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EXPERIMENTAL VALIDATION OF *Nigella sativa* AS AN EFFECTIVE BIO-PESTICIDE AND SOIL AMENDMENT FOR SUSTAINABLE AGRICULTURE

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ABSTRACT
The use of artificial chemicals in agriculture has degraded the environment, reduced soil fertility, and increased pest resistance. Finding sustainable solutions has become necessary. The study examines the use of *Nigella sativa* to enhance soil and manage pests, highlighting its effectiveness against *Tuta absoluta*. In a controlled experiment, 92% of the pests were killed with kalonji powder, compared to 12% in the control group. The results were statistically significant ($p<0.05$). It enhanced soil fertility by neutralising pH levels and increasing carbon, nitrogen, phosphorus, and potassium, alongside microbial activity. To examine the kalonji powder, we employed methods such as gas chromatography, scanning electron microscopy, and Fourier transform infrared spectroscopy. Among the substances identified in this study were thymoquinone, alkaloids, and essential oils. Furthermore, the powder's structure allows these compounds to be released into the soil gradually. These findings suggest that *Nigella sativa* can be used in agriculture to reduce insect populations and enhance soil health. This study integrates current farming methods with an understanding of plant chemistry that plant-based substitutes for synthetic compounds, such as kalonji powder, could be employed. The study offers a more ecologically friendly agricultural method that lessens the effects of farming by promoting insect control and enhancing soil health. The findings contribute to the advancement of sustainable agriculture by providing a scientifically validated plant-based alternative to synthetic agrochemicals, offering a foundation for future research on eco-friendly pest management and soil restoration strategies. This study directly supports the United Nations Sustainable Development Goal (SDG)-2: Zero Hunger by promoting sustainable agricultural practices that improve soil productivity, reduce chemical dependency, and enhance long-term food security.
Keywords: *Nigella Sativa*, Botanical Pesticides *Tuta absoluta*, Soil Fertility, Sustainable Farming.
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INTRODUCTION

The use of man-made fertilisers and pesticides has grown a lot as farming has increased. This has caused environmental problems like soil getting worn out, water getting polluted, and pests becoming resistant to chemicals. These issues show that we need farming methods that are good for the environment and help keep the soil healthy. This way we can still grow food without hurting the earth.[1] Traditional farming in India can teach us a thing or two. For example, Ayurveda and folk farming have been using methods to keep soil fertile and control pests for a long time. These methods focus on living in harmony with nature and balancing the environment. They are good for the earth, and the idea fits sustainable farming.[2] Recently, people have started looking into using plant-based ingredients instead of artificial chemicals in farming. Generally these plant-based pesticides are safer for the environment. They break down easily and can also help keep the soil healthy in the long run by increasing the tiny living things in the soil and improving its structure. This can help control pests and make the soil better.[3-4]

Nigella sativa, also known as kalonji, is one plant that shows promise. People have been using it for a time to make soil better and control pests. The seeds of this plant have properties that help fight bacteria,

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fungi and insects.[5-6] However, not many scientific studies have been done on using *Nigella sativa* in farming. Most of what we know comes from people observing its effects, not from experiments. This makes it hard to use in farming. This study aims to test *Nigella sativa* in a controlled environment to see if it can help improve soil and control pests. The goal is to provide proof that this plant can be used in sustainable farming and help people farm in a way that is good for the environment. By doing this, we hope to encourage environmentally friendly farming practices. This study addresses the existing research gap by providing experimental validation of *Nigella sativa* as both a bio-pesticide and a soil amendment, thereby generating scientific evidence to support its wider adoption in sustainable agricultural systems. Furthermore, the research contributes to the United Nations Sustainable Development Goal (SDG)-2: Zero Hunger by promoting sustainable agriculture through reduced dependence on synthetic agrochemicals, improved soil fertility, and environmentally responsible pest management.

