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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Insecticidal efficiency of green-synthesized zinc oxide nanoparticles on bean weevil, *Acanthoscelides obtectus* Say. (Coleoptera: Chrysomelidae)

Yeşil sentez ile üretilen çinko oksit nanopartiküllerinin fasulye tohum böceği, *Acanthoscelides obtectus* Say. (Coleoptera: Chrysomelidae) üzerindeki insektisidal etkinliği

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ABSTRACT

The use of zinc oxide nanoparticles (ZnO-NPs) as a bio-insecticide has gained increasing attention due to their eco-friendly properties and proven efficacy in controlling pest populations. This study comprehensively assessed the insecticidal activity of ZnO-NPs against the bean weevil, *Acanthoscelides obtectus Say.* (Coleoptera: Chrysomelidae) adults, by analyzing mortality rates in a dose-dependent manner under controlled laboratory conditions. ZnO-NPs were synthesized and characterized using Scanning Electron Microscopy (SEM), which confirmed their spherical shape and nanoscale dimensions (~100 nm). Adult mortality was monitored over a 10-day period at doses of 100, 250, 500, 750 and 1000 mg kg^{-1}. The two-way ANOVA results revealed that both dose and exposure duration had significant effects on insect mortality rates. Furthermore, one-way ANOVA showed a significant dose-dependent increase in mortality, with the highest dose (1000 mg kg^{-1}) achieving a corrected mortality rate of 93.3%. These findings underscore the potential of ZnO-NPs as a sustainable alternative to conventional chemical insecticides, particularly for integrated pest management strategies in stored products. Future studies should focus on optimizing control practices in storage facilities and evaluating the long-term effects on non-target organisms and explore various doses and application methods to ensure safe and effective use.

ÖZET

Çinko oksit nanopartiküllerinin (ZnO-NP) biyo-insektisit olarak kullanımı, çevre dostu özellikleri ve zararlı popülasyonlarının mücadelesinde giderek daha fazla ilgi görmektedir. Bu çalışmada, ZnO nanopartiküllerinin fasulye tohum böceği*, Acanthoscelides obtectus Say.* (Coleoptera: Chrysomelidae) erginleri üzerindeki insektisidal aktivitesi, kontrollü laboratuvar koşulları altında farklı dozlarda ölüm oranlarının analiz edilmesi yoluyla kapsamlı bir şekilde değerlendirilmiştir. ZnO nanopartikülleri, Taramalı Elektron Mikroskobu (SEM) kullanılarak sentezlenmiş ve karakterize edilmiş, küresel şekilleri ve nanoskaladaki boyutları (~100 nm) doğrulanmıştır. Ergin ölüm oranı, 100, 250, 500, 750 ve 1000 mg kg^{-1} dozlarında 10 günlük bir süre boyunca izlenmiştir. İki yönlü ANOVA sonuçları, hem dozun hem de maruz kalma süresinin böceklerin ölüm oranı üzerinde anlamlı etkileri olduğunu göstermiştir. Ayrıca, Tek Yönlü ANOVA ile yapılan istatistiksel analiz, ölüm oranlarında doza bağlı olarak anlamlı bir artış olduğunu göstermiş ve en yüksek dozda (1000 mg kg^{-1}), ölüm oranları %93.3'e ulaşmıştır. Bu bulgular, ZnO nanopartiküllerinin özellikle depolanmış ürünlerde entegre zararlı yönetimi stratejileri için insektisitlere sürdürülebilir bir alternatif olarak önemli potansiyelini vurgulamaktadır. Gelecekteki çalışmalar, depolardaki mücadele uygulamalarını optimize etmeye ve hedef dışı organizmalar üzerindeki uzun vadeli etkileri değerlendirmeye ve farklı doz ve uygulama yöntemlerinin güvenli ve etkili kullanımına yönelik araştırmaların yapılmasına odaklanmalıdır.

