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Bauhinia variegata mediated silver nanoparticles for destruction of foodborne pathogens

Monika M^{1†}, Ranjani S^{1†} and Hemalatha S^{1*}

Abstract

Bauhinia variegata is a legume plant that is well known for its potential properties in ayurveda and traditional medicinal system. The application of nanoparticles in food packaging represents advancement in the preservation and safety of food products. The current research was used to determine the ability of *Bauhinia variegata* leaf extract to control food borne pathogens. In this study we have synthesized silver nanoparticles using *Bauhinia variegata* leaves (BvNPs) and to test its antibacterial potential in food borne pathogens namely in *Enterobacter kobei*, *Enterobacter cloacae*, *Klebsiella oxytoca*, *Enterobacterbugandensis*, *Enterobacter chuandaensis*, *Enterobacter huaxiensis*. Synthesis of BvNPS was confirmed by UV visible spectroscopy showing the absorbance peak at 420 nm. Alcohol, alkyne, alkane, carbohydrates are the functional groups present in the *Bauhinia variegata* leaf extract was identified by FTIR. The average size of the synthesized BvNPs was identified as 301.6 ± 12.3 nm (mean $\pm$ SD, $n = 3$) by using DLS. The ZETA potential analysis identified the surface charge as -15.2 mV. FESEM presents spherical nanoparticles with sizes ranging from 18.23 nm to 29.82 nm. The toxicity level of synthesized nanoparticles was studied by using *Danio rerio* embryos which showed non-toxic nature of BvNPs. Anti-bacterial activity was performed in food borne pathogens, and the MIC values were found between $1.256 \mu\text{g/ml}$ – $6.25 \mu\text{g/ml}$, the maximum MBC values were observed at $25 \mu\text{g/ml}$. Action mechanisms of BvNPs in food borne pathogens were more effective than the antibiotics by inducing leakage of proteins, sugars and oxidative stress. Based on the observed antimicrobial activity of BvNPs, these nanoparticles have the potential to be incorporated into food packaging materials to enhance food safety and preservation. Future studies are needed to evaluate their effectiveness in inhibiting microbial growth and extending the shelf life of food products.

Keywords Silver nanoparticles, BvNPs, *Bauhinia variegata*, Food packaging, Food borne pathogens

[†]Monika M and Ranjani S contributed equally to this work.

*Correspondence:

Hemalatha S

hemalatha.sls@bsauniv.ac.in

¹School of Life Sciences, B. S. Abdur Rahman Crescent Institute of Science and Technology, Vandalur, Chennai, Tamil Nadu 600048, India

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Introduction

Nanotechnology is a well-developed technology that can be utilized in the applications in food packaging systems, despite its widespread use in electrical, mechanical, medical, agricultural sectors and many more. Nanotechnology provides an innovative solutions into a variety of processes associated with food supply chain including development, production, fabrication, packaging, storage and distribution (Biswas et al. 2022). Nanotechnology has enabled alternative food processing methods by improving physicochemical properties and enhancing nutrient stability and bioavailability (Patra et al. 2018). Nanotechnology is applied in the food industry to improve food security across the entire supply chain from farm to fork. For example, nano sensors can detect spoilage or contamination during manufacturing, processing, packing, storage, and transportation, ensuring higher food safety and quality (Shi et al. 2021).

The distinct chemical, optical, thermal, mechanical, and biological properties of silver nanoparticles have made them a prominent type of metal nanoparticles over the last 20 years (Ahn et al. 2019). Silver nanoparticles are demonstrated to have high biocompatibility, catalytic activity, and therapeutic potential even at lower concentrations (Fahimirad et al. 2019). The antibacterial and anticancer effects of Ag NPs are extensively supported by research (Haggag et al. 2019). The synthesis of silver nanoparticles using environmentally benign methods is referred to as green synthesis. Because of a one step process that can readily be extended for large scale production and does not need any hazardous chemicals, temperature, energy and high pressure (Zhang et al. 2016). Plants, fungi and micro-organisms can be utilized as bio reducing agents in this green synthesis of nanoparticles. Plant-based green nanoparticles synthesis utilizes phytochemicals such as flavonoids, tannins, and saponins, as reducing and stabilizing agents to synthesize nanoparticles with desirable properties. An eco-friendly foundation for the synthesis of nanomaterials is established by using agricultural fruits and vegetables, seeds as well as the other parts of the plants including stems, roots, and leaves for many therapeutic purposes. The plant based synthesized nanoparticles show potential range of utilizations due to their biocompatibility, easily modifiable physicochemical properties, and sustainable source (Adeyemi et al. 2022).

