment were exposed separately to pulsed electromagnetic field (PEMF) vibrations at frequencies of 4 Hz, 6 Hz, and 8 Hz for 20 minutes using a PEMF generator, while an untreated group served as the control. The number of individuals successfully reaching the pupal and adult stages following larval exposure to the respective electromagnetic frequencies was recorded.

Similarly, the experiment was conducted on *S. mauritia* pupae, and the number of emerged adults was recorded to determine the survival percentage.

Experiment – 02: Efficacy of PEMF against Callosobruchus maculatus and Tribolium castaneum

A sample of 200 cleaned, uninfested cowpea seeds was placed separately into five beakers. Ten newly emerged, unsexed adults of *Callosobruchus maculatus* were introduced into each beaker, and this set of five beakers was considered an experimental unit. The beakers were covered with muslin cloth to ensure adequate aeration while preventing insect escape.

One experimental unit was exposed to a pulsed electromagnetic field at a frequency of 4 Hz for 20 minutes per day during the first five days following the introduction of *C. maculatus*. Similarly, separate experimental units were exposed to the same frequency and duration during 6–10 days, 11–15 days, and 16–20 days after the introduction of the insects. The same exposure protocol was applied to additional experimental units at frequencies of 6 Hz and 8 Hz, respectively.

An additional experimental unit was maintained as an untreated control under identical laboratory conditions without exposure to the electromagnetic field. Each treatment was replicated three times. Seed weight loss (%) was determined on the 21st day using a standard gravimetric method to assess the effects of different electromagnetic field frequencies and exposure periods on seed damage caused by *C. maculatus*.

The same experimental procedure was adopted for *T. castaneum*, using 250 g of wheat flour as the host substrate. Following adult introduction and magnetic field exposure under the respective treatments, the experimental units were maintained under standard laboratory conditions. The number of newly emerged F_1 adults was recorded to evaluate the effect of different electromagnetic frequencies and exposure durations on reproductive performance.

Experiment – 03: Efficacy of PEMF against Aphis fabae

One hundred mature aphids were randomly selected and introduced into a small, lidded Petri dish containing a tender shoot of cowpea (*Vigna unguiculata*) as a food source. Each Petri dish containing 100 aphids and the host plant material was considered an experimental unit, and a total of twenty such units were prepared.

A pulsed electromagnetic field (EMF) generator was used to expose one experimental unit to an EMF intensity of 1.1×10^{-6} T for 10 minutes. Similarly, four separate experimental units were exposed to EMF intensities of 2.1×10^{-6} T, 3.2×10^{-6} T, 4.3×10^{-6} T, and 5.3×10^{-6} T, respectively. A control group was maintained under identical laboratory conditions without EMF exposure for comparison.

Each treatment, including the control, was replicated four times. The magnetic field intensities were applied in a randomized order rather than sequentially to minimize systematic bias and to facilitate the identification of an effective field intensity for subsequent detailed investigations. Following exposure, aphid survival was recorded at 24, 48, and 72 hours after treatment.

Experiment – 04: Efficacy of PEMF against *Spodoptera frugiperda*

Laboratory-reared third-instar larvae of *Spodoptera frugiperda* were individually placed in 10 mL glass vials fitted with perforated lids to allow adequate aeration. Twenty identical vials, each containing a single larva, were prepared for each treatment and collectively considered as an experimental unit. A pulsed electromagnetic field (EMF) generator was used to produce a magnetic field intensity of 1.1×10^{-6} T, and an experimental unit was exposed to this field for 15 minutes.

Similarly, four additional units were exposed individually to magnetic field intensities of 2.1×10^{-6} T, 3.2×10^{-6} T, 4.3×10^{-6} T, and 5.3×10^{-6} T, respectively, using the same exposure duration. A control group consisting of 12 vials, each containing a single larva, was maintained under identical laboratory conditions without electromagnetic field exposure for comparison.

Each treatment, including the untreated control, was replicated four times. Larval survival was recorded at 24, 48, and 72 hours after exposure. The entire experiment was repeated three times to ensure the reproducibility and reliability of the results.

20 Data Analysis

The data derived from these experiments were analyzed using R software (version 4.2). Treatment means were compared using Duncan's Multiple Range Test (DMRT) at a 5% level of significance.

