Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi
Afyon Kocatepe University – Journal of Science and Engineering
https://dergipark.org.tr/tr/pub/akufemubid

Araştırma Makalesi / Research Article
e-ISSN: 2149-3367 DOI: https://doi.org/10.35414/akufemubid.1844616
CITE: Afyon Kocatepe University Journal of Science and Engineering. 26(4) (2026) 887-896

Green Synthesis of Ag Nanoparticles in *Thymus* Extract and Use in Reduction of Organic Dyes

*Makale Bilgisi / Article Info
Alındı/Received: 24.12.2025
Kabul/Accepted: 07.05.2026
Yayımlandı/Published: : 03.08.2026

Thymus Özütünde Ag Nanoparçacıkların Yeşil Sentezi ve Organik Boyaların İndirgenmesinde Kullanımı

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Abstract

Catalysis is the most effective method for removing pollution in water resources caused by chemically stable aromatic organic dyes widely used in industrial processes. The use of catalysts that can be prepared by low-costing and simple methods using recyclable natural materials or wastes is important for sustainability. In the presented study, *Thymus* (thyme) plant aqueous extract was used directly for the stabilization of Ag^+ ions without the need for adsorption on any inorganic support material, and then Ag^0 nanoparticles were obtained by bioreduction with the natural components contained in the plant extract. The use of *Thymus* extract stabilized Ag^0 nanoparticles, prepared economically and practically by the green method, as catalysts in the reduction of 4-NP dye substrate was investigated. It was observed that the Thymus extract stabilized Ag^0 nanoparticle catalyst, which is a particularly ecologically friendly substitute due to its low metal content, catalyzed the reduction reaction of 4-NP substrate with 98% conversion in 5 minutes. The catalytic efficiency of Thymus extract stabilized Ag^0 nanoparticles on 4-NP, RhB and MB multi-dye mixture was also investigated and it was observed that they successfully catalyzed without any competition/selectivity.

Keywords: *Thymus plant; Green synthesis; Ag nanoparticles; Catalysis;4-Nitrophenol.*

Öz

Endüstriyel proseslerde yaygın kullanılan kimyasal kararlı aromatik organik boyaların su kaynaklarında yarattığı kirliliğin giderilmesinde kataliz en etkili yöntemdir. Geri dönüştürülebilir doğal materyaller ya da atıklar kullanılarak düşük maliyetli ve basit yöntemlerle hazırlanabilen katalizörlerin kullanımı sürdürülebilirlik açısından önem arz etmektedir. Sunulan çalışmada; anorganik bir destek malzemesine adsorpsiyona ihtiyaç duyulmaksızın *Thymus* (kekik) bitkisi sulu özütü doğrudan Ag^+ iyonlarının stabilizasyonunda kullanılmış, ardından yine bitki özütünde bulunan doğal bileşenler sayesinde biyoindirgeme ile Ag^0 nanoparçacıkları elde edilmiştir. Yeşil yöntemle ucuz ve pratik şekilde hazırlanan *Thymus* özütü stabilize Ag^0 nanoparçacıkların 4-NP boya substratının indirgenmesinde katalizör olarak kullanımı incelenmiştir. Düşük metal içeriği ile de oldukça çevreci bir alternatif olan *Thymus* özütü stabilize Ag^0 nanoparçacık katalizörünün 4-NP substratı indirgenme reaksiyonunu 5 dakikada 98% dönüşümle katalizlediği gözlenmiştir. *Thymus* özütü stabilize Ag^0 nanoparçacıkların 4-NP, RhB ve MB çoklu boya karışımındaki katalitik etkinliği de incelenmiş ve yarışma/seçicilik olmaksızın başarılı şekilde katalizlediği gözlenmiştir.

Anahtar Kelimeler: *Thymus bitkisi; Yeşil sentez; Ag nanoparçacık; Kataliz; 4-Nitrofenol.*

1. Introduction

Even low concentrations of aromatic dyes, which are extensively used in industries such as textiles, leather, paper, plastics, pharmaceuticals, and packaging, pose a serious threat to aquatic environments by significantly deteriorating water quality (Alouani et al. 2018, Rafatullah et al. 2010, Mokhtar 2017, Singh et al. 2019). These dyes typically consist of complex aromatic structures containing functional groups responsible for coloration (chromophore) and auxochrome groups that enhance water solubility (Chacko and Kalidass 2011, Pan et al. 2017, Salleh et al. 2011). Their complex structure and high chemical stability make the degradation process difficult by simple methods. Various physicochemical and biological techniques, including membrane filtration, ion exchange, ultrafiltration, electrochemical treatment, and photocatalytic degradation, have been widely applied for dye removal. However, these methods often suffer from limitations such as high operational cost, low efficiency, and the generation of secondary pollutants [Alouani et al. 2018, Mokhtar 2017, Belarbi and Hadjel 2015, Veerakumar etal. 2018, Robinson et al. 2001). Adsorption-based approaches using materials such as nanoclays (Mokhtar 2017), alumina nanoparticles (Thabet and Ismaiel 2016), zeolites (Belarbi and Hadjel 2015), and graphene-based composites (Oppong et al. 2018, Bomila et al. 2018) have also been extensively investigated due to their simplicity. Nevertheless, adsorption processes are generally limited by low selectivity and the need for regeneration of the adsorbent. To overcome these limitations, catalytic systems based on metal nanoparticles (NPs) have attracted considerable attention

