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IN-SITU APPLICATION OF ELECTROMAGNETIC WAVES IN COMBINATION WITH BOTANICAL EXTRACTS TO ENHANCE THEIR EFFECTIVENESS IN CONTROLLING SUCKING INSECT PESTS OF COTTON

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ABSTRACT

Sucking insect pests pose serious threats to various crops, necessitating effective integrated pest management (IPM) strategies. This study explores residue-free, alternative pest control techniques using electromagnetic waves in synergy with botanical extracts of *Azadirachta indica* (Neem), *Moringa oleifera* (Moringa), and *Citrus limon* (Lemon) for managing key sucking pests: *Bemisia tabaci*, *Aphis gossypii*, *Amrasca biguttula*, *Oxycarenus hyalinipennis*, and *Thrips tabaci*. Laboratory experiments were conducted under a Completely Randomized Design (CRD) with five microwave exposure durations (0, 5, 10, 15, and 20 seconds) and four concentrations (5%, 10%, 15%, and 20%) of each botanical extract, each replicated three times. Microwaves at 2.4 GHz were applied using a custom-built device. The 20-second exposure time resulted in the highest mortality across all insect species, with *B. tabaci* (27.6%), *A. gossypii* (22.3%), *A. biguttula* (21.1%), *O. hyalinipennis* (22.5%), and *T. tabaci* (21.8%). When combined with botanical extracts, mortality significantly increased—maximum mortality occurred after 72 hours with 20% *A. indica* (24.38%), *M. oleifera* (24.44%), and *C. limon* (21.54%) extracts. Integrating microwaves with botanicals demonstrated significant synergistic insecticidal activity under controlled laboratory conditions. This innovative, residue-free approach offers a viable alternative to synthetic insecticides, aligning with sustainable pest management goals. Future research should focus on field-scale validation, optimization of microwave delivery systems, and phytochemical profiling of botanicals to enhance efficacy and scalability.

Keywords: Microwaves, Plant extracts, Cotton, Sucking pest complex, Mortality

INTRODUCTION

Sucking insect pests pose a significant challenge to cotton (*Gossypium hirsutum:* Malvaceae) cultivation, threatening both crop health and agricultural productivity worldwide. These pests are particularly important due to their ability to not only damage the plants by feeding but also by spreading the diseases (Stafford et al., 2012). Thus, damage caused by sucking insect pests reduces crop quality, yield, and may result into crop failure (Wahsh et al., 2023). About 40-50% damage to crops have been reported due to the sucking insect pests like whitefly (*Bemisia tabaci* Gennadius, Hemiptera: Aleyrodidae), jassid (*Amrasca biguttula* Ishida, Hemiptera: Cicadellidae), thrips (*Thrips tabaci* Lind, Thysanoptera: Thripidae)), aphid (*Aphis gossypii* Glover, Hemiptera: Aphididae) and dusky cotton bug (*Oxycarenus hyalinipennis* Costa, Lygaidae: Hemiptera) (Dilshod et al., 2023).

The whitefly (*Bemisia tabaci*) is among the most destructive, damaging plants through sap feeding, virus transmission, and sooty mold formation (Pinto et al., 2023; Campos et al., 2023). It infests multiple hosts year-round, causing up to 60% yield loss in cotton (Nagrare et al., 2022). The jassid (*Amrasca biguttula*) tolerates high temperatures and induces phytotoxic symptoms such as leaf cupping, browning, and necrosis, collectively known as "hopper burn," with yield losses ranging from 0–100% depending on crop vigor (Castella et al., 2005; Khalid et al., 2023). The aphid (*Aphis gossypii*) weakens plants through continuous feeding, leaf curling, and honeydew deposition that promotes sooty mold, resulting in 20–60% loss (Jaouannet et al., 2014; Leroy et al., 2011). Early-season thrips (*Thrips tabaci*) cause leaf deformation and growth retardation leading to 30–50% yield reduction (Cook et al., 2011). Recently, the dusky cotton bug (*Oxycarenus hyalinipennis*) has emerged as a serious pest, deteriorating seed weight and oil quality by 20–30% through toxic feeding (Iqbal et al., 2018; Sahu and Samal, 2020). Collectively, these pests form a persistent complex challenging sustainable cotton production.

Insecticide remains the predominant tool employed for managing the sucking insect pests in cotton. However, the injudicious use of insecticides has led to an ecological disaster, affecting everything from natural predators and pollinators to drinking water and wildlife (Zaller 2020; Serrão et al., 2022; Gong et al., 2023). In addition to that, over 500 insect species are known to have developed resistance against synthetic insecticides, making the problem of pesticide resistance increasingly important and pervasive. Despite the alarming rate at which insects are developing resistance against insecticides, the frequency of application has been increased by 2 to 3 times (Zafar et al., 2022). Consumers, on the other hand, are becoming more health conscious and showing more concern for food being treated with pesticides (Gong et al., 2023).

Around the globe, there is growing emphasis on sustainable approaches like biological control, botanical extracts, and cultural practices to manage sucking insect pests. However, the effectiveness, speed of action, need for specialized labor, and availability of rearing facilities of biological control agents limit their practical application. Moreover, crop rotations policies are challenging to implement due to the rising demand for food. The use of botanical extracts is a promising alternative that is both environmentally stable and safe. Using plant extracts as insecticides has been a common practice for quite some time (Naeem-Ullah et al., 2020). Botanical insecticides have been proven as effective as chemicals against several important insect pests (Farooq et al., 2020). For example, neem crude extracts have been reported to negatively affect the feeding ability and molting process for a variety of sucking insects (Essani et al., 2020). Additionally, lemon oil, extracts of bitter gourd (*Momordica charantia* L.) and bakain (*Melia azedarach* L.) have been shown to reduce the *T. tabaci* and *A. biguttula* population in cotton by up to 40 % (Fiaz et al., 2012).

Another alternative to chemicals is the application of microwave, which is usually practiced in postharvest insect pest control, for example, in rice (Xiong et al., 2004), sorghum (More et al., 1992), and wheat (Shayesteh and Barthakur, 1996). Microwaves are essentially electromagnetic waves, and their effective frequencies typically range from 300 MHz to 300 GHz (Yadav et al., 2014). Use of electromagnetic waves as heat treatment or internal thermal induction is recommended for the processing of agricultural goods. This method leaves no trace on the goods, ensures highest possible quality, and has only a negligible impact on the surrounding environment (Yadav et al., 2014). The use of microwaves provides several benefits, one of which is the time required to control any insect pest and has no dangerous residual effects on products (Abed et al., 2023). This technique can be tailored according to the conditions like different in-vitro and in-vivo environment. Moreover, insect pests with different stages of metamorphosis can also be controlled (Wang and Tang, 2001).

Although considerable research has explored the individual efficacy of microwave radiation and botanical extracts in managing sucking insect pests of cotton (Rashkovan et al., 2003; Alam et al., 2019), limited attention has been given to their combined application. To address this gap, the present study was designed with two specific objectives: (i) to assess the insecticidal effect of different exposure durations of microwave radiation on key cotton insect pests, and (ii) to evaluate the synergistic impact of microwave treatment in combination with varying concentrations (5%, 10%, 15%, and 20%) of botanical extracts—*Azadirachta indica*, *Moringa oleifera*, and *Citrus limon*—under laboratory conditions. By integrating physical and botanical control methods, this study aims to develop a novel, residue-free, and environmentally sustainable alternative to conventional chemical pesticides for use in integrated pest management (IPM) programs.