Results and Discussion

Efficacy of PEMF against *Spodoptera mauritia*

Table 1. The number of transformed pupae and adults, *Spodoptera mauritia*, from larvae exposed to electromagnetic fields, 4, 6, and 8 Hz

Electromagnetic field (Hz)	Number of larvae exposed to treatment*	Percentage of larva transformed to pupa*	Percentage of adult emerged from pupa*
4	20	87.0 ^a	91.7 ^a
6	20	23.0 ^b	75.7 ^b
8	20	00.0 ^c	00.0 ^b
Un-treated control	20	92.0 ^a	95.7 ^a

* Each value represents the mean of five independent replicates (n = 5)

Means followed by the same letter in each column do not differ statistically at p<0.05 based on DMRT at a 5% significant level

24 The number of pupae formed and adults emerged following larval exposure to different pulsed electromagnetic field frequencies is presented in Table 1. Larval exposure to the 8 Hz frequency completely disrupted development, resulting in the absence of both pupal formation and adult emergence. In contrast, larvae exposed to 6 Hz and 4 Hz frequencies showed partial development, but the inhibitory effects on pupation and adult emergence were considerably higher than those

observed in the untreated control. Statistical analysis using Duncan's Multiple Range Test indicated significant differences among treatments ($P < 0.05$), with the untreated control showing the highest pupation and adult emergence rates, while the 8 Hz treatment resulted in complete developmental inhibition.

Table 2. The number of emerged adults, *Spodoptera mauritia*, from pupae exposed to electromagnetic fields, 4, 6, and 8 Hz

Electromagnetic field (Hz)	Number of pupae exposed *	Percentage of adult emerged from pupa*
4	20	98.7 ^a
6	20	96.3 ^a
8	20	30.1 ^b
Un-treated control	20	98.7 ^a

* Each value represents the mean of five independent replicates (n = 5)

Means followed by the same letter in each column do not differ statistically at $p < 0.05$ based on DMRT at a 5% significant level

Exposure of *Spodoptera mauritia* pupae to pulsed electromagnetic fields (EMF) significantly influenced adult emergence. Pupae exposed to 4 Hz and 6 Hz EMF exhibited emergence rates of 98.7% and 96.3%, respectively, which were not significantly different from the untreated control (98.7%), indicating minimal impact at these frequencies. In contrast, pupae exposed to 8 Hz showed a dramatic reduction in adult emergence to 30.1%, demonstrating that higher-frequency EMF severely disrupts pupal development and reduces survival to adulthood. These results suggest a frequency-dependent effect of EMF on pupal viability, with 8 Hz representing a threshold that markedly compromises metamorphosis.

Similar investigations have demonstrated that electromagnetic radiation can influence developmental and behavioral responses in several insect species, including locusts, mosquitoes, rice weevils, and honey bees at different frequency ranges (Krittigamas *et al.*, 2012; Thielens *et al.*, 2018), supporting the potential biological impact of EMF exposure.

Efficacy of PEMF against *Callosobruchus maculatus*

Table 3. Effect of different electromagnetic field frequencies on seed damage caused by *Callosobruchus maculatus*

(Hz)Exposure Duration (days after treatment)	Frequency of Electromagnetic field	*Number of damaged cowpea seeds by <i>C. maculatus</i>
1 – 5	4	52.0 ± 2.5 ^e
	6	49.0 ± 3.2 ^{de}
	8	8.7 ± 1.3 ^e
6 - 10	4	102.7 ± 12.0 ^{abcd}
	6	91.3 ± 1.9 ^{bcd}

11 - 15	8	73.3 ± 5.2 ^{cd}
	4	131.0 ± 5.8 ^{ab}
	6	73.3 ± 5.2 ^{cd}
16 - 20	8	8.7 ± 1.3 ^e
	4	94.3 ± 8.2 ^{bed}
	6	107.3 ± 11.1 ^{abc}
Untreated Control		151.0 ± 5.4 ^a

* Each value represents the mean of three independent replicates (n = 3)
Means followed by the same letter in each column do not differ statistically at p<0.05 based on DMRT at a 5% significant level

The number of damaged cowpea seeds varied significantly with electromagnetic field (EMF) frequency and exposure duration (Table 3). The untreated control recorded the highest seed damage (151.0 ± 5.4), indicating maximum survival and feeding activity of *C. maculatus*. In contrast, EMF exposure reduced seed damage to varying degrees depending on the frequency and the developmental stage of the insect at the time of exposure.

During 1–5 days after treatment, when eggs were present on the seed surface and neonate larvae had just begun to penetrate the seeds, exposure to 8 Hz resulted in a very low level of seed damage (8.7 ± 1.3), suggesting that this frequency may interfere with egg viability or early larval establishment within the seed.