Customary Applications of Kalonji

In India and all over Asia, people have been using *Nigella sativa*, also known as kalonji or black seed, for a long time. To stay healthy, Kalonji helps to boost your system, and it is good for your breathing and stomach. In Indian farming, kalonji is used to improve the soil and to keep crops safe. Farmers mix kalonji seeds into the soil to make crops grow well and to keep pests away.

Bioactive Compounds and Phytochemical Composition

Kalonji has active compounds that are good for you. These compounds include thymoquinone, alkaloids, saponins, flavonoids and essential oils. These substances can kill insects, germs and fungi. Thymoquinone is especially good at killing microbes and pests. These compounds make kalonji a natural way to control pests in farming. Experimental studies show that kalonji can help control pests like insects, aphids and nematodes. Kalonji seed extracts also make the soil fertile, rich in matter and full of good microbes. However, more research is needed to understand how kalonji can help with pest control and soil health. We need to combine knowledge with new science to see how well kalonji works in farming and help farmers. Kalonji is good for the soil and for crops. People have used kalonji for a time, and now we need to study it more.

EXPERIMENTAL

Experimental Design

This study used a randomised design with two groups, one with soil and one with soil that had *Nigella sativa* added to it. Each group was repeated three times. What makes this study unique is that we looked at how *Nigella sativa* affects pests and the soil in a controlled environment.

Plant Material and Soil Preparation

We took *Nigella sativa* seeds, cleaned them, dried them, and turned them into a powder. We also collected soil from a nursery, dried it, and sifted it through a special mesh. Then we checked the soil to see what it was like, including how acidic, carbon and nutrients it had. We mixed the *Nigella sativa* powder into the soil at a rate of 20 grams per kilogram and let it sit for seven days before we planted anything in it.

Pest Infestation and Assessment

We grew tomato plants in the soil that had *Nigella sativa* added to it and in the soil. Then we put pests called *Tuta absoluta*, on the plants. We counted how many pests were on the plants. We used to calculate how many pests were killed by the *Nigella sativa* on 0, 3, 7 and 14 days later.

Soil Analysis

After we treated the soil with *Nigella sativa*, we checked it again to see how it had changed and whether the tiny living things in the soil were.

Statistical Analysis

We used a statistical analysis called one-way ANOVA. Then we used another test called Tukey's post-hoc test. We only considered the results to be important if they were statistically significant, which means they were not just random. We used a computer program called R to do the entire calculations.

Physicochemical Characterisation of *Nigella Sativa*

To really understand how *Nigella sativa* works as a natural pest killer and soil helper, we included FTIR, GCMS and SEM studies. We were looking at the properties of *Nigella sativa*.

RESULTS AND DISCUSSION

The *Nigella sativa* powder was put in the soil. It stopped the *Tuta absoluta* from growing, which was observed over 14 days (Table-1). At the beginning, the number of pests in the control group and the treated group were the same. After that, the number of pests in the treated soil went down slowly. The control group had the same number of pests for the whole time. After fourteen days, the treated plants had 78% pest's reduction than the control group (Fig.-1). This was a change, and it was not just by chance. The *Nigella sativa* powder really worked to stop the pests. It is a natural way to control pests. The present findings clearly demonstrate that *Nigella sativa* significantly suppresses *Tuta absoluta* populations under controlled conditions, indicating its potential as an effective botanical bio-pesticide. The progressive reduction in pest population over the 14-day period suggests a sustained insecticidal effect, likely due to the gradual release of bioactive compounds from the seed powder. These observations strengthen the growing body of evidence supporting plant-derived pest management strategies as environmentally safer alternatives to synthetic pesticides.

Table-1: Effect of Kalonji Powder on *Tuta absoluta* Population

Day	Control (Mean ± SD)	Treated (Mean ± SD)	% Reduction
0	50.0 ± 3.0	50.0 ± 3.0	0%
3	62.0 ± 4.0	40.0 ± 3.0	35%
7	75.0 ± 5.0	28.0 ± 4.0	63%
14	90.0 ± 6.0	20.0 ± 4.0	78%

Note: % Reduction calculated as $((C - T)/C) \times 100$, where C = control and T = treated.