MATERIALS AND METHODS

Insect Collection: *B. tabaci*, *A. gossypii*, *A. biguttula*, *O. hyalinipennis* and *T. tabaci* were collected by hand net, aspirator, net traps and hand picking from different densely populated randomly selected healthy plants during June-July of 2022-23 from the Entomology Research Area, Young Wala University of Agriculture, Pakistan. All five insects were identified using their respective taxonomic key (Boykin et al., 2014; Margaritopoulos et al., 2006; Sagarbarria et al., 2020; Hamed 2023; Bhatti 1980). Collected insects were brought to the IPM-lab instantly and cultures were maintained at 28±2 ºC and 65±5 % R.H and photoperiod (14:10 L:D). Insects were reared on their respective natural host plants i.e. cotton (*Gossypium hirsutum*) for *B. tabaci*, *A. gossypii*, *A. biguttula*, and *O. hyalinipennis*, and onion (*Allium cepa*) for *T. tabaci* (Khan et al., 2012) for two generations. Bioassays were conducted on adult stages of all insect species (5–7 days post-emergence).The natural diet sterilized at 60ºC for 60-90 minutes in sterilized glass jars separately (Wu et al., 2023).

Preparation of Botanical Extracts and Working Solutions Leaves of *A. indica*, *M. oleifera*, and *C. limon* were collected from the entomological research fields of the University of Agriculture, Faisalabad. Plant identification was authenticated by a botanist at the same institution. The leaves were thoroughly rinsed with distilled water to remove surface contaminants, air-dried under shade to preserve active compounds, and then ground into fine powder using an electric grinder. The powdered material was passed through a 40-mesh sieve to ensure uniform particle size.

For extraction, 50 grams of leaf powder from each plant species was mixed with 100 ml of analytical-grade acetone in separate conical flasks. To minimize evaporation, the flasks were sealed with cotton plugs and covered with aluminum foil. The mixtures were placed on an electric stirrer set at 220 revolutions per minute (RPM) for 24 hours. After extraction, the solutions were filtered using Whatman No. 41 filter paper to obtain the clear stock extracts (Patil et al., 2023).

From the stock extract, four different concentrations (5%, 10%, 15%, and 20%) were prepared by diluting the appropriate volume of crude extract with distilled water containing 0.1% Tween-80 as an emulsifying agent. For example, to prepare a 5% solution, 5 ml of stock extract was mixed with 95 ml of diluent (distilled water + Tween-80). Similarly, 10 ml, 15 ml, and 20 ml of the stock extract were used to prepare 10%, 15%, and 20% solutions, respectively, each in total volume of 100 ml.

Development of Microwave Application Instrument: No commercial product was available locally to test the microwaves on insects. To start with, a home used microwave Oven (Dawlance DW 220 S 20 Microwave Oven) with Rating Power (w) (MWO) 700 W, Voltage (V) 220-240 and Frequency (Hz) 2.4(GHz), was modified by cutting off the oven from the dorsal and ventral sides, thus operating sides of the microwave were separated. The reason for cutting was to improve the range of the microwaves. All the required parts for proper functioning of the instrument were stored inside the oven body except magneton, which was set externally with a movable handle to facilitate instrument mobility to the field. However, these modifications were not very successful as they increased the range of microwaves only up to 5 cm from the oven.

In another attempt to make this device work, all electronic components from the oven were disassembled, linearized, and subsequently integrated onto a wooden piece. An electronic charge was generated by connecting a wire from the transformer to the capacitor and then finally to the magnetron. Thus, the effective range of microwaves increased up to 45.72 cm. To control the power of the microwaves, killing the power of key diodes was done by making necessary changes in the programming chip of the microwave which allowed the manipulation of auto power mode of the programming chip. A cooling fan and an automatic trip switch were also installed on the handle at the sides of the magnetron to ensure the magnetron's health and prevent over-heating of the device. By enclosing the magnetron within the steel enclosure, the microwaves within the chamber were restricted, thereby making the device user-friendly and safe. An antenna made of aluminum was attached to the outlet of the magnetron gun so that it could increase its range and prevent the formation of beams of waves.

Experiment 1: Evaluation of Microwave Exposure on Insect Mortality: This experiment was conducted under a Completely Randomized Design (CRD) in the laboratory of the Department of Entomology, University of Agriculture Faisalabad. All safety protocols and standard procedures for microwave application were followed, taking into account human health and energy safety considerations (Romeo and Zeni, 2023).

For each species, five microwave exposure durations (0, 5, 10, 15, and 20 s) were tested, each with three replicates (n = 3). Each replicate consisted of one Petri dish containing 10 adults (5–7 days post-emergence), resulting in 15 dishes per species (5 treatments × 3 replicates) and a total of 75 dishes across all species. Mortality was recorded at 0, 24, 48, and 72 h after exposure. The selected exposure durations (5–20 s) were based on preliminary trials and published evidence indicating that longer exposures at 2.4 GHz caused overheating and possible tissue damage (Wang and Tang, 2001; Abed et al., 2023).

To assess insect mortality, observations were made at four-time intervals: 0, 24, 48, and 72 hours post-treatment. Insects were considered dead if they showed no movement upon gentle probing with a fine brush. The exposure time that resulted in the highest mortality rate without damaging the test arena was selected for subsequent combination experiments with botanical extracts (McKay et al., 2023).

Experiment 2: Application of Microwaves on insects in combination with Botanicals: To evaluate the synergistic effect of botanical extracts and microwave radiation on insect mortality, adult-stage insects (n = 30 per treatment) were treated with 2 ml of botanical extract solutions at concentrations of 0% (control), 5%, 10%, 15%, and 20% for each of the three plant species (*A. indica*, *M. oleifera*, and *C. limon*). This design resulted in 15 treatment combinations in total (3 botanicals × 5 concentrations). After topical application of the botanical extracts, the treated insects were exposed to microwave radiation following four-time intervals: 0 hours (immediate exposure), 6 hours, 12 hours, and 24 hours post-application.

Each treatment combination (concentration × exposure time) was replicated three times. Insect mortality was recorded at 0, 24, 48, and 72 hours after microwave exposure. Mortality was confirmed by lack of movement upon gentle probing with a fine brush. This design allowed assessment of both the independent and interactive effects of botanical concentration and microwave timing on pest control efficacy.

Statistical Analysis: The data was first subjected to Shapiro-Wilk test to assess normality, while homogeneity of the variances was evaluated using Levene's test. The results confirmed that the data met the assumptions required for ANOVA, with Shapiro–Wilk W = 0.98, P = 0.24 indicating normal distribution and Levene's F = 1.62, P = 0.21 confirming equal variances among treatments. Therefore, One-way Analysis of Variance (ANOVA) was applied to compare effects of different treatments on insect's mortality. To analyze combined effects of botanical extracts and electromagnetic waves on insect's mortality, two-way ANOVA was performed. Whereas Tukey's HSD post hoc test was performed to check significant differences among multiple treatments at 5% level of probability (Cabra, 2008). The data were analyzed using Statistix 8.1 software.