Bauhinia variegata, also known as the Orchid Tree, is a species of flowering plant that belongs to the family *Fabaceae*. The origin of *Bauhinia variegata* is in the tropical and subtropical regions of Asia. *Bauhinia variegata* in India is the medium sized deciduous tree that grows up to 1500 m. Tribal communities in India have been traditionally using the various parts of *Bauhinia variegata* for medicinal purposes. In Ayurveda and Siddha,

the bark, leaves, flowers, and roots are used for treating wounds, diabetes, and inflammation. In Unani medicine, the bark and flowers are mainly employed for their astringent and anti-inflammatory effects, while in homeopathy, the flowers are used to prepare tinctures for managing inflammation, ulcers, and skin disorders. *Bauhinia variegata* contains a variety of phytochemicals including cardiac glycosides, terpenoids, tannins, saponins, and flavonoids. *Bauhinia variegata* is used extensively in traditional medicine to cure a wide range of diseases, including diabetes, infections, pain and inflammation. *Bauhinia Variegata* has strong antioxidant activity in its leaves, bark, flower and other parts (Shahana et al. 2017). *Bauhinia variegata* contains natural antioxidants, which may improve the overall health and enhances the functioning of when included in the diet (Abdel-Tawab et al. 2011). *Bauhinia variegata* was chosen for this study because it contains a wide range of bioactive compounds including flavonoids like kaempferol and quercetin, phenolic tannins, saponins, steroids, reducing sugars, anthraquinones, and other identified compounds such as 2,5-dimethylpyrrole, 2,3-diphenylcyclopropyl, methyl phenyl sulphoxide, and benzonitrile m-phenethyl which provide strong antioxidant and antimicrobial properties, making it suitable for the green synthesis of nanoparticles and their evaluation in biomedical applications. Notably, the hydroxyl (-OH) groups which are present in the phytochemicals play a key role in reducing silver nitrate during nanoparticles synthesis.

Contamination of food by foodborne pathogens poses a significant risk and can lead to serious illnesses, including infections, toxico-infections, and food intoxications. Outbreak of foodborne pathogens can result in increased mortality and morbidity. Foodborne illnesses are caused by consuming contaminated food, and the pathogens responsible can be human-specific (anthroponotic), zoonotic, or environmental in origin. *Klebsiella* species is one of the foodborne pathogens that can cause septicemia, diarrhea and liver abscesses in humans. In search of alternatives to control these food borne pathogens, nanotechnology plays a major role in developing novel nano materials by using *Bauhinia variegata* plant extract. Plants, fungi and micro-organisms can be utilized as bio reducing agents in this green synthesis of nanoparticles. These can be used as an alternative source for antibiotics and chemicals that are commonly used in food products to inhibit the bacterial growth (Nadaroglu et al. 2017). Food packaging has historically been thought of as a passive barrier that delays the impact of environmental influences on the product that is packaged. Current trends are shifting in favor of developing packaging materials that actively contribute to food preservation by interacting with their environment. As an alternative the green nanoparticles incorporated food packaging material can

be developed with potent antifungal and antibacterial activity. Nanoparticles incorporated in food packaging materials can control the outbreak of foodborne pathogens that cause many diseases. In addition, novel packaging material can act as a nutrient enhancer as well as the shelf life of the packed food can also be extended by inhibiting the bacterial growth. Hence, this study aims to synthesize silver nanoparticles using *Bauhinia variegata* leaf extract (BvNPs) and to assess their antimicrobial activity in selected foodborne pathogens, exploring their potential as an eco-friendly and effective alternative for controlling microbial contamination.