In the 6–10 day period, corresponding to the early larval instars developing within the seeds, seed damage increased under all frequencies, although the values remained lower than the control, indicating partial suppression of larval development.

During 11–15 days after treatment, when insects had reached the late larval or pupal stages, 8 Hz again produced minimal seed damage (8.7 ± 1.3), whereas higher levels were recorded at 4 Hz (131.0 ± 5.8) and 6 Hz (73.3 ± 5.2).

In the 16–20 day period, when most individuals were at the pupal stage, intermediate levels of seed damage were observed across treatments, suggesting that EMF exposure at this stage has a comparatively lower inhibitory effect than during the earlier developmental stages.

Overall, these results indicate that the effectiveness of EMF treatment depends not only on the frequency applied but also on the developmental stage of *C. maculatus* at the time of exposure. The consistently low damage observed at 8 Hz, particularly during the egg/neonate stage and the late larval–pupal transition, suggests that this frequency may disrupt critical developmental processes. Therefore, EMF treatment, especially at 8 Hz, may offer potential as a non-chemical approach for managing bruchid infestation in stored cowpea seeds.

Table 4. Number of newly emerged *Tribolium castaneum* at F1 generation

(Hz)Exposure Duration (days after treatment)	Frequency of Electromagnetic field	*Number of newly emerged <i>Tribolium castaneum</i> at F1 generation
1 – 5	4	94.3 ± 1.4 ^b
	6	115.7 ± 2.2 ^b
	8	88.0 ± 4.3 ^b
6 - 10	4	83.0 ± 2.3 ^b
	6	61.7 ± 3.7 ^c
	8	48.3 ± 2.5 ^c
11 - 15	4	96.0 ± 4.2 ^b
	6	23.3 ± 1.8 ^d
	8	3.9 ± 0.3 ^e
16 - 20	4	64.7 ± 2.1 ^c
	6	59.7 ± 3.2 ^c
	8	32.6 ± 0.8 ^d
Untreated Control		151.0 ± 5.4 ^a

* Each value represents the mean of three independent replicates (n = 3)

Means followed by the same letter in each column do not differ statistically at p<0.05 based on DMRT at a 5% significant level

14 The effect of pulsed electromagnetic field exposure on the emergence of *Tribolium castaneum* F₁ progeny (Table 4) varied significantly depending on both the frequency and the developmental stage at which the parental insects were exposed. In the 1–5 day exposure period, corresponding to the egg stage, all frequencies (4, 6, and 8 Hz) resulted in moderate reductions in adult emergence (88.0–115.7 individuals) compared to the control (151 individuals). This suggests that EMF exposure during early embryogenesis has a limited effect on egg viability, as eggs are relatively resistant to external stressors.

During the 6–10 day exposure period, when the parental insects' offspring were predominantly in the early larval instars, EMF exposure caused a more pronounced reduction in adult emergence, particularly at higher frequencies (61.7 and 48.3 individuals at 6 Hz and 8 Hz, respectively). This indicates that early larval stages are more susceptible to EMF-induced developmental disruption, likely due to their active feeding and growth processes.

The most substantial impact was observed during the 11–15 day exposure period, corresponding to late larval and pupal stages, where EMF exposure at 6 Hz and 8 Hz drastically reduced adult emergence (23.3 and 3.9 individuals, respectively). Pupae appear to be particularly sensitive to electromagnetic disturbances, possibly due to interference with metamorphic processes and hormonal regulation.

In the 16–20 day period, representing primarily pupal stages, the emergence was intermediate (32.6–64.7 individuals), showing that EMF effects persist but are less severe than during the peak sensitivity window (11–15 days). Low-frequency exposure (4 Hz) caused milder reductions, suggesting a frequency-dependent susceptibility.

Overall, the data demonstrate that both the developmental stage and the frequency of EMF exposure critically determine the reproductive success of *T. castaneum*. Eggs are relatively tolerant, early larvae are moderately sensitive, and late larvae/pupae are most vulnerable. These findings highlight the potential for EMF treatments to suppress pest populations by targeting the most susceptible developmental stages, offering insights for novel integrated pest management strategies.