RESULTS

Experiment 1: Efficacy of Microwaves on different sucking insect pests: The different exposure times of microwaves against the tested insect pests showed almost similar trend, with 20 seconds being the most effective whereas no mortality was observed in the control (zero second exposure time) (Figure 1).

Bemisia tabaci: Microwave exposure times had a significant effect on mortality of *B. tabaci* ($F_{4, 14}$ = 287, P < 0.0001, ANOVA). The mean number of adults died at 20 seconds after microwaves exposure was significantly higher than the adults exposed to microwaves for 15, 10, 5 seconds and control (20 sec = 8.34 ± 0.75, 15 sec = 3.56 ± 0.22, 10 sec = 0.79 ± 0.52, 5 sec = 0.13 ± 0.40 and control = 0.000 ± 0.006; P < 0.001).

Aphis gossypii: The mortality of *A. gossypii* was significantly influenced by different exposure times of microwaves ($F_{4, 14}$ = 32.6, P < 0.0001, ANOVA). The mean mortality of adults after 20 seconds of exposure to microwaves was significantly higher compared to the adults exposed for 15, 10, 5 seconds and control (20 sec = 7.25 ± 2.21, 15 sec = 2.88 ± 1.18, 10 sec = 0.74 ± 0.16, 5 sec = 0.21 ± 0.03 and control = 0.000 ± 0.004, respectively. Relatively higher SE values observed at shorter exposure durations reflect greater variability among replicates, likely due to inconsistent insect sensitivity and minor positional differences within the microwave field at lower energy levels. In contrast, mortality at longer exposure (20 s) was more uniform, indicating a consistent lethal threshold across replicates.

Amrasca biguttula: Microwave exposure times had significant effect on mortality of *A. biguttula* ($F_{4, 14}$ = 62.8, P < 0.0001, ANOVA). The mean number of adults died at 20 seconds after microwaves exposure was significantly higher than the adults exposed to microwaves for 15, 10, 5 seconds and control (20 sec = 9.59 ± 1.52, 15 sec = 5.02 ± 0.42, 10 sec = 1.38 ± 0.17, 5 sec = 0.06 ± 0.03 and control = 0.000 ± 0.005; P < 0.001).

Oxycarenus hyalinipennis: The mortality of *O. hyalinipennis* was significantly influenced by different exposure times of microwaves ($F_{4, 14}$ = 122, P < 0.0001, ANOVA). The mean mortality of adults after 20 seconds of exposure to microwaves was significantly higher compared to the adults exposed for 15, 10, 5 seconds and control (20 sec = 7.38 ± 1.26, 15 sec = 3.75 ± 1.54, 10 sec = 1.17 ± 0.23, 5 sec = 0.29 ± 0.17 and control = 0.000 ± 0.001; P < 0.001).

Thrips tabaci: The mortality of *T. tabaci* was significantly influenced by different exposure times of microwaves ($F_{4, 14}$ = 373, P < 0.0001, ANOVA). The mean mortality of adults after 20 seconds of exposure to microwaves was significantly higher compared to the adults exposed for 15, 10, 5 seconds and control (20 sec = 5.25 ± 0.67, 15 sec = 2.81 ± 0.72, 10 sec = 1.49 ± 0.25, 5 sec = 0.63 ± 0.08 and control = 0.000 ± 0.005; P < 0.001).

Neem *Azadirachta indica*: Microwave exposure in combination with *A. indica* extracts produced a highly significant effect on the mortality of all tested sucking pests (two-way ANOVA, $P < 0.05$). Overall, mortality increased with both rising extract concentration and exposure duration, showing a clear dose- and time-dependent pattern (Table 1).

For ***Bemisia tabaci***, mortality differed significantly among concentrations ($F_{4,14}$ = 420, $P < 0.05$). The highest mean mortality (24.38 ± 2.41) occurred at 20 % *A. indica* after 72 h, followed by 20.12 ± 2.61 at 48 h, 17.67 ± 2.61 at 24 h, and 8.67 ± 2.35 at 0 h. Control mortality remained minimal (1.57 ± 0.05 after 72 h). Column-wise comparison indicated that mortality increased progressively across observation times (A–D), with 72-h exposure differing significantly from earlier intervals.

In ***Aphis gossypii***, mortality also varied significantly with concentration and time ($F_{4,14}$ = 325, $P < 0.05$). The 20 % extract caused the greatest mortality (23.71 ± 2.65 at 72 h) compared with 16.67 ± 2.52 at 48 h, 9.31 ± 1.34 at 24 h, and 7.12 ± 1.26 at 0 h, whereas control mortality was only 11.01 ± 1.35 after 72 h. Mortality at 15, 10, and 5 % concentrations was significantly lower. Column-wise, all exposure intervals differed, confirming a cumulative lethal effect of microwave + botanical treatment.

Similarly, ***Amrasca biguttula*** exhibited maximum mortality of 22.50 ± 2.03 at 20 % concentration after 72 h, followed by 14.33 ± 1.55 at 48 h, 8.03 ± 0.85 at 24 h, and 6.83 ± 0.50 at 0 h ($F_{4,14}$ = 332, $P < 0.05$). Control mortality remained negligible (1.01 ± 0.51). Both concentration and time effects were highly significant, with consistent column-wise differences (A–E).

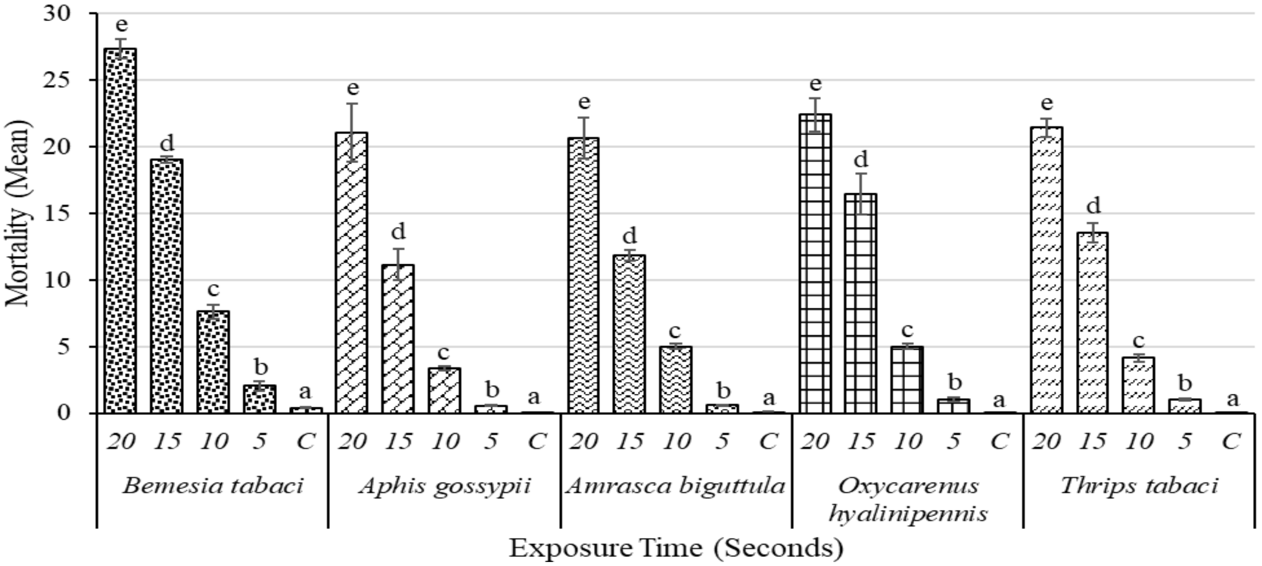

Figure 1. Effect of microwaves on different sucking insect pests. Bars with different letters indicate statistical significance at $P < 0.05$. Vertical Bars indicate standard error (SE).