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due to their high surface area and excellent catalytic activity. According to this approach, attaching metal NPs to a support material such as metal oxides (SiO_2, Al_2O_3, TiO_2), carbon-based porous materials (C-nanotube, graphene, C-black), or to a synthetic/natural polymeric support is a general practice (Thabet and Ismaiel 2016, Oppong et al. 2018, Sahiner et al. 2015, Hussain et al. 2023, Arif 2023, Ali et al. 2023). Thus, the difficulties in separating, purifying and recycling the metal catalyst from the reaction media are exceeded and their separation by simple methods such as filtration and extraction becomes possible (Ayala et al. 2004).

In particular, the catalytic reduction of 4-nitrophenol (4-NP) reduction has been widely employed as a model reaction to evaluate catalytic performance. In most reported systems, however, the reduction process requires the presence of strong chemical reducing agents such as $NaBH_4$, while metal NPs act primarily as electron transfer mediators. This approach reduces the sustainability of the process and limits its applicability within the framework of green chemistry although it is effective. The general method for preparing metal NPs is to stabilizing metal ions using support material (oxide, porous carbon material, synthetic and natural polymers) and then reducing the metal ions using a metal hydride such as $NaBH_4$. As an alternative to this method, which requires a variety of support materials, numerous chemical reactions and additional purification processes, it was aimed to use *Thymus* plant aqueous extract in the preparation of Ag NPs by green synthesis method. In recent years, plant-mediated green synthesis of metal NPs has emerged as an environmentally friendly alternative to conventional chemical methods. Plant extracts contain various bioactive compounds such as phenolics, flavonoids, and terpenoids, which can act as both reducing and stabilizing agents during NPs synthesis. However, in most studies, the role of plant extracts is limited to NP preparation, and the catalytic reactions still rely on external reducing agents. Therefore, the development of a fully integrated system in which plant extracts actively participate not only in NP synthesis but also in the catalytic reduction process remains insufficiently explored.

The *Thymus* plant, a member of the *Lamiaceae* family, is rich in bioactive compounds such as thymol, carvacrol, flavonoids, and phenolic acids, which exhibit strong antioxidant and redox properties (Figure 1). Depending on the type of *thyme*, linalool and *p*-cymene terpenes, flavonoids such as caffeic acid, rosmaric acid, hispidulin, apigenin and phenolic acids are antioxidants found in abundance in the thyme plant (Okut 2018, Nikolic et al. 2014, D'Antuono et al. 2000, Azizi et al. 2009, Azizi et al. 2009, Zheng and Wang 2001, Basyigit et al. 2017). These phytochemicals can interact with metal ions through functional groups and create a non-dense network-like structure by forming intermolecular H-bonds in the aqueous media, thereby enabling the formation and stabilization of metal nanoparticles without the need for additional support materials.

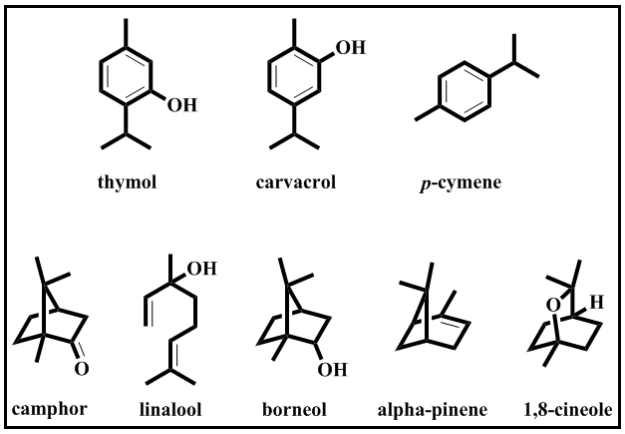


Figure 1. Major monoterpene derivatives and monoterpene phenols in *Thymus* plant.