Materials and methods

Collection of *Bauhinia variegata* leaf extract and phytochemical analysis

The fresh leaves of *Bauhinia Variegata* were collected from the campus of BS Abdur Rahman Crescent Institute of Science and Technology, Chennai in the month of November 2024. Disease free leaves were collected only once during the study. The phytochemical profile of the leaves may vary in different seasons and in geographic locations. Collected leaves were washed thoroughly under running water, and the foreign materials were removed. 50 gm of thoroughly washed and finely ground *Bauhinia variegata* leaves were mixed in 500 ml of distilled water, and the mixture was boiled for 5 min. The debris was removed by filtration using Whatman grade 1 filter paper. The phytochemical screening of *Bauhinia variegata* leaf extract was performed to determine the presence of tannins, steroids, proteins, tannins, alkaloids, amino acids, phenolic compounds and saponins. Standard qualitative tests based on Harborne's method were employed to detect these phytochemicals (Harborne 1998).

Biosynthesis of BvNPs by using *Bauhinia variegata* leaf extract

The leaf extract was added into with solution of AgNO_3 (0.169 mg of AgNO_3 powder in 1000 ml distilled water) and incubated at room temperature. The colour change of the solution from light brown to reddish brown indicates the formation of BvNPs (Gopinath et al. 2012). After confirming the synthesis of BvNPs, nanoparticles were collected by using centrifugation techniques (20 min at 15,000 rpm). Collected pellets of BvNPs were washed with ethanol to obtain pure nanoparticles for research studies.

Characterization of synthesized BvNPs

UV – visible spectroscopy was employed to perform spectral scanning between 200–800 nm with 1 nm resolution was employed to observe the strong SPR peak of BvNPs. The functional groups present in the synthesized

nanoparticles were examined by using FTIR spectrometer. By using the Dynamic light scattering method, the size of the BvNPs was determined (Ahmed and Ikram 2015). The surface charge of the BvNPs was determined by Zeta potential analysis. The micro-structure image of the BvNPs was determined by Field emission scanning electron microscope (FESEM). EDAX was used to determine the elemental composition of the synthesized nanoparticles (Ghasemi et al. 2024). XRD analysis was used to confirm the crystalline structure of synthesized BvNPs.

Toxicity studies of BvNPs in embryos of *Danio rerio*

The toxicity level of BvNPs was observed by treating the *Danio rerio* embryos with different concentrations. The embryos were exposed to various doses of BvNPs (1, 3.125, 6.25, 12.5, 25, 50, 75, and 100 $\mu\text{g/ml}$), whereas controls were left untreated. The death rate was assessed after 98 h of treatment (Kumar et al. 2024).

Evaluation of biomedical applications of BvNPs

Detection of antioxidant property of BvNPs

To evaluate the antioxidant properties of synthesized BvNPs, the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay was employed to assess their free radical scavenging activity. The BvNPs were compared with the standard, ascorbic acid, at concentrations of 12.5, 25, 50, 75, and 100 $\mu\text{g/mL}$.

Detection of anti-inflammatory activity of BvNPs

To assess the anti-inflammatory potential, BvNPs at concentrations of 100, 50, 25, and 12.5 $\mu\text{g/mL}$, along with the standard diclofenac, were prepared in triplicate in 96-well plates, to which bovine serum albumin (BSA) was added. The plates were incubated at 50 °C for 37 min, followed by heating at 57 °C for 3 min. After cooling, a buffer solution was added to make up the volume. Absorbance was measured at 417 nm.

Anti-bacterial potential of BvNPs in food borne pathogens

The antibacterial assays were performed on the following bacterial strains *Enterobacter kobei*, *Enterobacter cloacae*, *Klebsiella oxytoca*, *Enterobacter bugandensis*, *Enterobacter chuandaensis*, *Enterobacter huaxiensis*. Bacterial strains were revived and fresh log phase cultures were used for all the antibacterial and biofilm assays. These organisms were isolated from spoiled fruits and vegetables. Accession numbers of the organisms are as follows *E. kobei* (MZ245730), *E. cloacae* (MZ246448), *K. oxytoca* (MZ246548), *E. bugandensis* (MZ246580), *E. chuandaensis* (MZ246629), *E. huaxiensis* (MZ246628).

Determination of minimum inhibitory concentration of BvNPs

The minimum inhibitory concentration was

determined by visually monitoring the bacterial growth after 24 h of incubation at 37 °C. Antibacterial property of BvNPs were evaluated in microtiter plate assay to determine the minimal inhibitory concentration in each of the tested strains. Each well was filled with 100 µl of LB broth. BvNPs (1 mg/ml) were serially diluted. 2 µl of culture was inoculated to each well containing 100 µl of LB broth. Wells inoculated with strains alone were used as control. The wells containing only LB broth were considered as blank. The typical standard antibiotics against bacterial strains was 25 µg/ml of ampicillin (Ranjani and Hemalatha 2023; NajeerAhamed et al. 2023). The minimum inhibitory concentration of BvNPs in *Enterobacter* and *Klebsiella* species was determined by visually interpreting the bacterial growth based on turbidity.