Experiment 2: Mortality of insect pests in response to microwaves application in combination with Botanicals

Table 1. Comparison of mean mortality by microwave exposure of *Azadirachta Indica* (L.). Means followed by different lowercase letters within a row and different uppercase letters within a column are significantly different at $P < 0.05$ according to Tukey's HSD test. Values indicate by ± represents standard error (SE).

	Botanical concentrations %	After 0-hours application	After 24- hours application	After 48- hours application	After 72- hours application
Bemisia tabaci	20	8.67 ± 2.35^{AA}	17.67 ± 2.61^{BA}	20.12 ± 2.61^{BCA}	24.38 ± 2.41^{DA}
	15	8.23 ± 2.02^{AA}	15.81 ± 2.35^{BA}	17.34 ± 2.35^{BCA}	21.51 ± 2.23^{DA}
	10	6.69 ± 1.26^{AA}	12.73 ± 0.73^{BB}	14.26 ± 0.73^{CB}	17.63 ± 0.59^{DB}
	5	2.18 ± 0.35^{AB}	7.42 ± 0.35^{BC}	9.65 ± 0.35^{CC}	12.08 ± 0.65^{DC}
	C	0.00 ± 0.03^{AC}	0.3 ± 0.01^{BD}	0.45 ± 0.01^{CD}	1.57 ± 0.05^{DD}
Aphis gossypii	20	7.12 ± 1.26^{AA}	9.31 ± 1.34^{BA}	16.67 ± 2.52^{CA}	23.71 ± 2.65^{DA}
	15	6.59 ± 0.78^{AA}	7.29 ± 0.65^{ABB}	14.38 ± 1.44^{CA}	20.38 ± 1.27^{DA}
	10	4.08 ± 0.61^{AB}	5.64 ± 0.22^{BC}	11.55 ± 0.75^{CB}	18.55 ± 0.84^{DB}
	5	2.11 ± 0.54^{AC}	4.53 ± 0.6^{BD}	9.32 ± 0.34^{CC}	12.32 ± 0.6^{DC}
	C	0.00 ± 0.06^{AD}	0.41 ± 0.05^{BE}	0.01 ± 0^{ACD}	11.01 ± 1.35^{DD}
Amrasca biguttula	20	6.83 ± 0.5^{AA}	8.03 ± 0.85^{BA}	14.33 ± 1.55^{CA}	22.5 ± 2.03^{DA}
	15	6.24 ± 0.02^{AA}	7.21 ± 0.62^{BB}	11.24 ± 1.35^{CB}	19.41 ± 2.22^{DB}
	10	4.19 ± 0.05^{AB}	4.35 ± 0.50^{ABC}	9.62 ± 0.85^{CC}	13.52 ± 1.23^{DC}
	5	1.410 ± 0.001^{AC}	2.030 ± 0.003^{BD}	4.42 ± 0.25^{CD}	11.31 ± 0.80^{DD}
	C	0.00 ± 0.01^{AD}	0.01 ± 0.01^{ABE}	0.01 ± 0.01^{ABCE}	1.01 ± 0.51^{DE}
Oxycarenus hyalinipennis	20	7.27 ± 0.45^{AA}	7.34 ± 0.36^{ABA}	13.67 ± 0.70^{CA}	20.70 ± 1.63^{DA}
	15	6.56 ± 0.41^{AB}	6.42 ± 0.13^{ABB}	11.00 ± 0.65^{CB}	18.32 ± 1.70^{DB}
	10	6.09 ± 0.07^{AC}	6.62 ± 0.22^{BB}	8.34 ± 0.23^{CC}	10.56 ± 0.62^{DC}
	5	2.41 ± 0.04^{AD}	3.23 ± 0.05^{BC}	4.32 ± 0.20^{CD}	8.0 ± 0.4^{DD}
	C	0.00 ± 0.001^{AE}	0.01 ± 0.001^{ABD}	0.01 ± 0.001^{ABCE}	1.01 ± 0.05^{DE}
Thrips tabaci	20	5.31 ± 0.21^{AA}	6.42 ± 0.42^{BA}	10.62 ± 0.47^{CA}	15.34 ± 1.24^{DA}
	15	4.19 ± 0.20^{AB}	5.34 ± 0.34^{BB}	7.50 ± 0.55^{CB}	13.28 ± 1.13^{DB}
	10	3.78 ± 0.18^{AC}	4.67 ± 0.25^{BC}	4.91 ± 0.32^{BCC}	9.62 ± 0.18^{DC}
	5	1.11 ± 0.005^{AD}	2.02 ± 0.005^{BD}	2.67 ± 0.05^{CD}	5.47 ± 0.72^{DD}
	C	0.00 ± 0.005^{AE}	0.01 ± 0.005^{ABE}	0.03 ± 0.003^{BCE}	2.1 ± 0.5^{DE}

For ***Oxycarenus hyalinipennis***, the interaction between concentration and time was also significant ($F_{4,14} = 317$, $P < 0.05$). The 20 % *A. indica* treatment yielded 20.70 ± 1.63 mortality after 72 h, substantially higher than 13.67 ± 0.70 (48 h), 7.34 ± 0.36 (24 h), and 7.27 ± 0.45 (0 h). The control recorded only 1.01 ± 0.05 mortality. Column-wise, mortality increased significantly from 0 to 72 h (A–E), confirming time-dependent enhancement.

In ***Thrips tabaci***, mortality differed significantly across concentrations and times ($F_{4,14}$ = 11.3, $P < 0.05$). The highest mortality (16.34 ± 1.24) was recorded at 20 % concentration after 72 h, compared with 10.62 ± 0.47 (48 h), 6.42 ± 0.42 (24 h), and 5.31 ± 0.21 (0 h); control mortality was 2.10 ± 0.50 at 72 h. Column-wise analysis again revealed a consistent upward trend across observation times.

Uniform microwave exposure (20 s) thus amplified the effectiveness of *A. indica* extracts, producing statistically distinct mortality gradients both across concentrations (a–d) and among observation times (A–E).

Moringa, *Moringa oleifera:* Microwave exposure in combination with *Moringa oleifera* extracts produced a significant increase in mortality of all target insect pests ($P < 0.05$, two-way ANOVA), with mortality rising steadily with both concentration and exposure duration (Table 2).

