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Green-Synthesized Iron Oxide Nanoparticles from *Brassica oleracea* Extract: Insecticidal Activity Against *Musca domestica* and *Oryzaephilus surinamensis*

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ABSTRACT

This study investigated the insecticidal efficacy of green-synthesized iron oxide nanoparticles (FeONPs) using *Brassica oleracea* leaf extract against *Musca domestica* and *Oryzaephilus surinamensis*. An extract of *Brassica oleracea* was prepared and mixed with $FeSO_4$ solution, leading to nanoparticle formation. The FeONPs were characterized using spectroscopic techniques. Bioassays were conducted on *Musca domestica* and *Oryzaephilus surinamensis*, with mortality rates assessed at varying concentrations (200-800 ppm). The green synthesis of FeONPs from *Brassica oleracea* extract was successfully achieved. Ultraviolet-visible spectroscopy confirmed the formation of nanoparticles with an absorption peak at approximately 300 nm. Atomic force microscopy and X-ray diffraction (XRD) analyses revealed the crystalline structure and average particle size of the synthesized nanoparticles, with the XRD pattern corresponding to the α-Fe_2O_3 phase. The insecticidal activity demonstrated a dose-dependent increase in mortality rates. At 400 ppm, *Oryzaephilus surinamensis* exhibited 93.3% mortality, reaching 100% at 600 and 800 ppm. Similarly, *Musca domestica* achieved 100% mortality at 800 ppm. The effectiveness was attributed to the production of reactive oxygen species (ROS) and physical blockage of respiratory pathways, highlighting the nanoparticles' potential as an eco-friendly insecticide. The green synthesis method of FeONPs offers a sustainable pest control solution and reduces the use of harmful chemicals.

1. INTRODUCTION

Brassica oleracea var. capitata (cabbage) is a rich source of antioxidants, with certain varieties containing up to eight times more antioxidants than green cabbage [1]. Purple cabbage contains vitamin C, carotenoids, and flavonoids, including anthocyanins and kaempferol [2]. Anthocyanins are pigments responsible for the red, orange, blue, and purple colours found in many vegetables and fruits. A high intake of anthocyanins and other phytochemicals has been linked to a reduced risk of cardiovascular disease [3]. Cabbage is a rich source of vitamin A, which the body absorbs in various forms, including lutein, zeaxanthin, and beta-carotene. Vitamin A is particularly important for maintaining eye health. Both lutein and zeaxanthin help protect the retina and reduce the risk of macular degeneration. Beta-carotene is converted into retinol in the body, which plays a crucial role in light perception and its conversion into neural signals. Purple cabbage is a rich source of vitamin K1, commonly found in plant-based foods like leafy greens and cruciferous vegetables. This distinguishes it from vitamin K2, which is primarily found in animal-derived foods and fermented products. There is evidence that vitamins K1 and K2 are important for maintaining bone health and strength [2]. Research on the health benefits of cabbage has shown promising results. The study found that administering cabbage extract for 60 days helped lower blood sugar levels, restore kidney function, and promote weight loss. These findings suggest that cabbage may have potential therapeutic benefits for managing diabetes. The study also indicated that the antioxidant and blood sugar-lowering properties of purple cabbage extract might help improve diabetes. However, these findings have not been fully confirmed, and further research is needed to validate their effects in humans [4].

Nanopesticides are innovative formulations that harness nanotechnology to improve the efficiency and environmental safety of pest control agents. Their nanoscale size enhances adhesion to plant surfaces and improves penetration into pests, allowing for lower dosages and reduced environmental runoff. Additionally, nanocarriers enable controlled and sustained release of active ingredients, while targeted delivery helps protect beneficial organisms [5]. Current research focuses on developing novel formulations like nanoemulsions and nanocapsules, assessing potential toxicity, and aligning with sustainable agricultural practices [6]. However, challenges such as establishing regulatory frameworks, educating stakeholders, and evaluating economic viability remain critical for widespread adoption [7]. With continued research and proper regulatory support, nanopesticides have the potential to revolutionize pest management by enhancing efficiency and reducing environmental impact.

Nanoparticles are highly sought after for their minute size, large surface area-to-volume ratio, catalytic activity, and diverse shapes, making them promising tools for addressing challenges in primary production and enhancing agricultural yields [8]. The primary methods of synthesizing metal oxide nanoparticles include physical, chemical, and green synthesis approaches. Physical methods often require high temperatures, expensive materials, and specialized equipment. Chemical methods, while effective, commonly involve hazardous reducing agents, such as sodium borohydride and hydrazine hydrate, which pose risks to both the environment and living organisms [9]. Due to these limitations, green synthesis is proposed as a viable alternative to physical and chemical methods. Green synthesis offers an environmentally friendly alternative to traditional physical and chemical methods, boasting lower toxicity and reduced environmental impact [10]. This eco-friendly approach utilizes bacteria, fungi, algae, and plants to produce nanoparticles, which can be used in environmentally friendly pesticides.

Plant extracts are the preferred choice for green nanoparticle synthesis as they enhance the reaction rate and reduce the risk of contamination. They provide a rich and abundant source of bioactive compounds, including fatty acids, proteins, enzymes, amino acids, polysaccharides, and polyphenols. The chemical composition and structural properties of cabbage extracts have been extensively studied based on their key bioactive components [9] and are commonly linked to geographic races or ecotypes. When utilizing cabbage oil for insecticide production, it is crucial to identify the specific compounds responsible for its insecticidal activity. Evaluating its toxicological properties ensures effectiveness and safety.