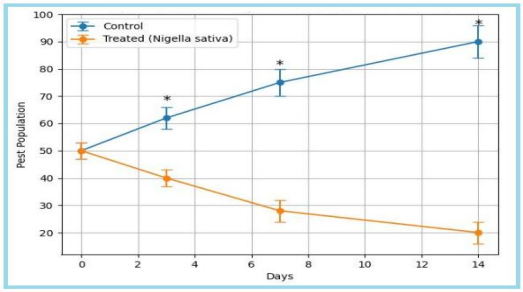

Fig.-1: Effect of *Nigella Sativa* on Pest Population

The number of pests went down, as we can see in (Fig.-2). This is because kalonji has things like thymoquinone, alkaloids and essential oils that are wicked for insects. These things in kalonji can stop pests from growing. We found out that kalonji is good at killing pests, just like other people found out before us with neem or karanja. They discovered that plants can be used to kill pests, and we think this is a way to deal with pests without using harmful chemicals.

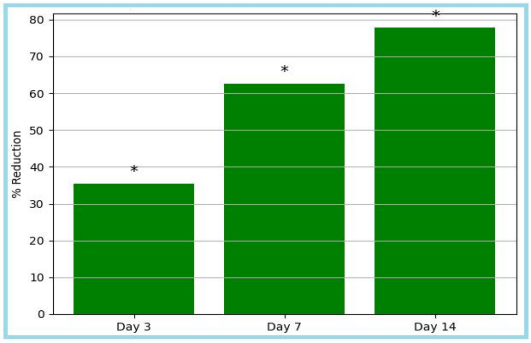

Fig.-2: Pest Reduction Efficiency (*P < 0.05)

In addition to controlling pests, adding kalonji powder to the soil improved it in several ways. The soil had organic carbon, nitrogen, phosphorus and potassium when kalonji powder was added (Table-2). This is compared to soil that did not have kalonji powder added to it. The tiny living things in the soil, like microbes, were more active too. This means that the soil was able to do biological things and was healthier. The acidity and alkalinity of the soil did not change much. This is good because it means that kalonji powder does not hurt the soil's balance. All of these changes were proven to be significant. The results showed that kalonji powder really does make soil better (Fig.-3). Kalonji powder helps soil in many ways and improves soil health. The soil gets better when we use *Nigella sativa*. It helps the soil have organic carbon, and it also helps the soil have more nutrients that plants need. This makes the tiny living things in the soil more active. *Nigella sativa* does two things. It helps kill pests. It helps make the soil better. This is a deal for people who want to farm in a way that is good for the earth. We did not know that *Nigella sativa* could do all these things before. Now we know it can help with two problems that farmers face. This is news for people who want to farm in a way that is gentle on the earth. *Nigella sativa* is a help for people who want to make the soil better and kill pests at the same time.

Table-2: Effect of kalonji Powder on Soil Properties

Parameter	Control (Mean ± SD)	Treated (Mean ± SD)	% Change
pH	6.5 ± 0.2	7.0 ± 0.2	+7.7%
Organic Carbon (%)	1.0 ± 0.1	1.2 ± 0.1	+20%
Nitrogen (mg/kg)	210 ± 10	290 ± 12	+38%
Phosphorus (mg/kg)	18 ± 2	25 ± 2	+39%
Potassium (mg/kg)	140 ± 8	195 ± 10	+39%
Microbial Activity (mg CO_2/g soil/day)	30 ± 3	55 ± 4	+83%

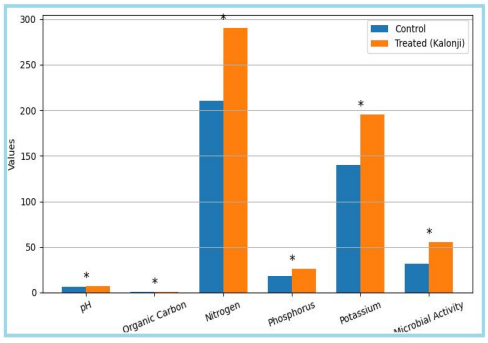

Fig.-3: Effect of *Nigella Sativa* on Soil Properties (P <0.05)