For ***Aphis gossypii***, mortality differed significantly among concentrations and observation times ($F_{4,14}$ = 445, $P < 0.05$). The highest mean mortality (24.44 ± 0.42) occurred at 20 % *M. oleifera* after 72 h, followed by 19.32 ± 0.44 at 48 h, 14.60 ± 0.47 at 24 h, and 7.19 ± 0.55 at 0 h, whereas control mortality was minimal (0.010 ± 0.006 after 72 h). Mortality at 15, 10, and 5 % concentrations was significantly lower. Column-wise comparisons indicated a consistent rise across all time intervals (A–E), confirming cumulative lethal effects of the botanical–microwave interaction.

In ***Bemisia tabaci***, mortality also increased significantly with both concentration and time ($F_{4,14}$ = 502, $P < 0.05$). The maximum mean mortality (22.00 ± 2.51) was recorded at 20 % concentration after 72 h, followed by 18.67 ± 2.55 at 48 h, 14.34 ± 2.47 at 24 h, and 8.32 ± 2.35 at 0 h. Control mortality was negligible (0.02 ± 0.002 after 72 h). Mortality declined sharply at 15, 10, and 5 % concentrations. Column-wise, mortality values increased significantly over time, showing a clear time-dependent enhancement (A–E).

Similarly, ***Amrasca biguttula*** exhibited a highly significant difference among concentrations and time intervals ($F_{4,14}$ = 332, $P < 0.05$). The highest mortality (22.00 ± 0.63) occurred at 20 % concentration after 72 h, compared with 15.02 ± 0.54 at 48 h, 10.00 ± 0.55 at 24 h, and 6.41 ± 0.36 at 0 h. Control mortality (1.00 ± 0.44 after 72 h) remained low. Mortality increased consistently both across concentrations (a–d) and across time intervals (A–E), indicating a synergistic effect of *M. oleifera* extract and microwave exposure.

For ***Oxycarenus hyalinipennis***, the combination treatment also showed significant variation across concentrations and times ($F_{4,14}$ = 317, $P < 0.05$). The highest mean mortality (20.65 ± 0.63) was observed at 20 % concentration after 72 h, followed by 13.64 ± 0.73 at 48 h, 9.32 ± 0.36 at 24 h, and 7.26 ± 0.29 at 0 h. Control mortality was only 1.00 ± 0.005. Column-wise, all exposure durations differed significantly (A–E), reflecting cumulative mortality over time.

In ***Thrips tabaci***, mortality also followed a similar increasing trend ($F_{4,14}$ = 13.01, $P < 0.05$). The 20 % *M. oleifera* treatment caused maximum mortality (13.55 ± 0.80) after 72 h, followed by 10.67 ± 0.47 at 48 h, 8.59 ± 0.42 at 24 h, and 5.28 ± 0.29 at 0 h, whereas control mortality reached 2.67 ± 0.58 after 72 h. Lower concentrations produced significantly reduced mortality. Column-wise analysis again demonstrated a steady and significant increase from 0 to 72 h (A–E).

Overall, uniform microwave exposure (20 s) significantly enhanced the insecticidal performance of *M. oleifera* extracts. The combined treatment produced clear statistical separation among concentrations (a–d) and across exposure durations (A–E), underscoring the synergistic potential of this integrated control approach.

Lemon, *Citrus limon:* Application of *Citrus limon* extract integrated with 10-s microwave exposure caused a highly significant increase in insect mortality across all tested pests ($P < 0.05$, two-way ANOVA). Mortality generally increased with both higher extract concentration and longer post-application exposure time (Table 3).

For ***Bemisia tabaci***, mortality differed significantly among concentrations and exposure durations ($F_{4,14}$ = 506, $P < 0.05$). The highest mean mortality (21.54 ± 0.51) occurred at 20 % concentration after 72 h, followed by 15.32 ± 0.63 (48 h), 10.47 ± 0.42 (24 h), and 8.28 ± 0.36 (0 h). Control mortality remained negligible (0.010 ± 0.001 at 72 h). Lower concentrations (15 %, 10 %, 5 %) produced significantly reduced mortality. Column-wise comparisons (A–E) showed a consistent, significant rise in mortality across all time intervals, confirming a cumulative lethal response to the integrated treatment.

In ***Aphis gossypii***, mortality also increased significantly with both concentration and time ($F_{4,14}$ = 506, $P < 0.05$). Maximum mortality (21.67 ± 0.51) was observed at 20 % concentration after 72 h, followed by 15.40 ± 0.63 (48 h), 9.73 ± 0.42 (24 h), and 7.07 ± 0.36 (0 h). Control mortality was minimal (0.010 ± 0.001 after 72 h). Mortality at lower concentrations declined progressively, while column-wise trends again indicated a steady increase from 0 to 72 h (A–E).

For ***Amrasca biguttula***, the combination treatment resulted in maximum mean mortality of 20.00 ± 0.55 at 20 % concentration after 72 h, compared with 12.00 ± 0.73 (48 h), 10.68 ± 0.42 (24 h), and 6.56 ± 0.59

(0 h) ($F_{4,14}$ = 396, $P < 0.05$). Control mortality was negligible (0.010 ± 0.001 after 72 h). Both row-wise (a–d) and column-wise (A–E) analyses showed significant increases in mortality, demonstrating a clear dose- and time-dependent effect.

Table 2. Comparison regarding mean mortality for microwave exposure of *Moringa oleifera*. Means followed by different lowercase letters within a row and different uppercase letters within a column are significantly different at *P* < 0.05 according to Tukey's HSD test. Values indicate by ± represents standard error (SE)