Musca domestica (housefly) is a medium-sized insect measuring approximately 5.3 to 5.6 mm in length. The grayish-black creature has a spherical head, large compound eyes, thick-haired antennae, a spongy mouth, a swollen abdomen, black spots on the dorsal surface, and a light lower surface and sides [11]. Female insects lay eggs in garbage and dirt, hatching into larvae and pupae, and producing ten generations per year, each lasting about two weeks. This insect is globally widespread and remains active year-round, though it is most abundant in April, May, June, and September, particularly in cities and villages where environmental conditions favor its reproduction [12]. The fly, with its thick hair, transmits diseases like typhoid, cholera, and diarrhea to humans through attachment to microbes and a biological cycle within its body [13]. *Oryzaephilus surinamensis* (sawtoothed grain beetle) is a global pest that attacks grains, other food products, dried fruits, meats, sugar, biscuits, and chocolates, and is widespread in stored grain and other food items [14]. This insect infects flour and stored medicines, but not healthy grains. Adults and larvae can be found in packages infested with other pests and stored in poor conditions [15]. This insect has also been observed to prefer packaged foods over those prepared for direct consumption, regardless of their location. The adult insect usually lives for 6 to 10 months, but some individuals can survive for up to 3 years [16]. Table 1 provides a clear comparison between the two insects, *M. domestica* and *O. surinamensis,* in terms of their classification, habitat, physical traits, diet, and impact.

This study aimed to evaluate the insecticidal effectiveness of iron oxide nanoparticles synthesized from *Brassica oleracea* extract against two pest species: *Musca domestica* and *Oryzaephilus surinamensis*. The evaluation focused on the nanoparticles' effects on mortality rates, behavior, and other physiological impacts on these insects.

Table 1. A comparison of *Musca domestica* (housefly) and *Oryzaephilus surinamensis* (saw-toothed grain beetle)

Feature	*Musca domestica* (Housefly)	*Oryzaephilus surinamensis* (Sawtoothed Grain Beetle)
Classification	Order: Diptera, Family: Muscidae	Order: Coleoptera, Family: Silvanidae
Common Habitat	Found in homes, farms, and garbage dumps	Found in stored grains, cereals, and processed foods
Physical Appearance	Greyish body with four dark stripes on the thorax; one pair of wings	Small, flat, brown beetle with saw-like projections on the thorax
Size	6–7 mm in length	2.5–3 mm in length
Life Cycle	Complete metamorphosis: egg → larva → pupa → adult	Complete metamorphosis: egg → larva → pupa → adult
Reproductive Rate	Females lay up to 500 eggs in a lifetime	Females lay around 200–250 eggs in stored food
Diet	Feeds on organic waste, decaying matter, and sugary substances	Feeds on grains, flour, cereals, and packaged food products
Pest Status	Nuisance pest; vector of diseases like dysentery, typhoid, and cholera	A major pest of stored food, causing contamination and economic losses
Control Methods	Sanitation, insecticides, traps, and biological control	Proper food storage, fumigation, and insecticides

Adapted from study [17]

2. MATERIALS AND METHODS

2.1 Plant extract preparation

The *Brassica oleracea* plant was purchased from the local market. Cabbage leaves were cut into pieces using a sterile knife. Then, 20 g of leaves were boiled for an hour at 60°C in 200 mL of water, vacuum-filtered, and stored at 4°C for subsequent use.

2.2 Nanoparticle preparation

An aqueous solution of ferrous sulfate ($FeSO_4$) was prepared. Approximately 5 mL of the water extract was mixed with 50 mL of $FeSO_4$ (1.0 mM) under continuous stirring. The reaction mixture was typically heated to a controlled temperature of 60°C to facilitate the reduction of iron ions, resulting in the appearance of a black colloidal color, indicating the formation of iron oxide nanoparticles. The phytochemicals in the extract act as reducing and stabilizing agents. The solution was incubated overnight at 60°C to allow the complete formation of nanoparticles. The mixture was then subjected to ultrasonication for 15 minutes, followed by agitation at 400 rpm for an additional 15 minutes. After separation, the nanoparticles were stored at room temperature for several weeks in foil-sealed glass conical flasks.

2.3 Fourier-Transform Infrared (FTIR) spectroscopy

Fourier-Transform Infrared (FTIR) spectroscopy is one of the most popular analytical tools, due to its simplicity in handling and acquiring spectra, practicality, and its capacity to deliver a huge amount of structural information. It is a useful tool for the characterization of the properties and molecular structures of organic and inorganic compounds and is also used for quantitative analysis.

According to the method, covalent bonds and functional groups of a molecule absorb certain frequencies of the IR radiation. This absorption gives rise to specific bands in the spectrum associated with vibrational modes of the molecule and forms a characteristic “spectral fingerprint” of each substance. Moreover, FTIR is capable of identifying the crystalline and amorphous regions as it provides information on molecular structures in different phases of a material.

2.4 Characterization of nanoparticles

The final product of the biologically synthesized nanoparticles was dried and subjected to characterization techniques. A biocrom biowave ultraviolet-visible (UV-Vis) spectrometer, set at room temperature and operating within a wavelength range of 200–800 nm, was used to confirm nanoparticle formation. Also, X-ray diffraction (XRD) spectroscopy and atomic force microscopy (AFM) were used to assess size and morphology. The crystallite size (D) in nanometers for a known X-ray wavelength (λ) at a diffraction angle (θ) of an iron oxide thin film was calculated using the Scherrer formula:

$$D = \frac{(0.94\lambda)}{(\beta \mathrm{COS}[\theta])} \tag{1}$$

Microstrains arise during the growth of thin films due to stretching or compression in the lattice, leading to deviations in the c-lattice constant from the ASTM value. Strain broadening occurs due to the varying displacements of atoms from their reference lattice positions [2]. This strain can be calculated using the following formula [3]:

$$\eta = \frac{(0.9\,\lambda)}{(\mathrm{FWHM\ COS}\,[\theta])} \tag{2}$$

η (eta) is the crystallite size (commonly denoted by D in your provided table).