In this study, Ag^0 NPs were synthesized using aqueous *Thymus* extract via a green approach, without employing any external reducing agent such as $NaBH_4$. The catalytic efficeincy of *Thymus* extract–stabilized Ag^0 NPs in organic dye reduction was studied. Unlike conventional heterogeneous catalytic systems, reduced Ag^0 NPs were added to the reaction medium as a suspension in *Thymus* extract, thus aiming to benefit from the synergistic activity of the extract and NPs together. This approach allows the simultaneous contribution of both Ag^0 NPs and plant-derived biomolecules to the reduction process, thereby exploiting their synergistic effects. The catalytic performance of the biosynthesized Ag^0 NPs system was investigated for the reduction of 4-nitrophenol, demonstrating a simplified, sustainable, and integrated strategy for pollutant removal. In the studies conducted on concerning the preparation of Ag^0 NPs in *Thymus* extract, the parameters affecting NP formation (such as extract concentration, Ag^+ ion source concentration, and temperature) and bioactivity studies were reported. (Alamdari et al. 2025 and Alkherreaz et al. 2026). Also the recent studies on the catalytic reduction of organic dyes using green synthesized Ag NPs obtained from various plant extracts reported in the literature rely on the use of $NaBH_4$ reducing metal hydride to achieve catalytic performance (Raj et al. 2020, Riaz et al. 2020, Selveraj et al. 2025, Sudhokar et al. 2025). So the catalytic process is based on the premise that the metal hydride acts as an electron donor, while the NPs enable the electron

transfer. In the presented study, Ag NPs suspended in *Thymus* extract were used directly in the reaction medium without the need for any reducing agent. Thus, it demonstrates a fundamentally different catalytic pathway in which the phytochemical components of *Thymus* extract contribute to the electron transfer process and catalytic stabilization. Consequently, a practical and sustainable catalyst system has been obtained that eliminates dependence on chemical reducers, is directly applicable, and simplifies the overall catalytic process.

2. Materials and Methods

The *Thymus* leaves were obtained from a herbalist. Then repeatedly cleaned with water to get rid of the dust and contaminants, dried at room temperature and used in extract preparation after grounded. Silver nitrate ($AgNO_3$, 99%, Merck) used as Ag metal source for Ag^0 NPs synthesis. 4-Nitrophenol (4-NP, 99%), rhodamine B (RhB, 99%) and methylene blue (MB, 98%) as aromatic dye sources for catalytic studies were purchased from Sigma Aldrich. Deionized water was used for all experimental solutions and the analytical-grade chemicals were employed without any purification.

FT-IR / ATR spectrometer (Perkin Elmer Spectrum One) and X-Ray diffractometer (PANalytical Empyrean) were used in the characterization of *Thymus* extract stabilized Ag^0 NPs catalyst. JEOL JEM-1400 PLUS transmission electron microscope was used for the morphological characterization of Ag^0 NPs. Catalytic reduction reaction for 4-NP, RhB and MB dye substrates were monitored by UV-Vis spectrophotometer (Perkin Elmer Lambda 35).

2.1 Preparation of Thymus aqueous extract

Thymus aqueous extract was prepared by boiling dried plant material (10 g) in distilled water (500 mL) in a conical flask at 70-80 °C and 1000 rpm stirring speed for 1 hour. This was intended to allow the active metabolites in *Thymus* plant to pass into the aqueous solution. The resulting aqueous extract was cooled to room temerature and filtered out and kept in a refrigerator at +4 °C for freshly use in Ag nanoparticles manifacturing (Masooleh et al. 2019, Rolim et al. 2019, Gottimukkala)

2.2 Green synthesis of Ag^0 NPs in Thymus aqueous extract

Ag^0 NPs were synthesized via green and environmentally method using aqueous extract of *Thymus* as both reducing and stabilizing agent. $AgNO_3$ was used as the Ag metal precursor. For NP synthesis, a rection mixture containing 70% (v/v) $AgNO_3$ solution (0.1 M) and 30% (v/v) *Thymus* extract was prepared. The mixture was stirred continuously at 1000 rpm and maintained at 70°C. During the Ag^0 NPs preparation process, a significant part of the Ag^+ ions are oxidized to form Ag_2O, thus reducing the NP yield. To prevent this, the reduction process was carried out in a dark environment.

The progress of the reaction was monitored visually thyough the color change from yellow-orange to dark Brown, indicating the formation of Ag^0 NPs due to the bioreduction of Ag^+ ions. To ensure complete reduction, the reaction was continued for an additional 30-60 minutes after the initial color change. The resulting colloidal solution was then cooled to room temperature. Then filtered off, wash with water several times, centrifugated, dried and kept for characterization studies. Thus the stability of the NPs was attributed to the capping effect of phytochemicals present in the *Thymus* extract (Figure 2). Finally, the NP suspension was stored at +4 °C for further catalytic applications (Masooleh et al. 2019).