	Botanical concentrations %	After 0-hours application	After 24- hours application	After 48- hours application	After 72- hours application
Bemisia tabaci	20	8.32 ± 2.35^{AA}	14.34 ± 2.47^{BA}	18.67 ± 2.55^{CA}	22 ± 2.51^{DA}
	15	7.49 ± 2.02^{AA}	9.63 ± 2.32^{ABB}	15.34 ± 2.28^{CA}	16.68 ± 2.28^{CDB}
	10	5.88 ± 1.26^{AB}	6.34 ± 0.26^{ABC}	10.5 ± 0.34^{CB}	13.34 ± 0.34^{DC}
	5	1.73 ± 0.35^{AC}	2.58 ± 0.35^{BD}	8 ± 0.35^{CC}	10.64 ± 0.35^{DD}
	C	0.00 ± 0.001^{AD}	0.20 ± 0.05^{ABE}	0.32 ± 0.08^{CD}	0.02 ± 0.002^{ABDE}
Aphis gossypii	20	7.19 ± 0.55^{AA}	14.6 ± 0.47^{BA}	19.32 ± 0.44^{CA}	24.44 ± 0.42^{DA}
	15	6.53 ± 0.39^{AB}	11.72 ± 0.42^{BB}	13 ± 0.32^{CB}	16.02 ± 0.28^{DB}
	10	3.87 ± 0.34^{AC}	8.30 ± 0.34^{BC}	10 ± 0.34^{CC}	12.18 ± 0.30^{DC}
	5	1.24 ± 0.35^{AD}	3.57 ± 0.35^{BD}	6.67 ± 0.35^{CD}	9.57 ± 0.35^{DD}
	C	0.000 ± 0.006^{AE}	0.32 ± 0.05^{BE}	0.32 ± 0.05^{BCE}	0.01 ± 0.006^{ADE}
Amrasca biguttula	20	6.41 ± 0.36^{AA}	10 ± 0.55^{BA}	15.02 ± 0.54^{CA}	22 ± 0.63^{DA}
	15	4.66 ± 0.25^{AB}	7.34 ± 0.39^{BB}	11.42 ± 0.39^{CB}	19.32 ± 0.44^{DB}
	10	2.53 ± 0.05^{AC}	4.62 ± 0.26^{BC}	8.65 ± 0.26^{CC}	13.34 ± 0.26^{DC}
	5	0.310 ± 0.002^{AD}	1.41 ± 0.52^{BD}	6.22 ± 0.52^{CD}	11.01 ± 0.52^{DD}
	C	0.00 ± 0.001^{AE}	0.34 ± 0.05^{BE}	0.34 ± 0.05^{BCE}	1 ± 0.44^{DE}
Oxycarenus hyalinipennis	20	7.26 ± 0.29^{AA}	9.32 ± 0.36^{BA}	13.64 ± 0.73^{CA}	20.65 ± 0.63^{DA}
	15	5.19 ± 0.26^{AB}	7.43 ± 0.25^{BB}	11.43 ± 0.51^{CB}	18.34 ± 0.26^{DB}
	10	2.07 ± 0.05^{AC}	3.66 ± 0.5^{BC}	8.66 ± 0.5^{CC}	10.67 ± 0.05^{DC}
	5	0.17 ± 0.002^{AD}	1.02 ± 0.002^{BD}	4.32 ± 0.002^{CD}	8 ± 0.002^{DD}
	C	0.00 ± 0.005^{AE}	0.01 ± 0.001^{ABE}	0.01 ± 0.001^{ABCE}	1 ± 0.005^{DE}
Thrips tabaci	20	5.28 ± 0.29^{AA}	8.59 ± 0.42^{BA}	10.67 ± 0.47^{CA}	13.55 ± 0.8^{DA}
	15	4.67 ± 0.21^{AB}	6.34 ± 0.34^{BB}	7.61 ± 0.14^{CB}	15.42 ± 0.69^{DB}
	10	1.29 ± 0.25^{AC}	2.67 ± 0.29^{BC}	4.32 ± 0.29^{CC}	9.64 ± 0.72^{DC}
	5	0.83 ± 0.002^{AD}	1.29 ± 0.002^{BD}	2.63 ± 0.002^{CD}	5.41 ± 0.5^{DD}
	C	0.00 ± 0.005^{AE}	0.01 ± 0.005^{ABE}	0.32 ± 0.005^{CE}	2.67 ± 0.58^{DE}

Similarly, ***Oxycarenus hyalinipennis*** showed significant variation in mortality across concentrations and exposure periods ($F_{4,14}$ = 364, $P < 0.05$). The highest mortality (17.34 ± 0.51) occurred at 20 % concentration after 72 h, followed by 13.00 ± 0.42 (48 h), 9.85 ± 0.42 (24 h), and 7.18 ± 0.29 (0 h), while control mortality was 0.34 ± 0.05 after 72 h. Mortality declined significantly at 15, 10, and 5 % concentrations. Column-wise comparisons confirmed a consistent increase in mortality over time (A–E).

In ***Thrips tabaci***, mortality also rose markedly with increasing concentration and time ($F_{4,14}$ = 34.4, $P < 0.05$). The maximum mean mortality (13.24 ± 0.69) was recorded after 72 h at 15 % concentration, followed closely by 20 % concentration (11.23 ± 0.80 after 72 h). Mortality at 48, 24, and 0 h intervals for the 20 % treatment was 8.66 ± 0.47, 7.80 ± 0.42, and 5.38 ± 0.29, respectively, whereas control mortality remained low (2.67 ± 0.58 after 72 h). Column-wise comparisons (A–E) again revealed progressive increases across all observation times.

Overall, uniform microwave exposure for 20 s markedly enhanced the insecticidal potential of *C. limon* extract. The combined treatment produced clear statistical separation both across concentrations (a–d) and across time intervals (A–E), highlighting a strong synergistic interaction between microwave irradiation and botanical toxicity (Table 3).

Mortality comparison of insect pests in response to microwave's application in combination with Botanicals with 20% concentration at 72 hours after application: The mortality caused by *A. indica* extract with 20% concentration after 72 hours of application was recorded maximum against *B. tabaci* (24.38) followed by *A. gossypii* (23.71), *A. biguttula* (22.5), *O. hyalinipennis* (20.7) and *T. tabaci* with 15.34 mortality. This suggested that neem extract is superior to other plant extracts when used in combination with microwave application. On the other hand, with mortality rate of 24.44, 20% *M.oleifera* extract was most effective against *A. gossypii*, followed by *B. tabaci*, *A. biguttula*, *O. hyalinipennis* and *T. tabaci* with mortality of 22, 22, 20.65 and 13.55 respectively after 72 hours of application. *C. limon* extract was found to be less effective in comparison to *A. indica* and *M. oleifera*, while effective against most pests. After 72 hours of application of 20% *C. limon* extract maximum mortality was recorded in *A. gossypii* (21.67) followed by *B. tabaci* with non-significant difference at 21.54. While *A. biguttula* (20) and *O. hyalinipennis* (17.34) showed a significant difference in mortality in comparison to *T. tabaci* with 11.23 % mean mortality. Overall, the *A. indica* extract posed maximum mean mortality (21.32) against all the insects pests followed by *M. oleifera* with 20.52 and *C. limon* with 18.35 (Figure 2).

Table 3. Comparison regarding mean mortality for microwave exposure of *Citrus limon* (L.). Means followed by different lowercase letters within a row and different uppercase letters within a column are significantly different at $P < 0.05$ according to Tukey's HSD test. Values indicate by ± represents standard error (SE)