λ (lambda) is the wavelength of the X-ray radiation (e.g., Cu Kα = 1.5406 Å).

FWHM is the Full Width at Half Maximum of the diffraction peak (in radians).

θ (theta) is the Bragg angle (which is half of the 2θ value listed in your table) [4]:

$$\delta = \frac{1}{D^2}\left(\frac{\mathrm{lines}}{\mathrm{nm}}\right)^2 \tag{3}$$

The synthesis involved iron nitrate at a specific molar concentration combined with blue saffron extract. The nanoparticles were deposited on glass using the drop-casting method at a rate of five drops, resulting in a film thickness not exceeding one micrometer, as calculated by the gravimetric method (XRD).

2.5 Bioassay for vermin mortality

The insect colony source was the housefly (*Musca domestica*), which was free of pathogens and pesticides. The colony was maintained in the animal house of the Department of Biology, College of Science, Al-Mustansiriyah University. Ten adult *Musca domestica* were placed in a cage, and a glass dish containing cotton moistened with 9 mL of the treatment solutions (nanoparticles, iron oxide, and cabbage extract) at concentrations of 200, 400, 600, and 800 ppm was introduced. Each treatment solution was supplemented with 1 g of sugar to create a 10% sugar solution. For the control, a 10% sugar solution without any treatment was used. Each treatment was performed in triplicate. The mortality percentage was calculated using the following equation:

$$Mortality\ percentage = \frac{X-Y}{X} \times 100 \tag{4}$$

where, *X* represents the primary number, *Y* represents the number after treatment.

The adult *Oryzaephilus surinamensis* insects were treated using the spraying method. Ten insects (five males and five females), aged 1–2 weeks, were placed in a small Petri dish and sprayed separately with nanoparticles, iron oxide, or cabbage extract at concentrations of 200, 400, 600, and 800 ppm. After 30 seconds, the insects were transferred to 100 mL plastic containers containing 5 g of sterilized wheat. The container openings were covered with cloth and secured with rubber bands. The dishes were incubated at 27 ± 2°C with a relative humidity of 60 ± 10%. Each concentration was tested in triplicate. The control treatment was sprayed with distilled water containing 1 mL of ethanol, two drops of Tween 80 as a spreading agent, and liquid paraffin as an adhesive. Mortality rates were recorded after 3, 7, and 10 days of treatment. The mortality percentage was calculated using Eq. (4).

3. RESULTS AND DISCUSSION

3.1 FTIR

The infrared spectrum in Figure 1 of *Brassica oleracea* extract-synthesized iron oxide nanoparticles has characteristic peaks corresponding to specific functional groups, wherein 3321.49 cm^{-1} and 1346.12 cm^{-1} is ascribed to O-H stretching and bending vibrations of an alcohol or hydroxy compound, 2816.89 cm^{-1} indicates aldehyde C-H stretching, 1787.16 cm^{-1} is the signal for carbonyl (C=O) stretching region, 1052.13 cm^{-1} represents to C-O stretching of ether or oxy compound, at 877.75, 833.10, and 612.23 cm^{-1} bands are due to aromatic bending vibrations of C-H, however, the sharp peak observed at 2435.36 cm^{-1} does not match with any of the known functional groups.

The characteristic absorptions of the main functional groups in the IR spectrum (Figure 2) of *Brassica oleracea* extract resonate with the structural features. The bands at 3330.45, 2119.66, 1637.50, 1503.22, 1337.62, 1231.80, and 1014.32 cm^{-1} correspond to the O-H stretching in alcohols or hydroxy alkynes bond, alkyne C≡C stretching, N-O stretching in nitro compounds, aromatic C=C stretching, O-H bending, C-O-C stretching in alkyl aryl ethers, and S=O, respectively. Otherwise, the assignments of functional groups for the absorptions at 2325.04, 1148.93, and 1042.86 cm⁻¹. So far, the assignments to the functional groups of absorptions at 2325.04, 1148.93, and 1042.86 cm⁻¹ have no name.