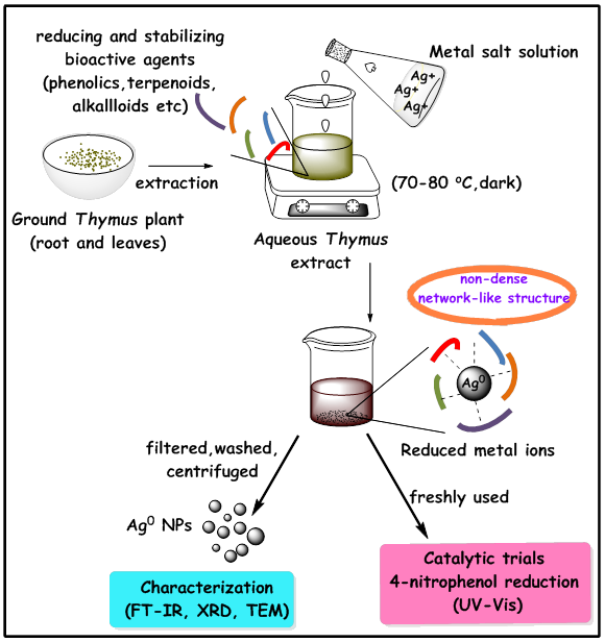


Figure 2. Schematic representation for the *Thymus* extract stabilized Ag^0 NPs preparation.

2.3 Catalytic studies

The catalyst prepared in situ by stabilizing Ag^0 NPs in *Thymus* aqueous extract using green synthesis method, was employed as a catalyst to directly reduce the 4-NP dye substrate without any separation or purification process. For the catalytic reaction, the Ag NP suspension obtained directly from the *Thymus* extract was used without any further purification. A defined volume of the nanoparticle –containing extract was added directly into the UV-Vis cuvette containing the 4-NP solution. In the catalytic experiments carried out for this purpose, 4-NP dye solution ($5x10^{-4}$ M, 3.0 mL) was transferred into the UV cuvette. Following the additon of the varying volumes of catalyst solution, the reaction progress was monitored

by recording the UV-Vis spectra at regular time intervals. The characteristic absorption peak of 4-NP (around 400 nm in alkaline conditions) was observed to decrase over time, indicating its reduction to 4 aminophenol (4-AP). 20 µL of *Thymus* extract stabilized Ag^0 NPs catalyst solution was determined as the optimum catalyst amount for the 4-NP reduction reaction, all experiments were carried out at room temperature, and the measurements were repeated to ensure reproducibility. Then, the performance of *Thymus* extract stabilized Ag^0 NPs catalyst for the reduction of ternary dye mixture containing 4-NP, RhB and MB under the determined optimum reaction conditions was investigated.

3. Results and Discussions

3.1 *Characterization of Thymus extract stabilized Ag^0 NPs catalyst:*

Ag^0 NPs, prepared by stabilizing and then reducing Ag^+ ions in *Thymus* aqueous extract using the green synthesis method, were separated from the plant extract medium by filtration, washed with water, and used in characterization studies after drying in an oven. The structural, morphological, and chemical properties of the synthesized Ag^0 NPs were comprehensively characterized using FT-IR, XRD and TEM analyses.

FT-IR analysis was performed to identify the functional groups present in the *Thymus* extract and to investigate their role in the reduction and stabilization of Ag^0 NPs. Figure 3(a) shows the FT-IR spectra of *Thymus* extract stabilized Ag^0 NPs recorded in the range of 4000-400 cm^{-1}. Characteristic peaks corresponding to hydroxyl (-OH), carbonyl (C=O), and other phytochemical functional groups confirmed the involvement of plant metabolites in the bioreduction and capping processes. When the spectrum is examined, it is thought that the peak at 3241 cm^{-1} belongs to the O-H stretching of the hydroxy groups of thymol and carvacrol phenolics, which are the major components in the *Thymus* extract. Since *Thymus* aqueous extract contains phenolic compounds as major components, a broad O-H stretching peak was observed due to intermolecular H-bonds. The peaks at 2917 cm^{-1} and 2853 cm^{-1} indicate aliphatic C-H stretchings in the structure of the bioactive components. The bands seen between 1900 and 2100 cm^{-1} indicate the C=C conjugation presence. The signal at 1688 cm^{-1} designates to the C=O stretching of the acid carbonyl group present in phenolic acid structures such as caffeic acid and rosmarinic acid found in *Thymus* extract. C=C stretching peaks for the aromatic structures of bioactive compounds were observed at 1591, 1508, 1459 and 1432 cm^{-1}. The peaks at 1166 and 1015 cm^{-1} are belong to C-O single bond stretchings.