	Concentrations %	After 0-hours application	After 24- hours application	After 48- hours application	After 72- hours application
Bemisia tabaci	20	8.28 ± 0.36 aA	10.47 ± 0.42 bA	15.32 ± 0.63 cA	21.54 ± 0.51 dA
	15	8.12 ± 0.25 aA	10.07 ± 0.29 bA	11 ± 0.44 cB	17 ± 0.36 dB
	10	6.54 ± 0.05 aB	8.2 ± 0.26 bB	8 ± 0.38 bcC	13.67 ± 0.3 dC
	5	4.49 ± 0.003 aC	5.8 ± 0.34 bC	3.64 ± 0.21 cD	9.61 ± 0.21 dD
	C	0.00 ± 0.001 aD	0.03 ± 0.003 abD	0.34 ± 0.05 cE	0.01 ± 0.001 abdE
Aphis gossypii	20	7.07 ± 0.36 aA	9.73 ± 0.42 bA	15.40 ± 0.63 cA	21.67 ± 0.51 dA
	15	6.62 ± 0.25 aAB	9.04 ± 0.29 bB	11.42 ± 0.44 cB	17.00 ± 0.36 dB
	10	6.34 ± 0.25 aB	8.01 ± 0.20 bC	8.34 ± 0.34 cC	13.62 ± 0.34 dC
	5	1.02 ± 0.002 aC	2.67 ± 0.15 bD	3.34 ± 0.5 dD	9.64 ± 0.5 dD
	C	0.00 ± 0.001 aD	0.01 ± 0.001 abE	0.34 ± 0.05 cE	0.01 ± 0.001 abdE
Amrasca biguttula	20	6.56 ± 0.59 aA	10.68 ± 0.42 bA	12 ± 0.73 cA	20 ± 0.55 dA
	15	6.21 ± 0.42 aA	8.32 ± 0.29 bB	9.34 ± 0.51 cB	16.67 ± 0.39 dB
	10	4.13 ± 0.5 aB	5.47 ± 0.5 bC	6.4 ± 0.35 cC	11.15 ± 0.35 dC
	5	2.06 ± 0.002 aC	3.04 ± 0.05 bD	2.67 ± 0.5 cD	7.00 ± 0.51 dD
	C	0.00 ± 0.001 aD	0.32 ± 0.1 bE	0.32 ± 0.1 bcE	0.01 ± 0.001 adE
Oxycarenus hyalinipennis	20	7.18 ± 0.29 aA	9.85 ± 0.42 bA	13 ± 0.42 cA	17.34 ± 0.51 dA
	15	6.76 ± 0.21 aB	8.09 ± 0.29 bB	9.67 ± 0.29 cB	14 ± 0.23 dB
	10	6.29 ± 0.05 aC	7.64 ± 0.5 bC	4.34 ± 0.5 cC	8.67 ± 0.50 dC
	5	01.47 ± 0.002 aD	1.47 ± 0.002 abD	1.60 ± 0.002 cD	4.55 ± 0.5 dD
	C	0.00 ± 0.001 aE	0.01 ± 0.001 abE	0.34 ± 0.001 cE	0.34 ± 0.05 cdE
Thrips tabaci	20	5.38 ± 0.29 aA	7.80 ± 0.42 bA	8.66 ± 0.47 cA	11.23 ± 0.8 dA
	15	4.24 ± 0.21 aB	5.52 ± 0.34 bB	6.11 ± 0.14 cB	13.24 ± 0.69 dB
	10	4.03 ± 0.25 aC	4.18 ± 0.29 abC	3.10 ± 0.29 cC	6.98 ± 0.72 dC
	5	1.10 ± 0.002 aD	0.99 ± 0.002 bD	1.99 ± 0.002 cD	3.4 ± 0.5 dD
	C	0.00 ± 0.005 aE	0.01 ± 0.005 abE	0.32 ± 0.005 cE	2.67 ± 0.58 dE

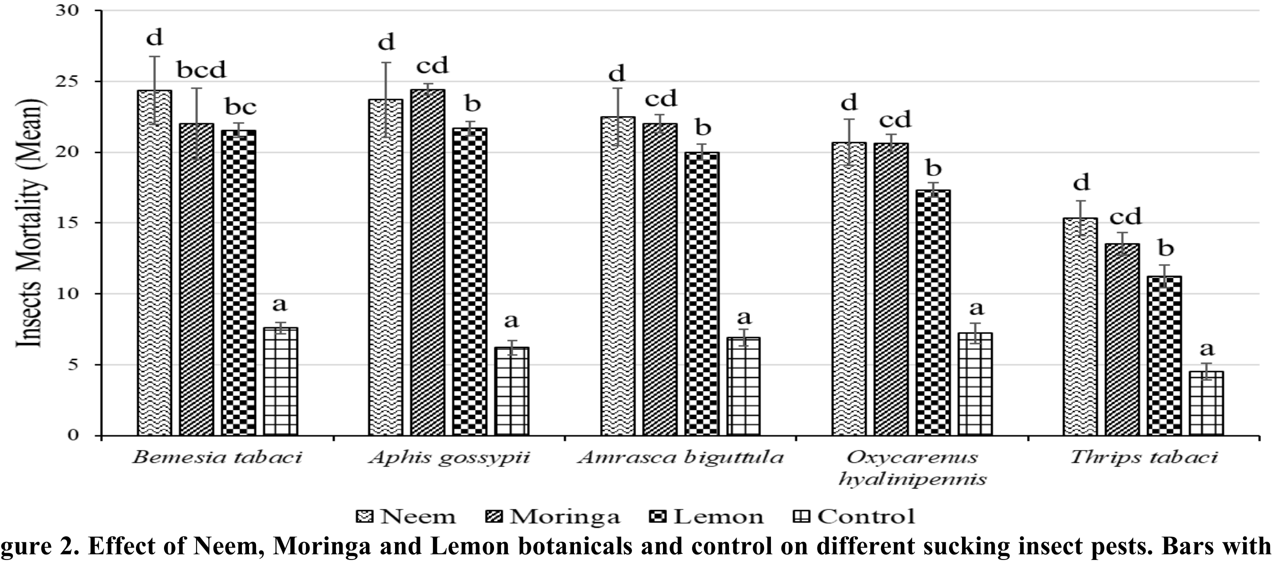

Figure 2. Effect of Neem, Moringa and Lemon botanicals and control on different sucking insect pests. Bars with different letters indicate statistical significance at $P < 0.05$. Vertical bars indicate standard error (SE).

DISCUSSION

The results of this study provide a valuable insight into the application of electromagnetic waves along with botanical extracts in controlling the sucking insect pests of cotton. The application of electromagnetic waves (EMWs) in combination with botanical extracts had significantly reduced the tested population of insects in lab. compared to the microwave application alone. Although there were no significant differences among the three tested botanicals in controlling the tested insect pest populations, the mortality caused by *A. indica* extract was higher, while *C. limon* extract had lowest mortality. These findings support the hypothesis that electromagnetic waves can enhance the efficacy of botanical extracts in controlling sucking insect pests of cotton.

EMWs are known to have negative impacts on the behavior and physiology of insects like ants and bees, by interfering with their olfactory receptors and neural activities (Sharma and Kumar, 2010; Cammaerts, 2017). EMWs can also alter the orientation, reproduction, development and metabolism of insects by affecting their endocrine and nervous systems (Balmori, 2010; Favre, 2011). The application of EMWs in pest management has predominantly been explored in postharvest settings, with limited literature investigating their use against insect pests on live crops. Early studies by Nelson (1996) and Wang and Tang (2001) demonstrated the efficacy of microwave radiation in disinfesting stored grains, reporting rapid insect mortality through internal heating and disruption of cellular structures. Rashkovan et al. (2003) extended this concept, proposing the use of EMWs to manipulate insect behavior in greenhouses. In line with these findings, our study expands the scope by applying EMWs in a laboratory setup to control sucking insect pests of cotton (*B. tabaci*, *A. gossypii*, *A. biguttula*, *O. hyalinipennis*, and *T. tabaci*), showing that a 20-second exposure significantly increased mortality across all tested species. These results support and advance previous findings by suggesting that controlled microwave application can be integrated into pest management strategies—not only for disinfestation but also as a synergistic tool to enhance botanical insecticide efficacy. While past work has highlighted EMWs' effects on stored product pests (Wang et al., 2005), our study is among the few to experimentally demonstrate their potential in preharvest insect suppression, thereby offering a novel direction for sustainable pest control research.