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INTRODUCTION

Common bean (*Phaseolus vulgaris L.*), belonging to the Fabaceae family, is one of the oldest cultivated legume crops and remains fundamental for millions worldwide due to its highly nutritious seeds (Yeken, 2023; Yilmaz et al., 2023). Renowned for its high fiber, protein, and iron content, dry beans are considered a valuable whole food that significantly contributes to global nutrition (Bouchenak & Lamri-Senhadji, 2013; Kaale et al., 2022). In 2022, global dry bean production exceeded 29.6 million tons, cultivated across approximately 37.5 million hectares (FAO, 2024). In Türkiye, dry bean production surpassed 240.000 tons in 2023, spread over 884.500 decares (TUIK, 2024). Despite advancements in agricultural practices that have improved bean crop yields, significant losses continue to occur during the storage phase (Schoonhoven & Cardona, 1986; Wong-Corral et al., 2013). In many developing regions, on-farm storage systems are widely used to ensure year-round food availability, playing a critical role in household food security (Manandhar et al., 2018; Şener & Kaya, 2022). However, these storage methods are susceptible to post-harvest losses, with estimates indicating up to 15% lost in the field, 13–20% during processing, and 15–25% during storage (Abass et al., 2014). Such losses not only reduce the overall food supply but also compromise its quality, thereby contributing to food insecurity. Insect pests are the leading cause of post-harvest damage in legumes, with reported losses ranging from 30–73% (Mesele et al., 2019; Endshaw & Hiruy, 2020; Chidege et al., 2024).

One of the most notorious pests affecting stored legumes is *Acanthoscelides obtectus Say.* (Coleoptera: Chrysomelidae), commonly known as the bean weevil. This pest poses a significant threat to stored beans globally, particularly due to its destructive feeding behavior within grain warehouses (Şen et al., 2020; Chidege et al., 2024). The bean weevil is widely regarded as the most damaging pest of stored dry beans worldwide, causing extensive damage to grains in storage facilities (Abdel-Baki et al., 2024). Well-adapted to low-humidity environments, the bean weevil primarily infests leguminous grains. Its larvae develop by feeding on the seed cotyledons, burrowing tunnels within the grains that lead to ignificant structural destruction. Moreover, their rapid population growth can result in severe infestations, causing extensive crop damage within just a few months (Abdel-Baki et al., 2024). Eggs are often concealed within stored grains or on fresh green beans in agricultural fields. Adult weevils, which are capable of flying, enter storage facilities to initiate infestations. Their rapid population growth can result in severe infestations, causing extensive crop damage within just a few months (Paul et al., 2009; Jevremović et al., 2019).

The control of *A. obtectus* in storage facilities continues to rely heavily on synthetic insecticides. Chemicals such as phosphine, ethyl formate, sulfuryl fluoride, carbonyl sulfide, organophosphates, and pyrethroids remain the primary methods for managing bean weevil populations (Mohapatra et al., 2015). However, concerns regarding the environmental impact, potential health risks, and the development of insect resistance to these chemical treatments have spurred interest in alternative pest management strategies (Sertkaya et al., 2010; Koca and Yilmaz, 2025). Researchers are increasingly exploring eco-friendly approaches as sustainable alternatives (Regnault-Roger et al., 2012; Sertkaya, 2013; Kaya et al., 2018; Damalas & Koutroubas, 2020).

The pursuit of sustainable agriculture has accelerated in recent years, reflecting a growing global awareness of the necessity to balance food production with environmental preservation and human health protection (Yilmaz and Yilmaz, 2025). In line with these efforts, nanoparticles have emerged as a promising alternative to conventional insecticides, offering eco-friendly and safe strategies for controlling stored grain pests (Subramanyam & Roesli, 2000; Debnath et al., 2011; Raduw & Mohammed, 2020). Over the past decade, their application of nanoparticles in pest management has expanded significantly (Ziaee & Ganji, 2016). Various nanoparticles, including zinc oxide

(ZnO), silicon oxide (SiO2), silver nanoparticles (Ag-NPs), and aluminum oxide (Al2O3), have been commercially developed as effective pest and disease control agents on various crops (Şahin et al., 2021; Şahin et al., 2022; Soylu et al., 2022). Nanoparticles enter insects through physical contact, ingestion, and inhalation. Upon contact, they penetrate the exoskeleton and bind to sulfur-containing proteins or phosphorus in DNA, causing organelles and enzyme denaturation, ultimately leading to cellular disintegration and insect mortality (Abd-Elsalam and Prasad, 2018). Their high surface area-to-volume ratio enables nanoparticles to easily pass through insect cell membranes, causing significant internal damage (Alisha & Thangapandiyan, 2019). Additionally, nanoparticles often disrupt the lipid layer of the insect cuticle, leading to water loss and desiccation, which is a critical mechanism responsible for insect mortality in stored grain pest control (Athanassiou et al., 2018; Anandhi et al., 2020). Beyond physical disruption, nanoparticles exert various physiological and behavioral effects on stored grain insects, including toxic, antifeedant, repellent, and fecundity-reducing properties (Owolade et al., 2008). Most nanoparticles exhibit low toxicity to mammals while demonsrating high efficacy against a broad spectrum of insect pests, particularly those affecting stored products (Resham et al., 2015; Kitherian, 2017). Various nanoparticle formulations have been commercially developed and registered globally, allowing direct application to commodities (Mandal, 2019). Importantly, these nanoparticles do not adversely affect the milling, malting, or baking qualities of treated grains, and they can be easily removed through processes such as sieving, brushing, or washing (Korunic et al., 1996).