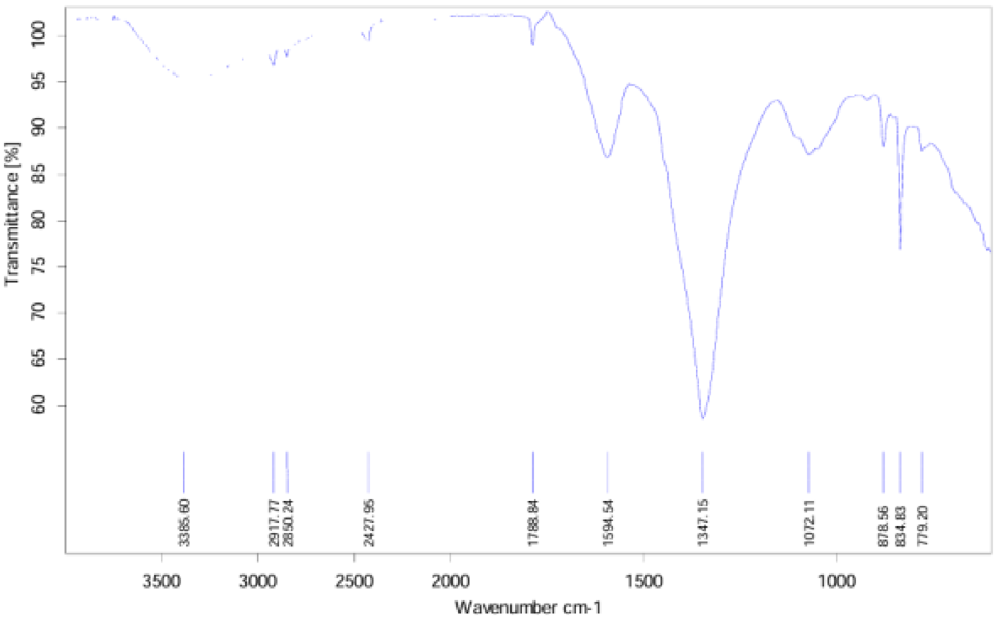


Figure 1. FTIR of *Brassica oleracea* extract-synthesized iron oxide nanoparticles

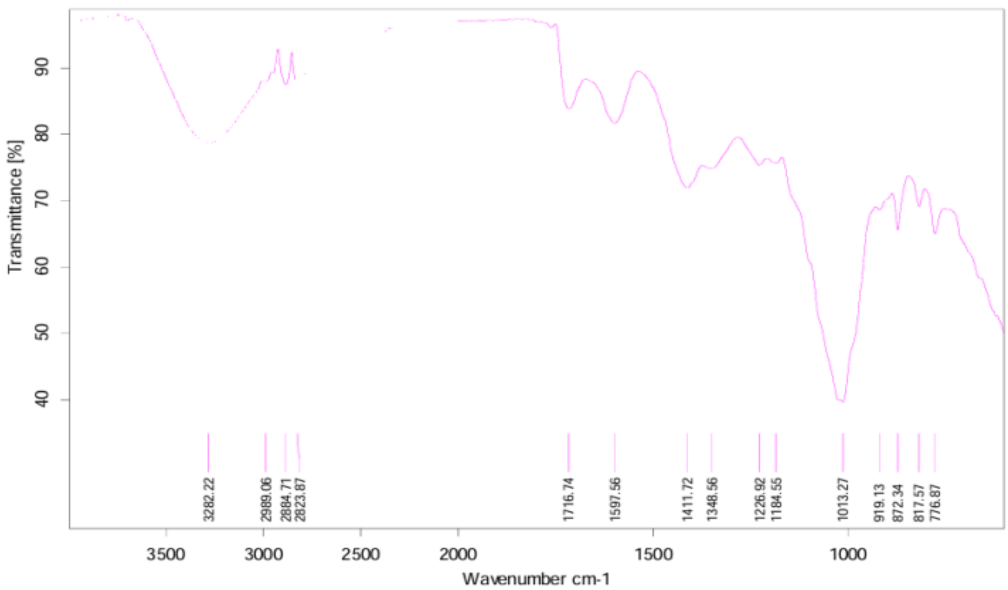


Figure 2. FTIR of *Brassica oleracea* extract

3.2 Nanoparticle properties

Iron oxide nanoparticles were successfully synthesized using cabbage-derived extract and confirmed through UV-Vis spectroscopy. The optical absorption spectrum shows that the material is not optically transparent in the 200–800 nm wavelength range. The results of this study, UV-vis absorption spectra, showed a noticeable absorption peak at a wavelength of around 380 nm Figure 3. This result is consistent with what would be expected from iron oxide nanoparticles, which have a considerable UV light absorption capacity.

The AFM image in Figure 4 provides vital data regarding the crystallographic features of the iron oxide nanoparticles that were fabricated using cabbage extract, as demonstrated in Table 2. Although the data unambiguously verify that the prepared nanomaterial is of a crystalline nature, a comprehensive comparison using standard reference data is necessary to confirm with certainty that the phase is hematite (α-Fe_2O_3), ycastle (α-Fe_2O_3), or oxidel (γ-Fe_2O_3).

The major uncertainty in the analysis is due to the absence of a clear correspondence between the measured diffraction peaks and the standard JCPDS (Joint Committee on Powder Diffraction Standards) database. For definitive phase identification, each peak in the XRD pattern should be indexed with its corresponding Miller indices (hkl) and compared with powder diffraction data for known standards.

Reference standard card: The standard card most used for hematite is JCPDS Card No. 33-0664 (or its updated version ICDD PDF# 01-089-0596) for α-Fe_2O_3.

Extensive Analysis: The experimental 2θ values, when compared with the standard 2θ and corresponding d-spacing data, demonstrate consistency with the JCPDS reference pattern for α-Fe_2O_3 (Card No. 33-0664). Table 3 presents a detailed comparative analysis of the experimental XRD results against the JCPDS standard, confirming the phase identification and crystallographic structure of the synthesized material.