XRD analysis was carried out to determine the crystalline structure and phase purity of the synthesized Ag^0 NPs. The four diffraction peaks observed at the angles of 28.26°, 44.46°, 64.53° and 77.45°Θ indicate the (111), (200), (220) and (331) cubic crystal structure (fcc) of Ag^0 (Figure 3(b)). The diffraction pattern exhibited distinct peaks corresponding to the face-centered cubic (fcc) structure of metallic silver, confirming the successful formation of crytalline Ag^0 NPs.

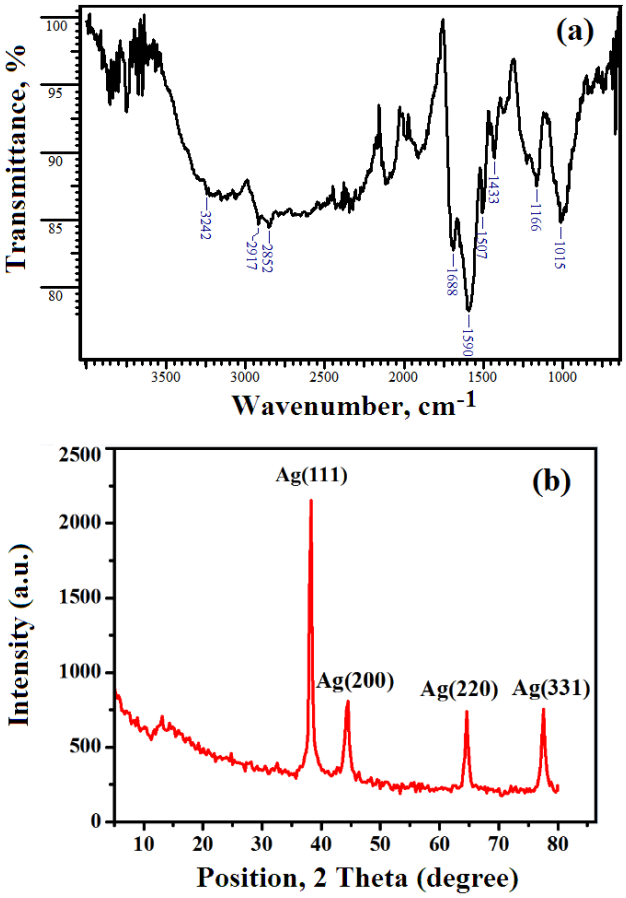


Figure 3. FT-IR spectrum (a) and XRD spectrum (b) of *Thymus* extract stabilized Ag^0 NPs.

TEM analysis was used to examine the morphology, size, and dispersion of the Ag^0 NPs stabilized in *Thymus* aqueous extract. After separated by filtration from the *Thymus* aqueous extract, washed and dried Ag^0 NPs were suspended in ethanol and dropped onto copper grid, and TEM images were recorded. The TEM image shown in Figure 4(a) revealed that the Ag^0 NPs obtained as a result of the green reduction of Ag^+ ions stabilized in the naturally formed network structure cavities by the intermolecular interactions with the metabolites found in the *Thymus* aqueous extract were prevented from aggregating and clumping. In addition, particle size distribution was analyzed by measuring the apprximate diameters of NPs from TEM image using ImageJ program. The obtained data were used to construct a particle size distribition histogram, which indicated a relativity narrow

size distribution and confirmed the size range of the synthesized NPs. According to the histogram given in Figure 4(b), it was observed that the majority of Ag^0 NPs were around 100 nm in size.

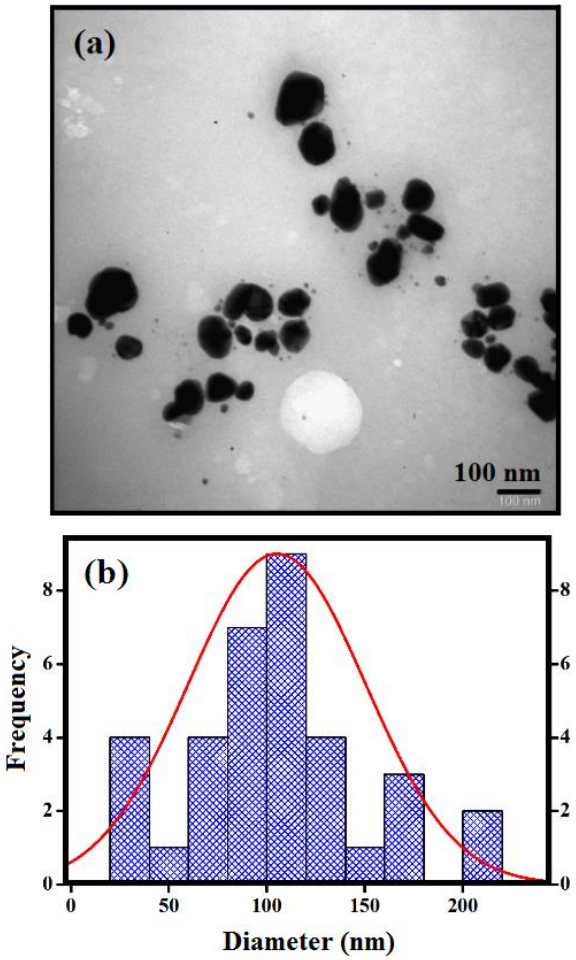


Figure 4. TEM images (a) and particle size distribution histogram (b) for *Thymus* extract stabilized Ag^0 NPs.