Determination of minimum bactericidal concentration of BvNPs The (MBC) minimum bactericidal concentration was determined using the minimum concentration of BvNPs necessary to prevent the formation of colonies on agar plates i.e. killing of the organism. Following MIC determination, one microliter of cultures from each well treated with BvNPs was inoculated onto LB agar plates. After 24 h, plates were monitored for bacterial growth and the concentration that completely eradicated the growth of organism was considered as MBC of BvNPs.

Measurement of growth kinetics Similar to the MIC assay, the growth kinetics of the tested bacterial strains were evaluated by measuring their growth (OD at 600 nm) at 12, 24, 36, and 48 h following treatment with BvNPs and ampicillin, and results were compared to the untreated control. The growth rate was measured by measuring the absorbance at 600 nm and the graph was plotted to study the effect of BvNPs in the growth of tested bacterial strains.

Biofilm formation assay Using the 96-well plate method, formation of biofilm was estimated by using staining technique. Similar to the MIC assay, the biofilm formation of tested bacterial strains was studied by measuring the formation of bacterial biofilm at 48 h of treatment with BvNPs, ampicillin and compared with control. The plates were thoroughly cleaned and allowed to dry. Plates were incubated for 15 min after adding a 0.1% solution of crystal violet. Following the incubation period, the crystal violet was discarded, and the plate was washed under running water. After washing, 100 µl of glacial acetic acid solution (30%) was added to the plates. After 5–10 min spectrophotometric measurement was recorded at 580 nm (Ranjani and Hemalatha 2023; NajeerAhamed et al. 2023). The formation of biofilm in both untreated and treated bacterial cells was quantified.

Assays to analyze the mechanism of action of BvNPs in food borne pathogens

All the following experiments were carried out with controls (respective bacterial cells alone), Ampicillin treatment (positive control), BvNPs treatment as test.

Estimating the leakage of sugars and proteins Bacterial strains were treated with sub-MIC concentrations of BvNPs and ampicillin. Strains were incubated at 37 °C for 6 h. The bacterial cells were centrifuged after incubation at 10,000 rpm for 30 min. Leaky cellular components which were present in the supernatant were collected and frozen at –20 °C for 4 h. Total sugars and proteins were analyzed by using the Anthrone method and the Bradford method, respectively. Quantifying the released cellular components can provide insights into how BvNPs affects the stability and the integrity of the bacterial cell membrane. Experiment was carried out with control (bacterial cells alone), Ampicillin treatment (positive control), BvNPs treatment as test.

Measurement of MDA Bacterial strains were treated with BvNPs and ampicillin, then mixed with SDS (10%) and thiobarbituric acid. After 60 min of incubation at 95 °C the solution was cooled at ambient temperature. At 5000 rpm the treated cells were spun for 10 min. After collecting the supernatant, the absorbance was measured using a spectrophotometer at 530 nm. Measuring MDA levels in bacterial strains can reveal the presence of oxidative stress and lipid peroxidation levels.

Estimation of catalase activity PBS was used to wash the bacterial pellet, and the cellular components were dissolved by suspending it in buffer. Samples were placed in a 96-well plate and analyzed for OD at 240 nm. After measuring the original absorbance at 240 nm, the samples were treated with hydrogen peroxide (H₂O₂) and measured again at 240 nm. At 240 nm catalase activity of bacterial strains treated with ampicillin and BvNPs was assessed, which reflects rate of catalase activity in breakdown of H₂O₂.

Estimation of superoxide dismutase activity The bacterial pellet was suspended in buffer after washed with PBS. The reaction mixture was prepared by mixing EDTA, methionine, and NBT in phosphate buffer. The bacterial cell pellet was added to the reaction mixture after dissolving it in PBS and incubated for 15 min in dark. Absorbance at 560 nm indicates the reduction of (NBT) nitroblue tetrazolium by superoxide radicals during the process. Superoxide dismutase, an enzyme that detoxifies superoxide radicals within bacterial cells which are responsible for the reduction reaction.