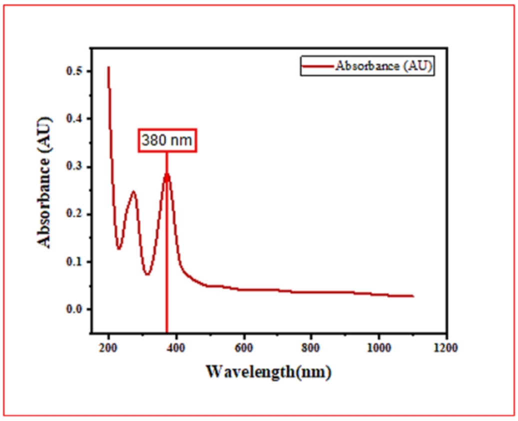
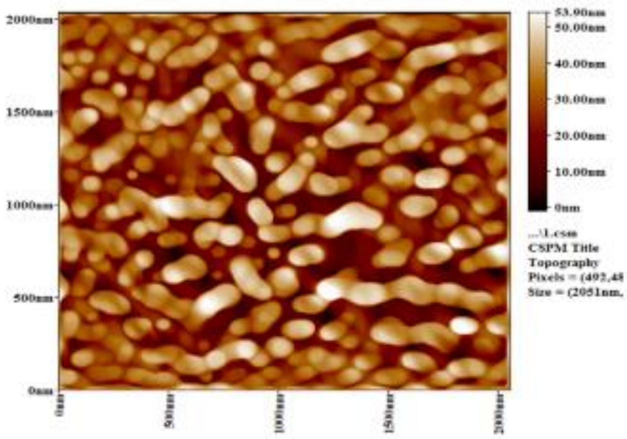
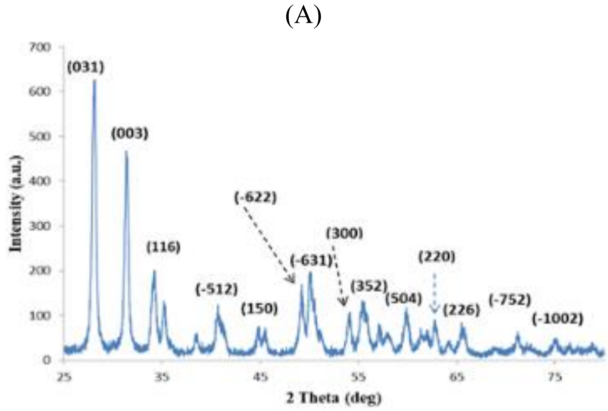


Figure 3. Ultraviolet-visible spectroscopy of *Brassica oleracea* extract-synthesized iron oxide nanoparticles



(A)



(B)

Figure 4. Characterization of *Brassica oleracea* extract-synthesized iron oxide nanoparticles. A: Atomic force microscopy; B: X-ray diffraction spectroscopy

Table 2. X-ray diffraction analysis of iron oxide nanoparticle thin film

2 Theta (deg)	FWHM (deg)	D (nm)	$\eta \times 10^{-4}$	$\delta \times 10^{14}$ lines.m^{-2}
28.08	0.45	19.92	17.38	25.18
31.36	0.56	16.54	20.93	36.51
34.06	0.5	19.11	18.12	27.37
34.34	0.3	31.96	10.84	9.789
38.28	0.41	24.61	14.07	16.50
40.66	0.36	29.02	11.93	11.87
44.66	0.4	27.87	12.42	12.86
49.18	0.5	24.29	14.26	16.93
50.00	0.6	20.59	16.82	23.57
53.96	0.44	30.72	11.27	10.59
59.76	0.54	29.32	11.81	11.63
62.70	0.41	42.48	8.1567	5.541
65.34	0.64	29.97	11.56	11.13
71.06	0.35	70.87	4.889	1.990
74.86	0.44	70.51	4.913	2.011

Table 3. Comparison of experimental XRD data with JCPDS Standard for α-Fe_2O_3 (Card No. 33-0664)

Experimental Data (From Table 2)		JCPDS 33-0664 Standard (α-Fe_2O_3)	
2θ (deg)	d-spacing (Å)	Assigned (hkl) Planes	2θ (deg)
24.18	3.68	(012)	24.14
33.16	2.70	(104)	33.15
35.64	2.52	(110)	35.61
40.88	2.21	(113)	40.85
49.48	1.84	(024)	49.48
54.10	1.69	(116)	54.09
62.46	1.49	(214)	62.45

3.3 Insecticidal properties

The bioactivity assessment demonstrated that the green-synthesized nanoparticles exhibited a dose-dependent increase in insect mortality. Figure 5(A) illustrates the mortality rate of adult *Oryzaephilus surinamensis* exposed to various test solutions. The results indicated that higher concentrations of the green-synthesized iron oxide nanoparticles from *Brassica oleracea* extract resulted in a notable increase in insect mortality. At 400 ppm, the mortality rate for *Oryzaephilus surinamensis* reached 93.3%, while complete mortality (100%) was observed at 600 and 800 ppm. Conversely, iron oxide precursor solution and *Brassica oleracea* extract showed a relatively lower mortality rate, indicating reduced efficacy. These findings indicate that the nanoparticles possess insecticidal properties, though to varying degrees. A similar observation was made when adult *Musca domestica* was exposed to the test solutions. The results (Figure 5(B)) of the mortality rate demonstrated a progressive increase in mortality with higher concentrations of *Brassica oleracea* extract-iron oxide nanoparticles. The nanoparticles exhibited the highest mortality rate, reaching 100% with 800 ppm exposure. In contrast, the iron oxide precursor solution and *Brassica oleracea* extract showed minimal mortality, confirming the validity of the experimental setup. The significantly lower mortality rates observed with the iron oxide precursor solution and cabbage extract alone confirm the enhanced insecticidal effect of the synthesized nanoparticles.