3.2 *Catalytic performance of Thymus extract stabilized Ag^0 NPs catalyst*

To examine the catalytic activity of Ag0 NPs catalyst made in situ using the green reduction technique in Thymus aqueous extract in the reduction and degradation of environmentally hazardous aromatic dyes, reaction conditions were optimized using 4-NP dye substrate, a commonly utilized model compound for catalytic research. The reaction was monitored by UV-Vis by tracking the decrease in absorbance at 400nm. To optimize the reaction conditions, the effect of substrate concentration was first examined. UV–Vis measurements were conducted at 4-NP concentrations of 0.125, 0.250, 0.500, and 1.000 mM. Among these, 0.500 mM (5×10^{-4} M) was selected as the optimum concentration, as lower and higher concentrations resulted in conversion values that were not suitable for reliable comparison. Subsequently, the effect of catalyst amount on the reduction reaction was evaluated by adding 10, 15, 20, 25, and 30 µL of the Ag^o NPs catalyst solution into the 4-NP solution. The results indicated that increasing the catalyst volume did not lead to a significant improvement in conversion efficiency. Therefore, 20 µL was selected as the optimum catalyst amount, as it enabled completion of the reaction within a reasonable and monitorable time frame.

Under the optimized conditions (3.0 mL of 5×10^{-4} M 4-NP and 20 µL catalyst), the reduction reaction reached 98% conversion within 5 minutes (Figure 5(a)). The kinetic profile, expressed as $\ln(C/C_0)$ versus time, exhibited a rapid decrease within the first 5 minutes, after which no significant change in concentration was observed, indicating completion of the reaction. ln(C/C0) curve for Thymus extract stabilized Ag0 NPs catalyzed 4-NP substrate reduction reaction is given in Figure 5(b).

Based on the synthesis composition (70% (v/v) 0.1 M $AgNO_3$ and 30% (v/v) Thymus extract), it was calculated that 20 µL of catalyst solution corresponds to approximately 0.15 mg of Ag^o NPs. This result demonstrates that a very low amount of catalyst is sufficient to achieve high catalytic efficiency.

To further evaluate the catalytic performance in more complex systems, reduction experiments were conducted using a ternary dye mixture consisting of 4-NP, RhB, and MB. For each experiment, 1 mL of 5×10^{-4} M dye solution (1.5 µmol total dye) was used, and the reactions were monitored at 400 nm (4-NP), 530 nm (RhB), and 665 nm (MB) (Figure 6(a)). After 10 minutes, conversion values of 98%, 43%, and 81% were obtained for 4-NP, RhB, and MB, respectively. Notably, the high conversion efficiency of 4-NP was preserved even in the presence of other dye molecules, indicating that the catalyst maintains its activity without significant competitive inhibition. The $\ln(C/C_0)$ curve indicating dye concentrations over time, shows that the reduction for the 4-NP dye was almost complete after 5 minutes, with no change in concentration values (Figure 6(b)). While RhB and MB exhibited relatively lower conversion efficiencies, both dyes showed rapid initial reduction within the first 2 minutes, followed by a gradual decrease in concentration over time. These findings demonstrate that *Thymus* extract stabilized Ag^o NPs exhibit high catalytic activity, even at low catalyst loading (0.15 mg), and maintain their performance in multi-component systems, highlighting their potential applicability in the treatment of complex wastewater streams. The enhanced catalytic reduction of organic dyes in the presence of biosynthesized Ag^0 NPs can be attributed to their role as an efficient electron transfer mediator.