Estimation of GSH BvNPs and ampicillin treated bacterial cells were centrifuged at 10,000 rpm for 30 min. The pellets were washed and lysed to extract cell components. Ellman's reagent was utilized to estimate the GSH level in bacterial cells. The levels of GSH was quantified by measuring the absorbance at 412 nm (Nunes et al. 2020). Absorbance levels of measured GSH levels indicate the antioxidant capability of bacterial cells on treatment with BvNPs (NajeerAhamed et al. 2023; Soundharajan and Srinivasan 2025; Yuan et al. 2017).

Statistical analysis

All experiments were performed in triplicate ($n=3$). Statistical analysis was conducted using Student's T-Test. Significance levels were defined as $P<0.05$ (*), $P<0.01$ (**), and $P<0.001$ (***)

Results and discussion

Phytochemicals screening in *Bauhinia variegata* leaf extract

Plants contain natural compounds, such as phytochemicals, which have been shown to provide various health benefits. Fresh leaves of *Bauhinia variegata* were collected (Fig. 1a) and subjected to extraction. Fresh extract contains phytochemical components namely carbohydrates, triterpenoids, phenol, flavonoids, saponins, protein, tannins, and glycosides. The stability of the BvNPs was maintained by phytochemicals, which served as a capping and reducing agent when Ag is reduced into

Ag⁺ ions (Harborne 1998). Silver (Ag) can be produced by reducing silver nitrate (AgNO₃) by the hydroxyl (-OH) group of tannins and phenols. -OH groups of phenols and tannins form the -O-Ag group when it reacts with silver ions from a silver nitrate solution. Phenols have anti-inflammatory and cardiovascular protective properties and are associated with other health benefits. Because of their anti-inflammatory and immunosuppressive properties, steroids are essential for the growth of plants and defense and are also used in pharmaceuticals. Because of the antioxidant qualities, tannins may protect against inflammation and heart disease. Health benefits of saponins include lowering cholesterol and regulating the immune system (Nunes et al. 2020).

Synthesis and characterization of synthesized BvNPs

Bauhinia variegata leaf extract mediated BvNPs were synthesized by mixing leaves extract with a silver nitrate solution. The synthesis of BvNPs was indicated by a colour shift from light brown to reddish brown (Fig. 1b). By using UV–visible spectroscopy the presence of silver nanoparticles was confirmed and displayed a peak at 420 nm (Fig. 1c). AgNPs clearly display an SPR peak around 200–800 nm wavelength (Almatroudi 2020). Hence BvNPs displays the peak at 420 nm. Furthermore, the spherical shape of BvNPs was revealed by the peak at 420 nm.

The functional groups present in BvNPs were analyzed by FTIR spectroscopy (Fig. 1d) (Table 1) Alcohol, alkane,