The insecticidal potential of nanoparticles against stored grain pests has been extensively studied worldwide. Studies have shown that silicon oxide nanoparticles (SNPs) and nanostructured alumina exhibit high toxicity against *Sitophilus oryzae L.* (Coleoptera: Curculionidae) and *Rhyzopertha dominica F.* (Coleoptera: Bostrichidae) (Debnath et al., 2011; Stadler et al., 2012). Similarly, SNPs and zinc oxide nanoparticles (ZnO-NPs) have proven highly effective against both larvae and adults of *Sitophilus granarius L.* (Coleoptera: Curculionidae), achieving up to 100% mortality within two weeks of application (Rouhani et al., 2019). Further research has shown ZnO-NPs causing mortality rates of 88.3%, 100%, and 38.3% against *Callosobruchus maculatus F.* (Coleoptera: Chrysomelidae), S. oryzae, and *Tribolium castaneum Herbst.* (Coleoptera: Tenebrionidae), respectively (Haroun et al., 2020). More recently, SNPs, aluminum oxide nanoparticles (ANPs), and ZnO-NPs have also demonstrated significant efficacy against *Trogoderma granarium Everts* (Coleoptera: Dermestidae) in barley and wheat (Raduw and Mohammed, 2020).

This study aimed to evaluate the insecticidal efficacy of ZnO-NPs against adult A. obtectus, with the objective of contributing to the development of alternative, environmentally friendly pest management strategies. By investigating the potential of ZnO-NPs as a control agent, present research seeks to reduce reliance on chemical pesticides and provide sustainable solutions for protecting stored grains from infestation. The findings could offer valuable insights into nanoparticle-based pest control methods and have broader implications for integrated pest management in agricultural systems.

MATERIALS and METHODS

Insect rearing

The initial population of A. obtectus was sourced from small bean-producing farms in Bolu province, Türkiye. To establish laboratory colonies, adults were collected from naturally infested dry beans (Göynük-98 variety) and transferred into 1 L glass jars for egg-laying. Following egg-laying, the emerging colonies were transferred to 3 L glass jars containing dry beans as a food source. The jars were covered with fine mesh to allow ventilation. The colonies were maintained in a controlled environmental chamber at 25 ± 1 °C and 50-60% relative humidity under total darkness. To prevent contamination by other insects, the sterilized bean grains were conserved at 4 °C for approximately one week before use (Hashem et al., 2022). This sterilization process was critical in ensuring that the rearing conditions remained free from external biotic interference, allowing for a more controlled assessment of A. obtectus biology and behavior.

Green biosynthesis of ZnO nanoparticles

The biological synthesis of zinc oxide (ZnO) nanoparticles using sage (*Salvia officinalis L.*) leaves was conducted following the method described by Abomuti et al. (2021). To prepare the aqueous extract, 5.0 g of ground dried sage leaves were placed in a 250 mL beaker containing 200 mL of distilled water. The mixture was heated to 60 °C on a magnetic stirrer for approximately 2 hours. After heating, it was sealed in an airtight container and left to sit overnight. The mixture was then filtered using Whatman No. 1 filter paper and stored in a refrigerator until further analysis.

In a separate step, 100 mL of 0.2 M $Zn(NO_3)_2$ was added to a 500 mL beaker and stirred at 50 °C for 10 minutes. Then, 100 mL of the preheated aqueous sage extract was gradually added to the zinc nitrate solution while maintaining the temperature. The reaction mixture was continuously stirred for 2 hours to promote the electrostatic interaction between Zn^{2+} ions and the biomolecules present in the leaf extract. This interaction facilitated the nucleation of ZnO nanoparticles, as indicated by a color change of the solution to light yellow, marking the onset of nanoparticle formation.