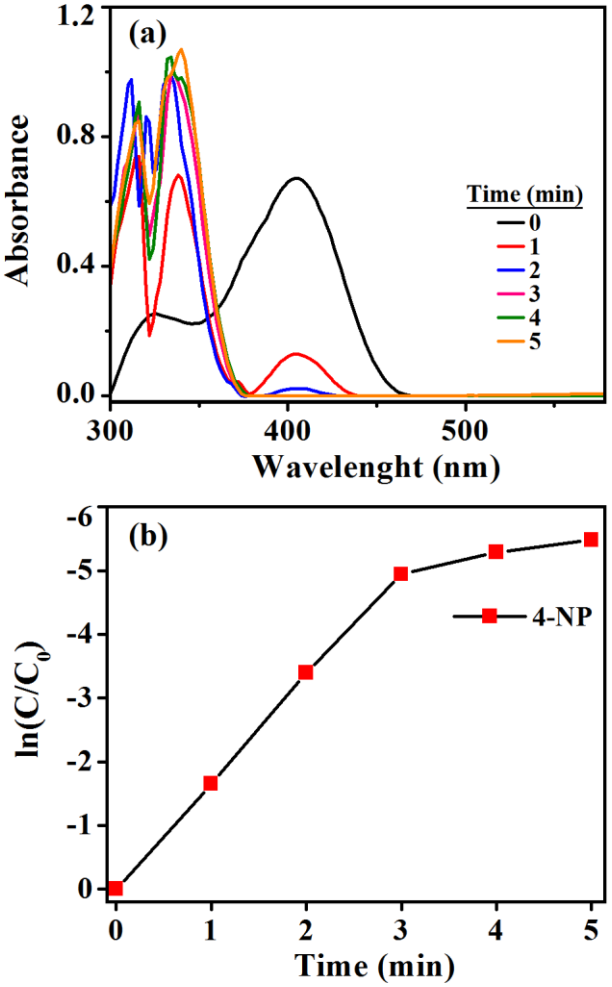


Figure 5. UV-Vis absorption spectra (a) and the ln(C/C$_0$) curve (b) for *Thymus* extract stabilized Ag^0 NPs catalyzed 4-NP substrate reduction reaction.

Phenolic components such as thymol, carvacrol, flavonoids, and phenolic acids, which are present as secondary metabolites in the aqueous extract of *Thymus*, possess electron-donating hydroxyl (–OH) groups. In aqueous reaction media, these functional groups can be oxidized to their corresponding quinone or carbonyl structures, simultaneously reducing Ag^+ ions to metallic Ag^o NPs. Initially, Ag^+ ions are stabilized by electrostatic interactions and weak chelation with oxygen-containing functional groups (–OH, –COOH) of phytochemicals. Then, a redox reaction occurs with the oxidation of phenolic groups and the transfer of electrons by Ag^+ ions, forming clusters of Ag^0 NPs. Furthermore, the phytochemical components of the *Thymus* extract play a crucial role not only in the green synthesis of Ag^0 NPs but also in their stabilization. These biomolecules form a capping layer that prevents aggregation, enhances dispersion, and may facilitate the adsorption of reactant species through surface functional groups. This synergistic effect contributes to the enhanced catalytic performance observed in this study. Thus, *Thymus* extract functions as both a reducing and stabilizing agent, enabling clean Ag^0 NPs synthesis via green method without the need for any metal hydrides.

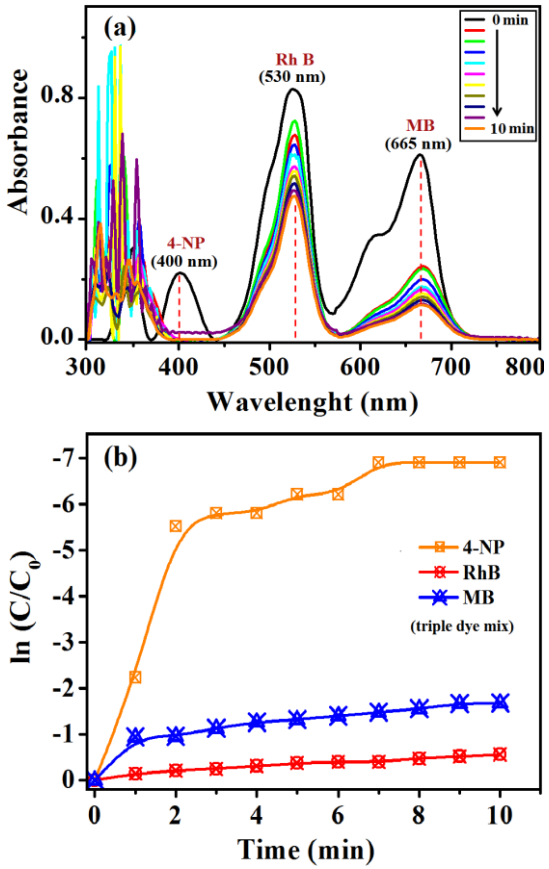


Figure 6. UV-Vis absorption spectra (a) and the ln(C/C$_0$) curves (b) for *Thymus* extract stabilized Ag^0 NPs catalyzed reduction of 4-NP, RhB and MB triple dye substrate mix.