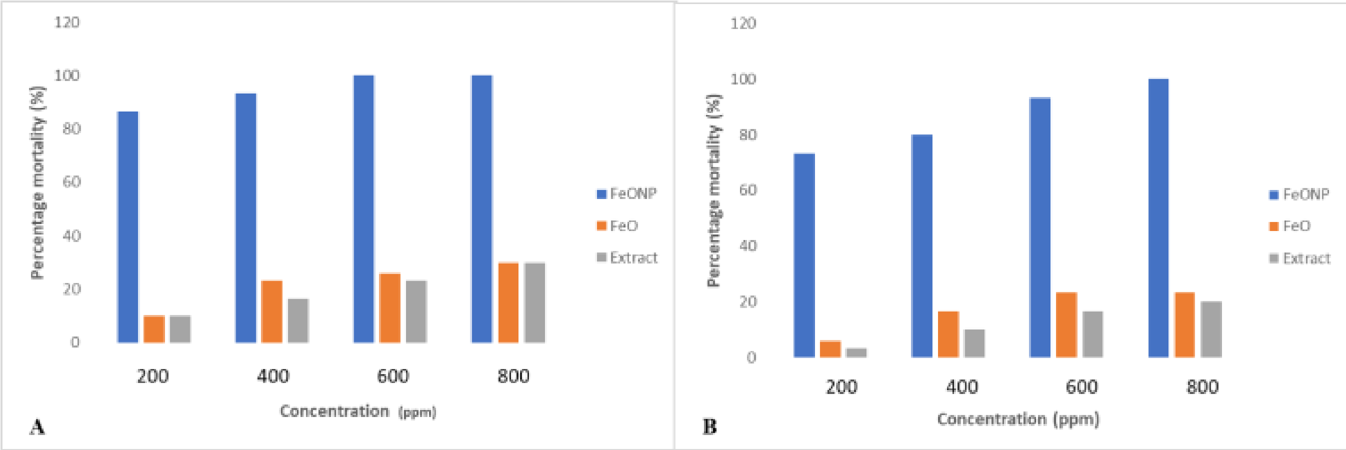


Figure 5. Mortality rate of adult insects induced by test solutions. A: *Oryzaephilus surinamensis*; B: *Musca domestica*

Figure 6. The toxic effect of nanoparticles, which act on insect eggs, prevents their progression to later developmental stages of *Musca domestica*

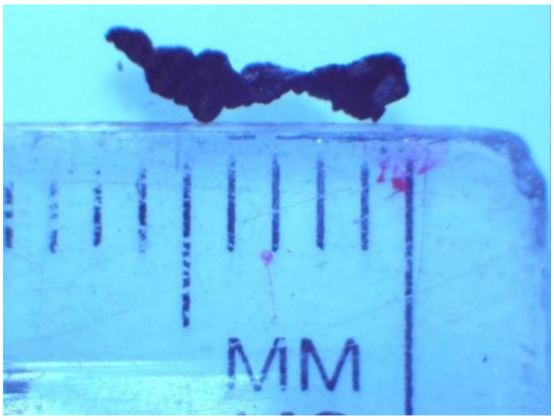


Figure 7. Effect of nanoparticles on the adult *Musca domestica*

To the best of our knowledge, cabbage leaf extract has not been previously utilized in iron nanoparticle synthesis. These nanoparticles demonstrated significant effectiveness against the *Oryzaephilus surinamensis* and *Musca domestica*. The rise in mortality rates among adult insects with increasing concentrations of the nanomaterial confirms its effectiveness. This finding aligns with previous studies [17-20]. There was variation in the mortality rates across the tested concentrations for both insects, likely due to the larger size of the insect, which increases cuticle thickness and, consequently, resistance. The nanoparticles exhibit a dual effect, targeting both the digestive tract and penetrating the insect's cuticle layer. The mechanism by which nanomaterials affect the insect involves penetrating the insect's cuticle, leading to desiccation. Additionally, during feeding, the nanoparticles enter the digestive tract, spread through the body cavity, and ultimately cause death. This lethal effect is primarily due to the production of reactive oxygen species (ROS), which play a key role in the insect's demise. Several studies have also reported that the ability of iron oxide nanoparticles to generate ROS is possibly the mechanism responsible for insect death through oral or cuticular membrane disruption [20, 21]. Due to their toxic effect, these particles produce ROS, which act on insect eggs, preventing their progression to later developmental stages (Figure 6) [22, 23].

Another reason for the death of insects treated with biologically synthesized nanoparticles is the accumulation of these particles on the respiratory stomata and bronchioles, leading to their blockage and impairing the insect's ability to breathe, ultimately causing death. Additionally, the nanoparticles can accumulate and adhere to the insect's cuticle, absorbing wax and fat, which results in desiccation and cracking, leading to the insect's demise. In addition, the physiological factors of the insect body, such as the salt concentration in the digestive tract and its pH, are influenced by nanoparticles (Figure 7). This effect is evident when silver and zinc oxide nanoparticles are combined with the fungus *Metarhizium anisopliae* and applied to adult insects [24]. From the above, it was found that the purple cabbage extract contains effective compounds such as anthocyanin and vitamin K. These compounds contribute to its interaction with iron to form effective nanoparticles as a nano extract. This extract has proven highly effective as an insecticide for adults of both *Oryzaephilus surinamensis* and *Musca domestica.* Consequently, it serves as an environmentally friendly insecticide for natural and biological control of insects.