The current study demonstrates the potential of microwave exposure in managing sucking insect pests under controlled laboratory conditions, the practical application of this technology in standing crops requires cautious consideration. Microwave radiation has been widely employed in postharvest pest control, particularly in stored grains, due to its ability to rapidly generate heat and eliminate insects without chemical residues (Wang and Tang, 2001; Nelson, 1996). However, the direct exposure of live plants to microwave energy in field settings may pose risks of thermal injury to plant tissues.

Nevertheless, recent findings suggest that when applied at standard operational frequencies (≤ 2.45 GHz) and under controlled exposure conditions, microwave treatment may be safe for live plant systems. For example, low-power microwave radiation at 2.45 GHz was shown to stimulate seedling growth in *Arabidopsis thaliana* without causing physiological harm (Senevirathna et al., 2020). Similarly, cereal grains subjected to microwave disinfestation maintained their thermophysical and structural integrity, indicating that such treatments can effectively control pests without compromising plant material quality (Barba et al., 2020). These findings support the feasibility of microwave-based pest control approaches that minimize the risk of plant injury.

Our research was designed as proof-of-concept, aiming to explore the insecticidal effects of microwave exposure and its synergistic potential with botanical extracts. We recognize that field-scale implementation would necessitate the development of precision-controlled microwave delivery systems capable of targeting insect pests while minimizing or avoiding phytotoxic effects. Emerging technologies such as enclosed microwave emitters, shielding mechanisms, or UAV-mounted directional microwave applicators could offer potential solutions for field-level applications in the future (Rashkovan et al., 2003; Romeo and Zeni, 2023). Further research will be essential to optimize exposure parameters, assess safety thresholds for crops, calibrated frequency of microwaves and evaluate ecological impacts before adopting this technique in practical pest management frameworks. In the second experiment, the study investigated the combined effect of microwave exposure and botanical extracts to enhance insect pest mortality. The results indicate that the concentration of the three botanicals i.e. *A. indica* (Neem), *M. oleifera*, and *C. limon* (Lemon) along with microwave exposure, played a crucial role in determining the mortality rates of the insect pests. Neem extract at 20% concentration showed remarkable effectiveness in combination with microwave exposure for 20 sec. The highest mortality rates were recorded for *B. tabaci*, *A. gossypii*, *A. biguttula*, *O. hyalinipennis*, and *T. tabaci* after 72 hours of application, with *B. tabaci* and *A. gossypii* showing the highest mean mortality (24.38 and 23.71, respectively). The mortality in *Tribolium castaneum* was increased when exposed to highest concentration (15%) of *A. indica* with the exposure time of 50 seconds to microwaves (Agha et al., 2017; Khan, 2013). Similarly, the highest concentration of *A. indica* caused 100% mortality in *A. gossypii* nymphs (Santos et al., 2004) which might be due to a compound, azadirachtin, that interferes with insect molting and exhibits growth regulatory and sterilant effects (Dawkar et al., 2019). This suggests that neem extract, when integrated with microwave treatment is highly effective in controlling a wide range of insect pests. *T. tabaci* population showed the lowest mortality to *A. indica* extract compared to the other insect pests. These findings were in line with the Gupta et al. (2017) who found the Neem based products didn't have significant impact on the *T. tabaci*. *M. oleifera* extract also demonstrated significant potential in pest control. The combination of *M. oleifera* extract and microwave exposure resulted in high mortality rates for *A. gossypii*, *B. tabaci*, *A. biguttula*, *O. hyalinipennis*, and *T. tabaci*. *A. gossypii* were particularly susceptible to this treatment, with a mortality rate of 24.44 after 72 hours of application. In one study, *M. oleifera* extracts showed control of *Phyllotreta cruciferae*, *Diabrotica undecimpunctata*, and *Bactrocera curcubitea*, with a reduction ranging from 50% to 64% depending on the concentration used (El-Masry et al., 2017; Outani et al., 2023), moreover behavior of sucking insect pests was modified by the application of electromagnetic waves (Rashkovan et al., 2003). Similarly, among the various tested concentrations, *M. oleifera* at 2.5% concentration was found to be more effective in suppressing the population of *Oxycarenus* spp. after *A. indica* and *Calatropis procera* (Abbas et al., 2015). Another study found that Rhamnosyloxy-benzyl isothiocyanate, a compound obtained from *M. oleifera* seeds, had an effect on the two spotted spider mite *Tetrancus urticae* and the cotton mealybug *Phenacoccus solenopsis*, with LC_{50} values ranging from 388 to 839.89 ppm (El-Masry et al., 2017).

Although *C. limon* extract showed effectiveness against the tested insect pests, it appeared to be less potent than neem and *M. oleifera* extracts. The highest mortality rates were recorded for *A. gossypii* and *B. tabaci* (21.67 and 21.54, respectively) after 72 hours of application. *C. limon* has shown insecticidal effects against sucking insect pests such as *A. gossypii* (Alam et al., 2019). The extract contains active components such as l-pipecolic acid, scopoletin, pulegone, γ-terpinene, carvone, menthone, myrcene, limonene, (-)-trans-isopiperitenol, geranial, and linalool, which contribute to its observed effects (Gupta et al., 2017). Additionally, terpenoids found in lemon, including γ-terpinene, menthone, β-pinene, limonene, and linalool, have also shown efficacy against other insect pests (Mossa, 2016; Bueno et al., 2023).

Comparing the efficacy of the three botanical extracts, *A. indica* showed the highest mean mortality (21.32) against all tested insect pests, followed by *M. oleifera* (20.52) and *C. limon* (18.35), although the differences among three extracts were not significant. This indicates that Neem extract had the broadest spectrum of effectiveness against the studied insect pests (Khater, 2012; Campos et al., 2016; Agbo et al., 2019). *M. oleifera* also demonstrated significant potential, especially against *A. gossypii* and *B. tabaci*. Overall, the results suggest that these botanical extracts, when combined with microwave exposure, have the potential to be valuable tools in integrated pest management strategies. However, the choice of botanical extract may depend on the specific pest and the desired level of control. GC-MS or LC-MS profiling in future studies is recommended to better correlate bioactivity botanical extracts with their phytochemical composition

Conclusion: This study demonstrates the potential of integrating microwave radiation with botanical extracts as an effective, eco-friendly strategy for managing sucking insect pests of cotton. The synergistic effect observed between electromagnetic exposure and botanicals—particularly *A.indica* and *M. oleifera*—resulted in significantly higher mortality rates compared to individual treatments, highlighting their utility in non-chemical pest management approaches. This integrated method holds promise to reduce dependency on synthetic pesticides, thereby minimizing environmental contamination and promoting agroecosystem sustainability. However, before its implementation in field settings, optimization of exposure duration, delivery methods, and safety thresholds is essential to avoid adverse impacts on non-target organisms and crop physiology. Future research should prioritize field trials to evaluate its practical feasibility, environmental selectivity, and compatibility within existing integrated pest management (IPM) frameworks. Moreover, assessing economic viability and potential regulatory considerations will be critical for transitioning this innovation from laboratory to large-scale agricultural use. Overall, this approach represents a novel contribution to sustainable agriculture by aligning pest control with environmental and economic sustainability goals.

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