As the nucleation process progressed, phytochemical constituents in the extract acted as stabilizing agents, allowing the system to reach equilibrium at a low pH (2.0). The pH of the reaction mixture was then gradually adjusted to 12.0 by dropwise addition of freshly prepared 2.0 M NaOH under continuous stirring. During the synthesis at 50°C, the solution gradually developed a pale-yellow precipitate, indicating the successful synthesis of ZnO nanoparticles. The reaction mixture was then centrifuged at 10.000 rpm for 20 minutes to collect the precipitate. The collected material was thoroughly washed several times with ethanol and distilled water to remove any residual impurities or unreacted substances. The purified precipitate was then dried in an oven at 80 °C for 24 hours to ensure complete dehydration. Finally, the dried material was finely ground using a porcelain mortar and stored for further applications.

Bioassay

The efficacy of ZnO-NPs against 24 to 48-hour-old adults of the bean weevil, A. obtectus, was evaluated using a contact toxicity assay at doses of 100, 250, 500, 750, and 1000 mg kg^{-1} ZnO-NPs. Sterilized bean grains were mixed with the appropriate amount of ZnO-NPs in 500 ml plastic jars, which were then shaken for 15 minutes to ensure even distribution. To standardize the age of A. obtectus, adult males and females (five individuals per jar) were transferred from a stock culture into small plastic jars and allowed to lay eggs for three days. After this period, the adults were removed and the eggs were left to develop. For each ZnO-NP treatment, 10 male and female adult weevils were placed in small plastic screw-capped jars containing 5 g of ZnO-NP-treated bean grains. Five replicates were conducted for each nanoparticle dose. Additionally, five replicates with untreated seeds and 10 adults served as the control. The jars were covered with muslin cloth and maintained at 30 ± 1°C and 60 ± 5% RH, under continuous darkness. Insect mortality was recorded on days 1, 3, 5, 7, and 10 after ZnO-NP treatment. Insects were considered dead if no leg or antennal movement was detected upon prodding with an entomological pin. The bioassay methodology was adapted from the studies by Haroun et al. (2020) and Raduw and Mohammed (2020) with some modifications.

Statistical analysis

All experiments were conducted using a completely randomized design with five replicates for each treatment. Mortality (%) was corrected for natural mortality in the control group using Abbott's formula (Abbott, 1925). The cumulative mortality data collected at different time intervals (1, 3, 5, 7, and 10 days) were subjected to arcsine square root transformation to normalize the data. In the first step, a Two-Way ANOVA was performed on the raw cumulative mortality rates to assess the combined effects of both exposure time (days) and ZnO-NP doses on A. obtectus mortality. This analysis evaluated the interaction between different doses and time intervals. In the second step, after applying Abbott’s correction, a separate One-Way ANOVA was conducted using only the mortality data from the final day (10th day) to assess the dose-dependent insecticidal efficiency. Means were compared using Tukey’s Honestly Significant Difference (HSD) test at a 5% significance level ($P < 0.05$). All statistical analyses were performed using SPSS for Windows (SPSS Inc., Illinois, USA).

RESULTS and DISCUSSIONS

Structural characterization of ZnO nanoparticles via scanning electron microscopy

The morphological characterization of ZnO nanoparticles (ZnO-NPs) was performed using Scanning Electron Microscopy (SEM), as shown in Figure 1. The SEM image reveals that the ZnO nanoparticles predominantly exhibit a spherical shape with some degree of agglomeration. The particles appear to be relatively uniform in size, with an average diameter estimated to be approximately 50-80 nm, based on 100 nm scale bar. The high magnification and detailed resolution provided by the SEM analysis confirms that the ZnO-NPs possess nanoscale dimensions, which are critical for their biological activity. The observed agglomeration is likely due to the high surface energy of nanoparticles, which promotes clustering. However, the clusters remain relatively small, ensuring adequate surface area exposure, which enhances their insecticidal activity.

The spherical morphology and nanoscale size of the particles are particularly advantageous for their application as insecticides. The nanoscale dimensions of ZnO nanoparticles enhances surface contact with the insect cuticle, potentially modifying its properties (Rebora, 2023) and facilitating deeper penetration (Meng, 2023). This increased interaction promotes the generation of reactive oxygen species (ROS), leading to oxidative stress, cellular damage, and ultimately, insect mortality (Khooshe-Bast et al., 2016). Additionally, the consistent size distribution of the nanoparticles ensures reproducibility in their insecticidal efficacy.

Overall, the characterization results confirm that the ZnO nanoparticles synthesized in the current study are well-suited for pest control applications, due to their nanoscale size, spherical morphology, and relatively uniform distribution. The nanoscale dimensions and spherical morphology of ZnO nanoparticles likely enhance their insecticidal efficiency by increasing surface contact with the insect cuticle, facilitating better penetration and the generation of reactive oxygen species (ROS). These properties are likely key contributors to the observed mortality rates of *A. obtectus* under different nanoparticle concentrations.