Efficacy of PEMF against *Aphis fabae*

Table 05. The number of surviving *Aphis fabae* after the application of an electromagnetic field

Treatment	*Survival rate of <i>Aphis fabae</i> (Days after the Treatment)		
	01	02	03
Untreated Control	100.0±0.0 ^a	93.0±1.0 ^a	73.0±1.0 ^a
2.1 × 10 ⁻⁶ T	98.0±0.5 ^a	80.0±0.8 ^a	70.0±1.2 ^a
3.2 × 10 ⁻⁶ T	100.0±0.0 ^a	83.0±1.0 ^a	58.0±1.0 ^a
4.3 × 10 ⁻⁶ T	70.0±1.0 ^b	45.0±1.3 ^b	30.0±1.4 ^b
5.3 × 10 ⁻⁶ T	00.0±0.0 ^c	00.0±0.0 ^c	00.0±0.0 ^c

* Each value represents the mean of four independent replicates (n = 4)
Means followed by the same letter in each column do not differ statistically at p<0.05 based on DMRT at a 5% significant level

Based on the results (Table 05), treatment effectiveness increased with concentration, showing a clear dose-dependent response throughout the study period. Significant differences were noted among the concentrations tested ($p < 0.05$). The lowest two concentrations (2.1×10^{-6} T and 3.2×10^{-6} T) did not differ significantly from the control, indicating limited impact. In comparison, the 4.3×10^{-6} T concentration led to a notable decrease in pest numbers, with mean values of 7.3 ± 1.0 , 4.5 ± 1.3 , and 3.0 ± 1.4 on Days 1 to 3. The highest concentration (5.3×10^{-6} T) resulted in complete mortality, recording zero counts throughout the study, and was statistically more effective than all other treatments. These results confirm that treatment effectiveness increases with concentration, with 5.3×10^{-6} T being the most potent under the tested conditions. Statistical analysis showed that the 5.34×10^{-6} T field strength was the best at reducing aphid survival. A prior study demonstrated that the impacts of EMF exposure on desert locusts included alterations in physiology, behavior, and stress protein levels (Wyszkowska *et al.*, 2016). This may be due to the disruption of the biological process, especially neurological and cellular, which resulted in mortality.

Efficacy of PEMF against *Spodoptera frugiperda*

Table 6. Survival rate of *Spodoptera frugiperda* larvae after the application for electromagnetic field

Treatments	*Survival rate of <i>Spodoptera frugiperda</i> (Hours after the Treatment)			
	24	48	72	96
1.1 × 10 ⁻⁶ T	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a
2.1 × 10 ⁻⁶ T	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a
3.2 × 10 ⁻⁶ T	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a

4.3 × 10 ⁻⁶ T	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a
5.3 × 10 ⁻⁶ T	4.0 ± 0.9 ^b	04.0 ± 0.9 ^b	04.0 ± 0.9 ^b	04.0 ± 0.9 ^b
Untreated	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a	100.0 ± 0.0 ^a
Control				

*Each value represents the mean of four replicates ± standard deviation.

Means followed by the same letter in each column do not differ statistically at p<0.05 based on DMRT at a 5% significant level.

After being exposed to varying electromagnetic field intensities for 24, 48, 72, and 96 hours, the survival of *S. frugiperda* third-instar larvae was evaluated (Table 6). Up to 4.3 × 10⁻⁶ T, larval survival was 100% in all treatments, with no discernible variation from the control. This suggests that there was no discernible effect of low-to-moderate EMF levels on larval survival. On the other hand, larval survival was drastically reduced when exposed to the greatest EMF intensity of 5.3 × 10⁻⁶ T; only 4.0 ± 8.9% of larvae survived over all time intervals. These results imply that while *S. frugiperda* larvae can withstand low-intensity electromagnetic fields (EMFs), exposure to a threshold intensity (5.3 × 10⁻⁶ T) can be fatal.

Electromagnetic field application as a tool in pest control

Murawska and his colleagues (2024) conducted a study in which *Apis mellifera* was subjected to a 50 Hz electromagnetic field at 5–10 kV/m for one to three hours. According to the study, the expression of certain genes changed when exposed to the E-field, with some modifications occurring in mRPL18, mRPS30, HBG3 and CQX5a genes. In another study, *Drosophila melanogaster* was exposed to electric fields of 12.0 kV/m and 5.7 kV/m for six consecutive days, eight hours per day, corresponding to distances from a 220 kV power line, and changes in their behavior and biology were investigated. Closer EF exposure had detrimental effects on memory, development, egg hatchability, adult emergence, movement, aggression, and food consumption (El-Gashingy *et al.*, 2024). Shepherd (2018) conducted a study to investigate the effect of low-frequency EMFs on honey bees and desert locusts. In locusts, it limited locomotion and increased the level of stress proteins. Similarly, in bees, it caused impaired olfactory responses, feeding, and flying behavior. Honeybee foraging behavior is adversely affected by exposure to stronger electric and electromagnetic fields (Erdogan and Cengiz, 2019). According to a different study, exposing *Ephestia cautella* eggs and larvae to a magnetic field for 40 minutes completely stopped adult emergence, lengthened the eggs' lifespan, and decreased infestation rates in dates from 81% to 50% (Nilly *et al.*, 2023).