Other metallic nanoparticles, such as silver nanoparticles [25, 26] and zinc oxide nanoparticles [27, 28], have been reported to possess insecticidal activities. Through oxidative stress and magnetic characteristics, iron oxide nanoparticles alter the physiology of insects [29, 30]. By generating reactive oxygen species and damaging cellular membranes, silver nanoparticles demonstrate strong toxicity [25]. Insect development and reproduction are impacted by zinc oxide nanoparticles' ability to absorb UV light and cause oxidative stress [26]. All three demonstrate eco-friendly, target-specific potential, making them promising alternatives to conventional insecticides.

Nanoparticles (NPs) impact insects through various mechanisms, such as causing physical damage to cell membranes, generating reactive oxygen species (ROS), and interfering with cellular and metabolic functions. The severity and nature of these effects can differ markedly across insect developmental stages. For instance, eggs may possess a certain level of resistance due to their protective chorionic layers, while larvae—being more metabolically active and engaged in feeding—tend to be more vulnerable to nanoparticle toxicity. Adults, on the other hand, may respond differently based on factors like body size, behavior, and exoskeleton structure. Therefore, the developmental stage is a key factor influencing how nanoparticles affect insect physiology.

4. CONCLUSION

The findings of the present study highlight the importance of green technology and innovation in pest control using sustainable solutions. Purple cabbage contains active compounds such as anthocyanins and vitamin K, which contribute to its interaction with iron to form nanoparticles. The biologically synthesized iron oxide nanoparticles have proven highly effective against target insects, making them a promising option for developing new, environmentally friendly insecticides. The research supports the shift to green technologies for manufacturing nanoparticles, which contributes to reducing the harmful environmental impacts associated with conventional methods. These nanoparticles can be utilized for pest control in agricultural fields or warehouses, with potential applications in other fields, such as water purification and medicine. However, further research is necessary to evaluate the long-term environmental impacts of these nanoparticles and their effects on non-target organisms. This will ensure the safe and sustainable application of green-synthesized iron oxide nanoparticles in integrated pest management systems.

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REFERENCES

[1] Mizgier, P., Kucharska, A.Z., Sokol-Letowska, A., Kolniak-Ostek, J., Kidoń, M., Fecka, I. (2016). Characterization of phenolic compounds and antioxidant and anti-inflammatory properties of red cabbage and purple carrot extracts. Journal of Functional Foods, 21: 133-146. https://doi.org/10.1016/j.jff.2015.12.004

[2] Zielińska, M., Lewandowska, U., Podsędek, A., Cygankiewicz, A.I., Jacenik, D., Sałaga, M., Kordek, R., Krajewska, W.M., Fichna, J. (2015). Orally available extract from *Brassica oleracea* var. *capitata rubra* attenuates experimental colitis in mouse models of inflammatory bowel diseases. Journal of Functional Foods, 17: 587-599. https://doi.org/10.1016/j.jff.2015.05.046

[3] Domínguez-Perles, R., Mena, P., Garcia-Viguera, C., Moreno, D.A. (2014). *Brassica* foods as a dietary source of vitamin C: A review. Critical Reviews in Food Science and Nutrition, 54(8): 1076-1091. https://doi.org/10.1080/10408398.2011.626873

[4] Ahmed, S.H., Hassan, H.E., Mahdi, F.M. (2023). Evaluation of the antioxidant and anti-inflammatory activities of *Moringa oleifera* Lam extracts and determination of their active components. Egyptian Journal of Chemistry, 66(7): 479-486. https://ejchem.journals.ekb.eg/article_251877_e0937ee0f7863fe11ea0d10350b4b1d1.pdf.

[5] Kah, M., Tufenkji, N., White, J.C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. Nature Nanotechnology, 14(6): 532-540. https://doi.org/10.1038/s41565-019-0439-5

[6] Campos, E.V.R., de Oliveira, J.L., Fraceto, L.F., Singh, B. (2015). Polysaccharides as safer release systems for agrochemicals. Agronomy for Sustainable Development, 35(1): 47-66. https://doi.org/10.1007/s13593-014-0263-0

[7] Fraceto, L.F., Grillo, R., de Medeiros, G.A., Scognamiglio, V., Rea, G., Bartolucci, C. (2016). Nanotechnology in agriculture: Which innovation potential does it have?. Frontiers in Environmental Science, 4: 20. https://doi.org/10.3389/fenvs.2016.00020

[8] Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. Green Chemistry, 13(10): 2638-2650. https://doi.org/10.1039/c1gc15386b

[9] Wiczkowski, W., Szawara-Nowak, D., Topolska, J. (2013). Red cabbage anthocyanins: Profile, isolation, identification, and antioxidant activity. Food Research International, 51(1): 303-309. https://doi.org/10.1016/j.foodres.2012.12.015

[10] Ahmed, S., Ahmad, M., Swami, B.L., Ikram, S. (2016). Green synthesis of silver nanoparticles using *Azadirachta indica* aqueous leaf extract. Journal of Radiation Research and Applied Sciences, 9(1): 1-7. https://doi.org/10.1016/j.jrras.2015.06.006

[11] Khan, S.T., Musarrat, J., Al-Khedhairy, A.A. (2016). Countering drug resistance, infectious diseases, and sepsis using metal and metal oxides nanoparticles: Current status. Colloids and Surfaces B: Biointerfaces, 146: 70-83. https://doi.org/10.1016/j.colsurfb.2016.05.046

[12] Agarwal, H., Kumar, S.V., Rajeshkumar, S. (2017). A review on green synthesis of zinc oxide nanoparticles–An eco-friendly approach. Resource-Efficient Technologies, 3(4): 406-413. https://doi.org/10.1016/j.reffit.2017.03.002