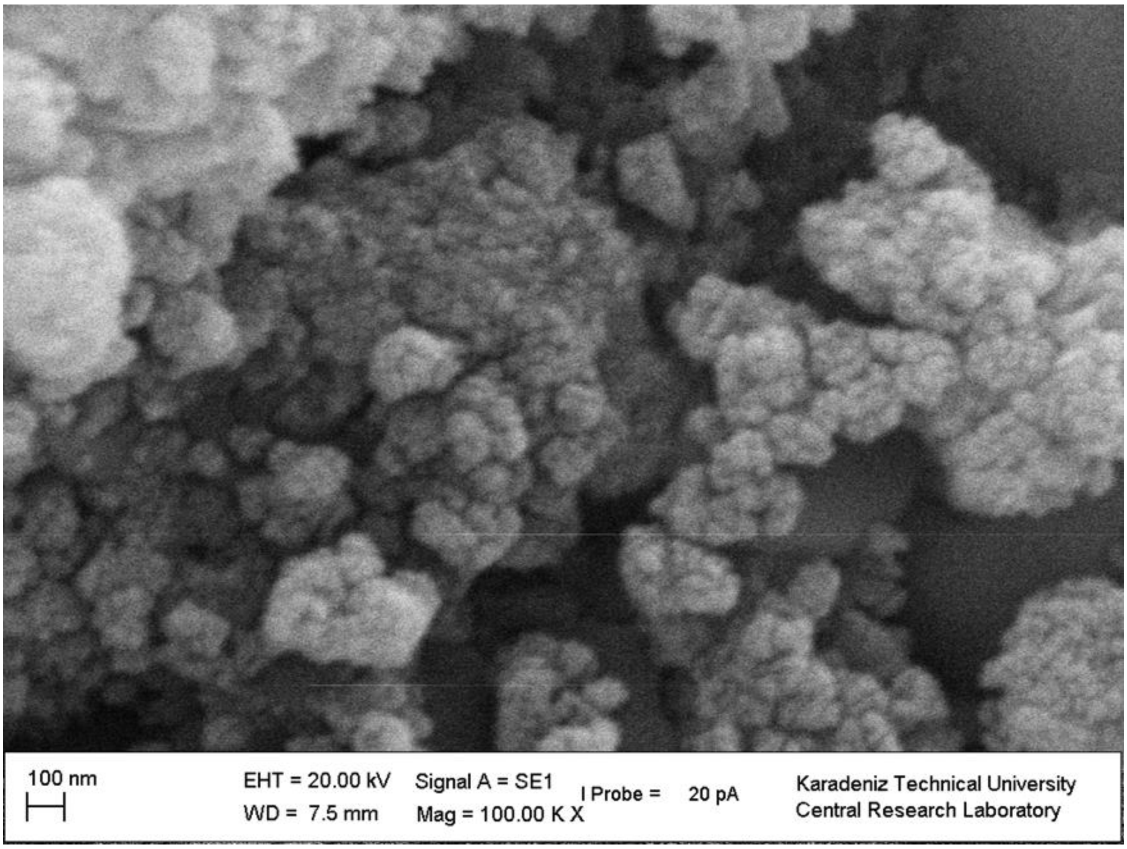

Figure 1. Scanning Electron Microscope (SEM) image of synthesized ZnO nanoparticles
Şekil 1. Sentezlenen ZnO nanopartiküllerinin Taramalı Elektron Mikroskobu görüntüsü

The elemental composition of the green-synthesized ZnO nanoparticles was analyzed using Energy Dispersive X-ray Spectroscopy (EDS), as shown in Figure 2. The results revealed substantial amounts of zinc (Zn), oxygen (O), and nitrogen (N), with weight percentages of 61.30%, 27.14%, and 11.56%, respectively. The high proportion of zinc indicates that the nanoparticles synthesized through the green approach predominantly consist of ZnO, confirming the successful formation of zinc oxide structures. The oxygen content (27.14%) further supports the establishment of ZnO crystals, reflecting efficient bonding between zinc and oxygen atoms during the synthesis process. These results align with previous studies that have demonstrated the effective formation of ZnO using plant-based extracts (Abomuti et al., 2021; Abd El-Latef et al., 2023). The detection of nitrogen at 11.56% is attributed to the $Zn(NO_3)_2$ solution used during the synthesis of nano iron from sage extract. These nitrogen-containing compounds could enhance the stability of the nanoparticles, potentially increasing their insecticidal activity by providing a protective organic layer on the nanoparticle surface.