Table 1. Comparison of the recent literature reports for 4-NP reduction catalyzed by Ag NPs obtained by green synthesis

Plant	Dye	Reference
Thymus	MB	Alamdari et al. 2025
Cynometra ramiflora	MO	Selveraj et al. 2025
Boerhaavia diffusa	MO	Sudhakar et al. 2025
Vigna unguiculata L. walp	4-NP	Mulu et al. 2024
Saussurea obvallata	4-NP	Sagar et al. 2024
Alchemilla vulgaris and Helichrysum arenarium	MB and 4-NP	Kahraman 2024
Mentha spicata	4-NP	Juarez et al. 2023
Fucus gardeneri	4-NP	Pricy and Gopinath 2021
Dodonaea viscosa	4-NP	Shah et al. 2021
Terminalia arjuna	MO, MB, 4-NP, CR	Raj et al. 2020
Ginger rhizome	MO	Riaz et al. 2020
Bistorta amplexicaule	4-NP	Shah et al. 2020
Tyhmus	4-NP and 4-NP,RhB,MB triple dye mix	This work

A comparative analysis of the recently synthesized Ag NPs-based catalysts via green methods using various plant extracts and their use in dye substrate reduction is summarized in Table 1. Unlike the majority of reported studies on the dye reduction, where an external reducing agent such as $NaBH_4$ is required, the present study demonstrates that the aqueous *Thymus* extract containing biosynthesized Ag^0 NPs can directly induce the reduction process without the addition of any external chemical reductant. In conventional systems, $NaBH_4$ acts as a strong electron donor, while metal NPs serve as electron relay centers. However, in this work, the reduction process is achieved through a synergistic interaction between the Ag^0 NPs and the phytochemical constituents of the *Thymus* extract. The biomolecules present in the extract, such as phenolic compounds and flavonoids, are known to possess intrinsic redox activity and can act as mild electron donors. It is therefore proposed that these phytochemicals donate electrons either directly to the dye molecules or indirectly via the Ag^0 NPs surface, which facilitates electron transfer and enhances the catalytic performance. However, due to the use of the Ag^0 NPs-containing extract in suspension form, catalyst reusability could not be evaluated in the present system, which may be considered a limitation compared to heterogeneous catalytic systems reported in the literature. Nevertheless, the proposed system offers a simplified and green methodology, highlighting the dual functionality of plant extracts as both reducing and stabilizing agents, while simultaneously enabling catalytic activity in a single-step process.

4. Conclusions

In this study, Ag^o NPs were successfully synthesized in situ via a green and sustainable approach using *Thymus* aqueous extract, which served both as a reducing and stabilizing agent by capping the Ag^+ ions in the H-bond network spaces through its rich phenolic content. The proposed method offers a simple, cost-effective, and environmentally benign alternative to conventional chemical synthesis routes.

The catalytic performance of the synthesized Ag^o NPs was systematically evaluated using the reduction of 4-nitrophenol (4-NP) as a model reaction. Under optimized conditions, a high conversion efficiency of 98% was achieved within 5 minutes using only 0.15 mg of catalyst, demonstrating the remarkable catalytic activity of the material even at low metal loading. Furthermore, the catalyst exhibited effective performance in more complex systems, as confirmed by the reduction of a ternary dye mixture containing 4-NP, RhB, and MB, with conversion values of 98%, 43%, and 81%, respectively. The preservation of high 4-NP conversion in the presence of other dyes indicates that the catalyst maintains its activity without significant competitive inhibition, highlighting its potential selectivity and robustness. Comprehensive characterization analyses confirmed that the synthesized Ag^o NPs possess a crystalline structure, and homogeneous morphology, all of which contribute to their enhanced catalytic performance.

Overall, the findings of this study demonstrate that *Thymus* extract-stabilized Ag^o NPs are extremely effective, inexpensive, and environmentally friendly catalysts with promising potential for use in environmental remediation and wastewater treatment. Metal NPs synthesized using other plant extracts are typically employed in conjunction with reducing agents to enhance reaction rates. However, in this study, the Ag NPs were synthesized directly within the *Thymus* extract and added to the reaction media without the need of $NaBH_4$. This approach eliminates the necessity for additional reducing agents, offering a more eco-friendly alternative, and allowing the reaction to proceed in a more natural manner. Future studies may focus on long-term stability, and extension to other environmentally relevant catalytic systems to further explore their practical applicability.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author 1: Investigation, methodology.

Author 2: Conceptualization, investigation, methodology, supervision and writing-review and editing.

Declaration of Competing Interest

The authors have no conflicts of interest to declare regarding the content of this article.

Data Availability Statement

All data generated or analyzed during this study are included in this published article. Datasets are available on request.

Acknowledgement

This research was supported by the TÜBİTAK 2209-A University Student Research Projects Support Program. (Project Number: 1919B012334826)

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