[13] Patiño-Ruiz, D.A., Meramo-Hurtado, S.I., González-Delgado, A.D., Herrera, A. (2021). Environmental sustainability evaluation of iron oxide nanoparticles synthesized via green synthesis and the coprecipitation method: A comparative life cycle assessment study. ACS Omega, 6(19): 12410-12423. https://doi.org/10.1021/acsomega.0c05246

[14] Devatha, C., Thalla, A.K., Katte, S.Y. (2016). Green iron nanoparticle production utilizing various leaf extracts for the treatment of domestic wastewater. Journal of Clean Production, 139: 1425-1435. https://doi.org/10.1016/j.jclepro.2016.09.019

[15] Al-Qasmi, N. (2022). Sustainable and efficacy approach of green synthesized cobalt oxide (Co_3O_4) nanoparticles and evaluation of their cytotoxicity activity on cancerous

cells. Molecules, 27(23): 8163. https://doi.org/10.3390/molecules27238163

[16] Juda, E.K., Khalaf, K.J., Salem-Bekit, M.M. (2024). Effect of growth conditions on hemolysin production from clinical isolates of *Escherichia coli*. Al-Mustansiriyah Journal of Science, 35(3): 36-47. https://doi.org/10.23851/mjs.v35i3.1442

[17] Vail, D.J. (1981). Micro-analytical biology workbook for food sanitation control analysts (Volume II). U.S. Department of Health and Human Services, Food and Drug Administration, Atlanta Region Office.

[18] Flamini, G., Cioni, P.L., Morelli, I., Macchia, M., Ceccarini, L. (2022). Main agronomic-productive characteristics of two ecotypes of *Rosmarinus officinalis* L. and chemical composition of their essential oils. Journal of Agricultural and Food Chemistry, 50(12): 3512-3517. https://doi.org/10.1021/jf011138j. PMID: 12033820

[19] Mohammad, M.K., Ahmed, S.H., Alameri, R.A.J. (2021). Green medicine: A novel preparation method for green synthesizing of iron nanoparticles derived from beta vulgaris extract. Archives of Razi Institute, 76(5): 1327-1332. https://doi.org/10.22092/ari.2021.355933.1740

[20] Robert, W., Hamley, W., Geoghegan, M. (2005). Nanoscale Science and Technology. England: John Wiley & Sons.

[21] Pradeep, T. (2007). Nano: The Essentials, Understanding Nanoscience and Nanotechnology. New Delhi: Tata McGraw-Hill Publishing.

[22] Ahmed, S.H. (2022). Synthesis of novel Iron Nanoparticles using the aqueous extract of the Pumpkin plant, and used it in the treatment of burns. Egyptian Journal of Chemistry, 65(3): 353-362.

[23] Hameed, R.S., Fayyad, R.J., Shafeeq, M.A.A., Nuaman, R.S. (2023). Manufacturing and characterization of an effective and eco-friendly nano insecticide with the aid of green alga Chlorella vulgaris in contrast to traditional insecticide. Indonesian Journal of Biotechnology, 28(2): 112-118. https://doi.org/10.22146/ijbiotech.79105

[24] Al-Hamdani, H., Ahmed, S., Hameed, R., Getan, A. (2021). The effect of environmentally safe nanosynthesis with copper particles by using *Citrus aurantium* fruit extract against harmful mosquitoes. Asian Journal of Water, Environment and Pollution, 18(3): 59-67. https://doi.org/10.3233/AJW210029

[25] Benelli, G. (2016). Green synthesized nanoparticles in the fight against mosquito-borne diseases and cancer-A brief review. Enzyme and Microbial Technology, 95: 58-68. https://doi.org/10.1016/j.enzmictec.2016.08.022

[26] Kamaraj, C., Gandhi, P.R., Ragavendran, C., Sugumar, V., Kumar, R.S., Ranjith, R., Priyadharsan, A., Cherian, T. (2024). Sustainable development through the bio-fabrication of ecofriendly ZnO nanoparticles and its approaches to toxicology and environmental protection. Biomass Conversion and Biorefinery, 14(22): 28533-28549. https://doi.org/10.1007/s13399-022-03445-6

[27] Mahlaule-Glory, L.M., Mapetla, S., Makofane, A., Mathipa, M.M., Hintsho-Mbita, N.C. (2022). Biosynthesis of iron oxide nanoparticles for the degradation of methylene blue dye, sulfisoxazole antibiotic and removal of bacteria from real water. Heliyon, 8(9): e10536. https://doi.org/10.1016/j.heliyon.2022.e10536

[28] Nie, D., Li, J., Xie, Q., Ai, L., Zhu, C., Wu, Y., Gui, Q., Zhang, L., Tan, W. (2023). Nanoparticles: A potential and effective method to control insect-borne diseases. Bioinorganic Chemistry and Applications, 2023(1): 5898160. https://doi.org/10.1155/2023/5898160

[29] Martínez-Cisterna, D., Rubilar, O., Tortella, G., Chen, L., Chacón-Fuentes, M., Lizama, M., Parra, P., Bardehle, L. (2024). Silver nanoparticles as a potent nanopesticide: Toxic effects and Action mechanisms on pest insects of agricultural importance—A review. Molecules, 29(23): 5520. https://doi.org/10.3390/molecules29235520

[30] Shahzad, K., Manzoor, F. (2021). Nanoformulations and their mode of action in insects: A review of biological interactions. Drug and Chemical Toxicology, 44(1): 1-11.