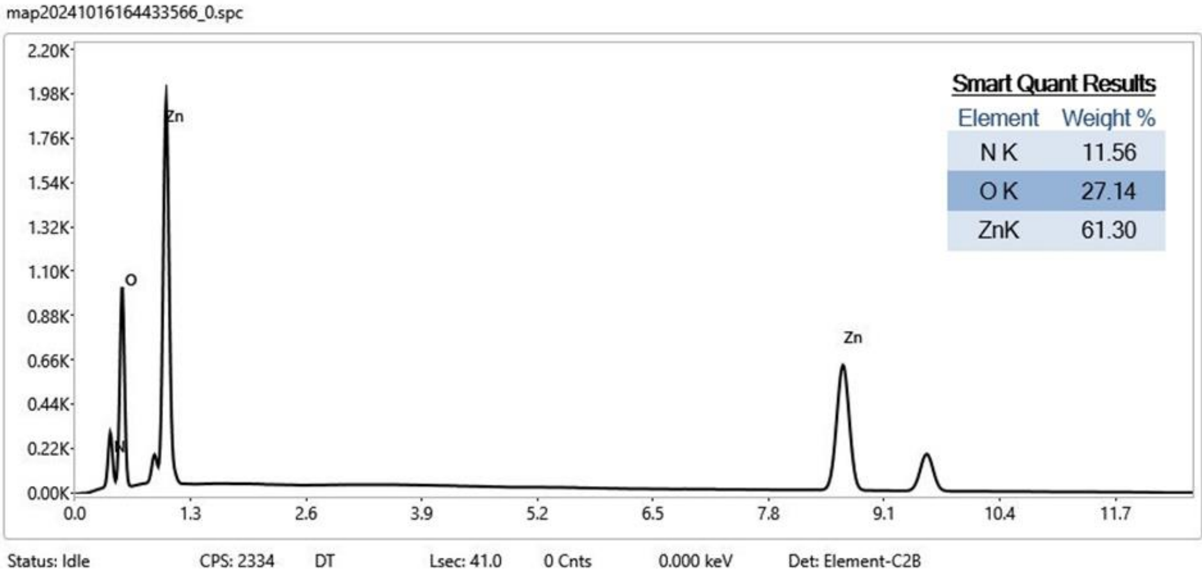

Figure 2. Elemental composition analysis of sage-synthesized ZnO nanoparticles using Energy Dispersive X-ray Spectroscopy (EDS)

Şekil 2. Enerji Dağıtıcı X-ışını Spektroskopisi kullanılarak adaçayından sentezlenen ZnO nanopartiküllerinin element bileşim analizi

Effects of ZnO nanoparticle on bean weevil mortality

The impact of ZnO nanoparticles on the mortality of bean weevil, *A. obtectus*, was statistically analyzed using Two-Way ANOVA and the results are summarized in Table 1. The analysis revealed that both exposure time (days) and dose (ZnO-NP doses) had statistically significant effects on bean weevil mortality rates ($P < 0.0001$). Additionally, a significant interaction between exposure time and doses ($P < 0.0001$) was detected, suggesting that the effectiveness of ZnO-NPs varied across different time points (Table 1). This interaction indicates that mortality rates were influenced by the combined effects of exposure time and nanoparticle concentration, emphasizing the time-dependent and dose-dependent nature of ZnO-NPs' insecticidal activity.

The factor with exposure time demonstrated the most pronounced effect on mortality rates of the weevils, as evidenced by the statistical analysis ($F5, 120 = 290.172$, $P < 0.0001$). Mortality percentages increased progressively with increasing exposure times, highlighting the cumulative effect of ZnO-NPs. This result aligns with previous findings, which reported that prolonged exposure to nanoparticles enhances insecticidal efficacy due to increased contact time and accumulation effects (Ziaee & Ganji, 2016; Ahmad et al., 2022). The effective penetration of ZnO-NPs through the insect cuticle and the subsequent increase in mortality rates are attributed to sufficient exposure time. This mechanism is supported by their hydrophobic adhesion properties of ZnO-NPs (Read et al., 2020) and the role of particle size on penetration efficiency (Ibrahim et al., 2022). Therefore, increasing exposure time enhances nanoparticle toxicity, leading to higher mortality rates.