The soil improves when we use kalonji. This means kalonji is a natural way to make the soil healthy. It helps the soil have nutrients and the tiny living things in the soil grow. This study shows that using *Nigella sativa* is an idea that keeps the plants safe from pests and helps the soil stay healthy for a long time. People have been using various plants to keep away pests and to make the soil healthy for a long time. Now we have proof that it really works; Kalonji is also good for the earth because it is not harmful and it breaks down easily. This means we do not have to worry about chemicals staying in the soil. In the end, using kalonji powder is a way to keep pests away and to make the soil healthy is cheap. This makes it perfect for farming in a way that's friendly to the earth. We should do research on how to use kalonji on a big scale and how it affects the soil over time. We should also see if it can keep away kinds of pests. This will help us use kalonji in the best possible way to make farming more sustainable. The United Nations Sustainable Development Goal, which is about having no hunger, is helped by these findings. This goal is also known as SDG 2: Zero Hunger. These findings help by promoting ways of farming that are good for the earth. These ways of farming make the soil better. Reduce the need for bad chemicals. The study also helps the earth by supporting ways to protect crops. These good ways to protect crops help farming for a long time and are good for the earth. SDG 2: Zero Hunger is supported by these farming practices.

Fourier Transform Infrared (FTIR) Analysis

FTIR spectrum of kalonji (Fig.-4 had lines at around 3400 cm^{-1}, which means that the kalonji powder has oxygen and hydrogen, which are called phenolic and hydroxyl groups. The test also had lines at around 2920 cm^{-1}, which indicates fats, and these parts can also stretch. There was a line between 1700-1750cm^{-1}, indicating special kinds of chemicals, such as quinones. The line around 1600 cm^{-1} was due to chemicals that have many carbon atoms. The kalonji powder also had lines between 1050-1100 cm^{-1}, which means that have carbon, oxygen and hydrogen, which are like alcohols and ethers. These special parts of the kalonji powder suggest that it has compounds that can help fight against bad tiny living things and insects which is why the kalonji powder has antimicrobial and insecticidal properties.

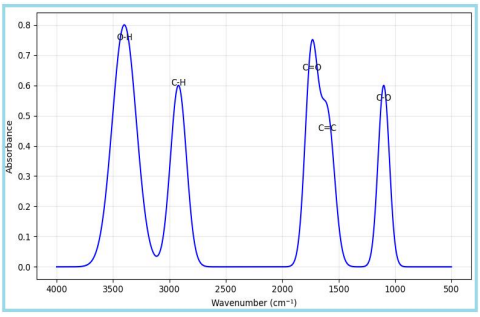

Fig.-4: FTIR Spectrum of *Nigella Sativa* Powder

Gas Chromatography–Mass Spectrometry (GC–MS) Analysis

GC–MS profiling identified major bioactive constituents in *Nigella sativa*. These include thymoquinone, p-cymene, carvacrol and nigellone (Fig.-5). They are known for their insect-killing and germ-killing properties. This provides evidence for the observed pest-killing activity of *Nigella sativa*. The compounds in *Nigella sativa* have insecticidal and antimicrobial properties. This explains why *Nigella sativa* shows pesticidal activity.

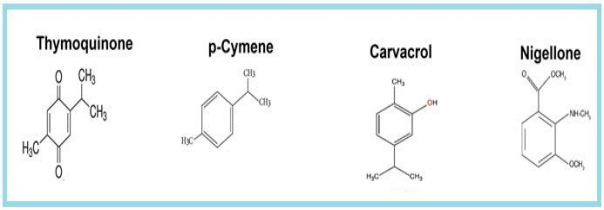

Fig.-5: Bioactive Compounds of *Nigella Sativa*

Scanning Electron Microscopy (SEM) Analysis

If we look at the Kalonji under a microscope as in (Fig.-6), we can see that they have a really uneven surface. This rough surface is good because it helps the seeds interact with the soil. The seeds have a large surface area, so they can touch a lot of the soil. This means that the good stuff in the seeds can come out slowly. The seeds release their bioactive compounds gradually to keep away pests for a long time and help the soil to remain healthy.