Impact of Electromagnetic Fields on Pest Physiology and Behavior

Electromagnetic fields act as a toxin to insects by affecting their physiology and behavior. According to a phenomenon suggested by Jankowska and his researchers (2015), insects exposed to magnetic fields exhibit increased intracellular concentrations of calcium ions in the membrane and activation of calcium channels. Changes in membrane polarization can interfere with the scorpion alpha toxin's ability to interact with the sodium channel, which depends on the orientation of charges, leading to muscle paralysis in insects. EMFs have an impact on N-Methyl-D-Aspartate (NMDA) (Agnati *et al.*, 2018) receptors and voltage-gated ion channels, which are essential for the transmission of nerve impulses and include calcium, sodium, and potassium channels. Nerve signal timing and synchronization may be affected by this interaction, which can change nerve fiber coupling, especially in insect antennal nerves. Increased intracellular calcium,

which is necessary for cellular processes but can result in oxidative stress when overactivated, is the result of EMF-induced calcium channel activation (Pilla *et al.*, 2012). Normal physiological functions are disrupted, and cellular components are damaged by this stress (Kim *et al.*, 2018). All things considered, EMFs affect insect biology by interfering with calcium signaling, oxidative stress, and brain function, which may influence the insects' physiology, behavior, and survival

Potential of electromagnetic fields as a tool in eco-friendly pest management

The electromagnetic force is a fundamental force consisting of two elements: electricity and magnetism. The electric force surrounding a stationary charged particle is represented by its electric field (EF). The magnetic field (MF), produced by moving charged particles, interacts with other moving charges (Jablonska *et al.*, 2022). Field intensity, frequency, and wavelength are the three main characteristics that define the EMF (Chrispin *et al.*, 2016). Stationary or dynamic electric fields are both achievable. Dynamic EFs are constantly changing, whereas static EFs originate from stationary charged particles and remain stable over time. Electric and magnetic fields are produced by moving electrical charges, resulting in electromagnetic fields. Both magnetic and electric forces act on a moving test charge in dynamic EMFs (Halliday *et al.*, 2014). Depending on the configuration and voltage, EF technologies can use electrostatic interactions to either capture, repel, or kill insects. Although these techniques work physically rather than biologically, there is evidence that insects may be able to sense electric fields, which raises the possibility of sensory involvement and potential areas for further study (Ndey *et al.*, 2024).

Sri Lankan farmers' perspective on electromagnetic fields in insect pest control

The application of electromagnetic field technology represents an entirely novel concept in Sri Lanka. To date, no scientific studies or documented records exist regarding the use of EMFs in either field or laboratory settings within the country. Recognizing this research gap and drawing upon global literature, we have developed a specialized device designed to generate and apply controlled electromagnetic fields for experimental purposes. This pioneering initiative aims to introduce EMF-based techniques to Sri Lanka's scientific community, potentially paving the way for research and innovation in pest management, agriculture, and related biological sciences.

Conclusion

The studies demonstrate that pulsed electromagnetic field (EMF) exposure exerts significant, stage- and intensity-dependent effects on the survival and development of multiple insect pests. In *Tribolium castaneum*, EMF exposure reduced F₁ adult emergence in a frequency- and developmental stage-specific manner. Similarly, exposure of *Callosobruchus maculatus* to EMFs significantly decreased seed damage, particularly when eggs and early larval stages were targeted, indicating potential for pest population suppression at critical developmental windows.

For sucking pests, the survival of *Aphis fabae* declined sharply with increasing EMF intensity, achieving complete mortality at the highest flux density (5.3×10^{-6} T). In contrast, *Spodoptera frugiperda* larvae exhibited high tolerance to lower EMF intensities, with significant mortality only at the maximum exposure (5.3×10^{-6} T), highlighting species-specific susceptibility.

Similarly, the larvae and pupae of *S. mauritia* showed susceptibility at the maximum exposure to EMF intensity.

Overall, the findings reveal that EMF exposure can selectively disrupt development, reduce survival, and suppress reproductive success in insect pests, with the magnitude of effect strongly dependent on species, developmental stage, and EMF frequency or intensity. These results provide a scientific basis for the potential integration of EMF-based treatments into pest management programs, offering an environmentally friendly alternative for the control of storage and field pests.

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