The dose factor significantly influenced the mortality of *A. obtectus*, with higher doses of ZnO-NPs resulting in increased mortality rates. The post-hoc analysis (Tukey HSD test) indicated significant differences among applications, with the highest doses leading to the most pronounced mortality rates by the end of the 10-day period. These findings are consistent with previous studies, which demonstrated that higher doses of nanoparticles induce severe oxidative damage to insect cells, leading to protein denaturation and lipid peroxidation (Pauksch et al., 2014; Chinnathambi et al., 2020; Dubey et al., 2015).

The interaction between the exposure time and doses was significant, indicating mortality effects of ZnO-NPs varied with dose and exposure time. Higher doses proved increasingly effective with extended exposure, resulting in significantly higher mortality rates. These findings confirm that the insecticidal efficacy of ZnO-NPs depends on the combined influence of dose and exposure time, aligning with previous studies on the cumulative effects of prolonged treatment (Salem et al., 2015; Haroun et al., 2020; El-Bakry et al., 2025). Both factors are critical for achieving effective control of the bean weevil. Optimizing these parameters can substantially enhance the insecticidal efficiency of ZnO nanoparticles.

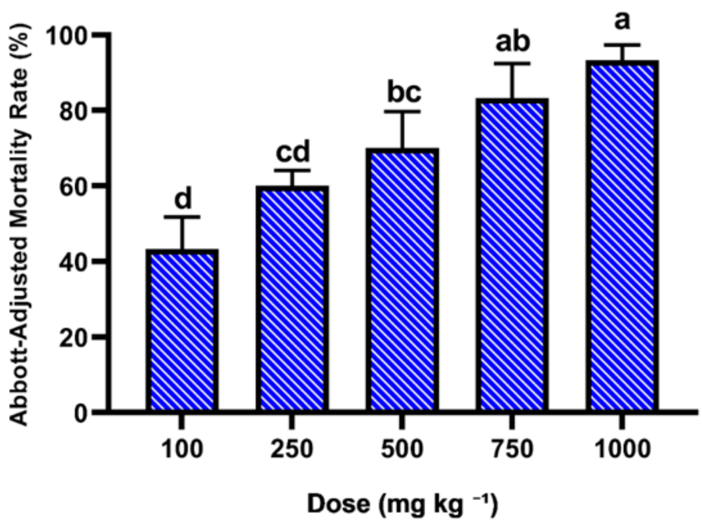

Figure 3. Corrected mortality rates of Acanthoscelides obtectus treated with different ZnO nanoparticle doses. (Different letters on the columns indicate significant differences according to the Tukey test ($p \leq 0.05$))

Şekil 3. Farklı ZnO nanopartikül dozlarıyla muamele edilen Acanthoscelides obtectus'un düzeltilmiş ölüm oranları. (Sütunların üzerindeki farklı harfler Tukey testine göre anlamlı farklılıkları göstermektedir ($p \leq 0.05$))

The high efficacy of ZnO-NPs at a dose of 1000 mg kg^{-1} observed in the present study underscores the potential as effective bio-insecticides against A. obtectus. While the production of reactive oxygen species (ROS) was not directly assessed in this experiment, existing literature emphasizes the critical role of ROS in enhancing the insecticidal activity of ZnO-NPs. For instance, Eskin and Nurullahoğlu (2022) reported that ZnO-NPs caused significant reductions in pupal weights and adult emergence rates in *Galleria mellonella L*. (Lepidoptera: Pyralidae) likely due to oxidative stress. Similarly, ZnO-NPs have been shown to disrupt cellular integrity by generating ROS, leading to apoptosis in insect cells (Mao et al., 2018). Furthermore, recent advancements in nanoparticle research indicate that doping ZnO-NPs with metals such as copper can further enhance insecticidal efficiency, achieving up to 95% pest mortality (Abd El-Latef et al., 2023). In contrast, the present study demonstrated that undoped ZnO-NPs alone achieved a corrected mortality rate of 93.3%, confirming their effectiveness as potent agents for pest control in stored grains, without additional modifications. Emerging research highlights the potential to further improve the efficacy of ZnO-NPs. For instance, combining ZnO-NPs with natural essential oils, such as those extracted from C*itrus sinensis* (L.), can significantly improve mortality rates even at lower nanoparticle doses. This synergistic effect is attributed to mechanisms including oxidative stress and enzymatic inhibition, which collectively increased insecticidal efficacy (El-Bakry et al., 2025). Although the integration of essential oils was beyond the scope of the present study, these results suggest a potential pathway for future research to optimize nanoparticle formulations, potentially reducing required doses and minimizing ecological damage. The use of plant extracts in nanoparticle synthesis aligns with the increasing demand for sustainable pest control solutions. Biogenic zinc oxide nanoparticles (ZnO-NPs) synthesized from plant sources, such as river oak, demonsrated significant larvicidal activity, with mortality rates reaching up to 61.8% against *Tenebrio molitor L.* (Coleoptera: Tenebrionidae) larvae, offering environmentally friendly alternative to chemically synthesized nanoparticles (Omar & Ali, 2024).