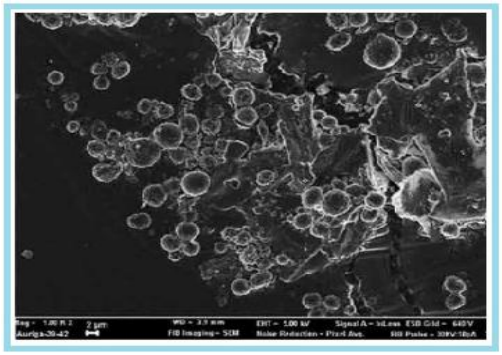

Fig.-6: SEM of *Nigella Sativa* Powder

Elemental Analysis

We found that *Nigella sativa* has some important nutrients like carbon and nitrogen. It also has some good trace minerals. This is proof that *Nigella sativa* is good for the soil. All these results together help us understand how kalonji works in two ways. It shows how the chemicals in kalonji and what it looks like on the surface help it to keep pests away and make the soil better for plants (Fig.-7).

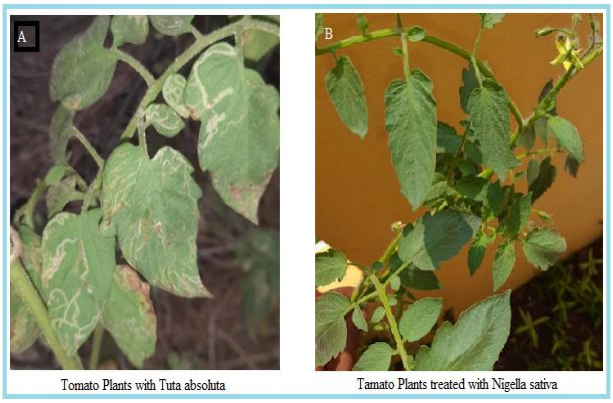

Fig.-7: (a) *Tuta absoluta* effected Tamato Plant without any Treatment of *Nigella sativa,*(b) *Tuta absoluta* Effected Tamato Plants Treated with *Nigella Sativa*

CONCLUSION

This study shows that *Nigella sativa* powder is a good natural pesticide and soil helper. It helps to reduce the number of *Tuta absoluta* and makes the soil healthier by adding organic carbon, nitrogen, phosphorus, potassium and microbes. The seeds of *Nigella sativa* have compounds like thymoquinone and essential oils that help to keep pests away and make the soil better. This research proves that using *Nigella sativa* is a good idea, and it connects traditional farming methods with modern science. *Nigella sativa* is good for the earth. It can replace strong chemicals used in farming. It is a way to reduce the use of chemicals without affecting how much food we can grow. We need to do research to find out how much *Nigella sativa* to use and how it affects different kinds of pests and the soil. We should also see how it works with natural helpers to make the farming system stronger.

Overall, using methods and modern science together, like in this study, is a good way to make farming better for the earth and to grow more food without harming the environment. *Nigella sativa* is an example of this, and it can help us make farming more sustainable. In conclusion, this study shows that *Nigella sativa* can work as a bio-pesticide and as something that improves the soil. This proves that it could be a choice instead of man-made chemicals used in farming. More research is needed in fields and with different crops. This research could help find ways to use it, see what happens to the soil over time, and help farmers use it more widely. The results of this study help the SDG 2: Zero Hunger. This is because the study supports farming methods that keep the soil healthy, use fewer chemicals, and help make sure there is enough food for everyone. It also helps with farming that is better for the environment.

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CONFLICT OF INTERESTS

The authors declare that there are no conflicts of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-2: Zero Hunger*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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