Benelli et al. (2017) emphasized the advantages of green-synthesized nanoparticles in minimizing the use of toxic chemicals while enhancing bioactivity. Their research demonstrated the superior surface reactivity of biogenic nanoparticles, which is attributed to their smaller and more uniform size distribution, leading to enhanced insecticidal efficacy. Notably, over 100 studies have validated the effectiveness of plant-derived nanoparticles, particularly in controlling mosquito vectors. Our findings with sage-synthesized ZnO-NPs are consistent with these observations, demonstrating significant insecticidal effects, especially at higher doses. These results highlight the potential of biogenic nanoparticles as a valuable tool in pest management strategies. Furthermore, the ability of green-synthesized ZnO-NPs to degrade more readily in the environment reduces potential risks to non-target organisms, making them particularly suitable for integrated pest management systems. This eco-friendly degradation profile offers a sustainable alternative to synthetic pesticides while minimizing ecological damage (Benelli et al., 2017).

The findings of the current study indicate that ZnO-NPs hold significant potential for integration into pest management strategies targeting stored grain pests such as A. obtectus. Using ZnO-NPs as an alternative to synthetic chemical insecticides presents a promising and environmentally friendly solution, particularly in response to increasing concerns over pesticide resistance and environmental pollution (Raduw & Mohammed, 2020; Benelli et al., 2017; Pittarate et al., 2021). Nevertheless, the ecotoxicological effects of ZnO-NPs, particularly at higher doses, need further investigation to ensure their safe application in agricultural systems. As Benelli (2018) highlighted, nanoparticles may have unintended effects on non-target organisms and the environment, emphasizing the need for comprehensive risk assessments before large-scale implementation. Overall, the current study revealed the significant insecticidal activity of ZnO-NPs against A. obtectus, with a clear dose-response relationship. The highest efficacy was observed at dose of 750 mg kg-1 and above, indicating that ZnO-NPs can serve as an effective alternative to conventional pesticides. Future research should focus on optimizing nanoparticle formulations and exploring green synthesis methods to mitigate potential ecological risks while maximizing pest control efficacy.

In conclusion, this study revealed the significant insecticidal potential of ZnO nanoparticles against *A. obtectus*, a major pest in stored legume. The dose-dependent increase in mortality, particularly at higher doses such as 750 and 1000 mg kg^{-1}, confirms the effectiveness of ZnO-NPs in controlling bean weevil populations. Corrected mortality rates, reached a peak of 93.3% at the highest dose, highlighting the capability of ZnO-NPs to deliver effective pest control under controlled conditions. Our findings further indicate that the insecticidal activity of ZnO-NPs is influenced by both dose and exposure time, with prolonged exposure times significantly enhancing mortality rates. Additionally, the use of green synthesis methods with sage extracts further contributed to the environmental sustainability of the nanoparticles, positioning them as a viable alternative to conventional chemical insecticides. Elemental composition analysis confirmed the high purity of the green-synthesized ZnO-NPs, which likely enhances their bioactivity and insecticidal efficacy by minimizing impurities.

Although these results are promising, further studies are necessary to assess the long-term impacts of ZnO-NPs on non-target organisms and to confirm their suitability for use in storage environments. Optimizing synthesis processes and exploring different formulations could enhance their efficacy, paving the way for more sustainable and eco-friendly pest management solutions. Additionally, refining green synthesis techniques to improve nanoparticle stability while minimizing ecological risks could significantly advance the development of effective pest control strategies. Such improvements would be particularly valuable for protecting stored grains, promoting food security, and supporting environmental sustainability.

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STATEMENT OF CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

AUTHOR'S CONTRIBUTIONS

The authors declare that they have contributed equally to this study.

STATEMENT OF ETHICS CONSENT

Ethical approval is not applicable, because this article does not contain any studies with human or animal subjects.

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