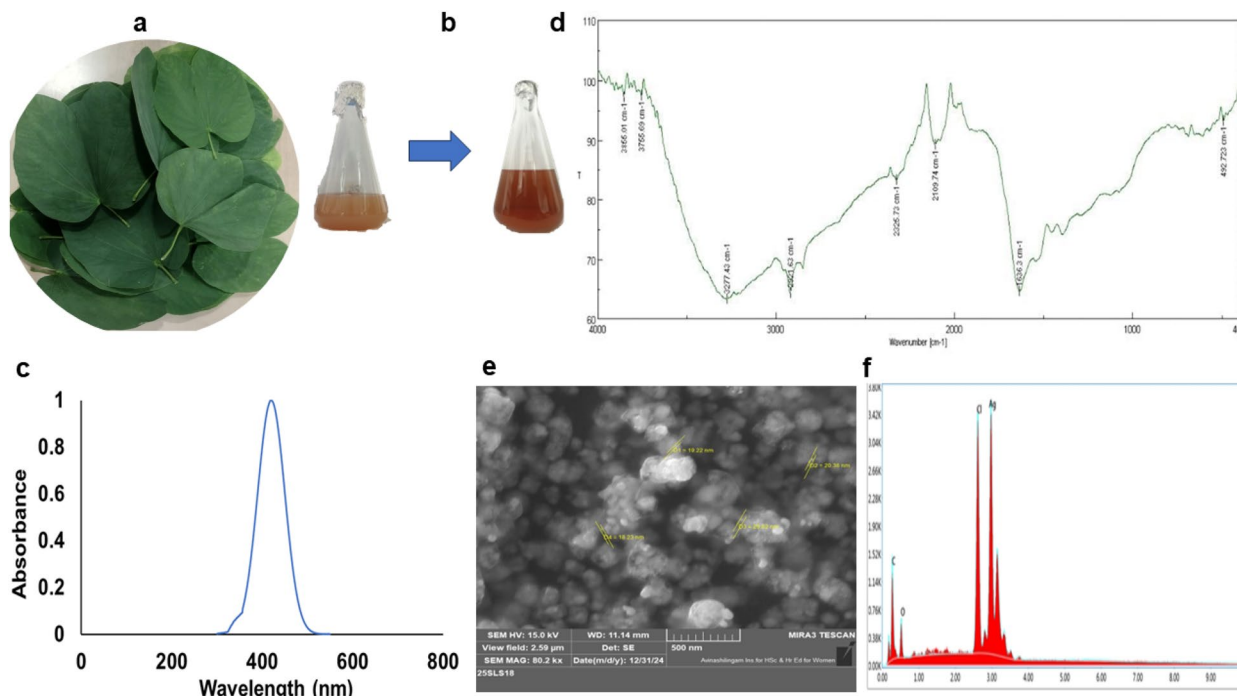


Fig. 1 Synthesis and characterization of BvNPs: (a) Fresh leaves of *Bauhinia variegata* (b) Colour change from orange to reddish brown confirms the synthesis of BvNPs (c) UV visible spectrum of BvNPs (d) FTIR analysis of BvNPs (e) FESEM analysis BvNPs (f) EDAX spectrum of BvNPs

Table 1 FTIR footprints of synthesized BvNPs

S. No	Frequency (cm ⁻¹)	Bond	Functional group
1	3700.53	Alcohol	O–H stretching
2	3277.43	Alkyne	C–H stretching
3	2921.63	Alkane	C–H stretching
4	2325.73	Carbohydrates	O=C=O stretching
5	2109.74	Alkyne	C=C stretching
6	1636.3	Alkene	C=C stretching

carbohydrates and alkenes are functional groups found in BvNPs. By converting Ag into Ag⁺ ions, these functional groups are crucial in determining the stability and the charge of the nanoparticles. Silver nitrate (AgNO₃) was reduced to silver (Ag) by the (-OH) group of phenols and tannins. Both the leaf extract and BvNPs showed signs of OH stretching. The peak in the BvNPs FTIR spectrum at 3700.53 cm⁻¹ represents O–H stretching of alcohol. The peak at 3277.43 cm⁻¹ confirms the presence of C–H stretching of alkyne, while the O–C–O carbohydrates stretching are represented by the peak at 2325.73 cm⁻¹. Silver nitrate splits into Ag⁺ and NO₃⁻ ions upon dissolution in water. -OH groups of phenols or tannins donate H⁺ ions and acquire a negative charge. Ag⁺ ions were reduced by the electrostatic interaction between the negative functional group of tannins and phenols. Ag that was present in the free metallic state, Ag⁰, to synthesize BvNPs. The FTIR spectrum of BvNPs showed the -OH stretching of alcohol. One possible explanation for

the peak at 3700.53 cm⁻¹ was hydrogen bond breakdown, which contributes to the formation of silver nanoparticles from the reduction of silver ions.

Using a FESEM the shape, size, and morphology of BvNPs was observed as spherical nanoparticles at a resolution of 500 nm and with magnification of 80.2 kx (Fig. 1e). On comparison of results with previous findings [19] the size of the silver nanoparticles found below 100 nm. The size of nano particles below 100 nm is important for its antibacterial action. Strong correlation has been observed between the size and the SPR peak of BvNPs. A significant elemental peak at 3 keV was determined (Fig. 1f) in the EDAX analysis of BvNPs which corresponds to the silver ions in the nanoparticles and demonstrated the higher concentration of silver in BvNPs. In terms of weight and atoms, silver displayed a higher percentage. Other elements including carbon, oxygen, and chlorine, were also found in the BvNPs (Ghasemi et al. 2024).

The DLS analyzer identified the BvNPs PDI, hydrodynamic size, and surface charge (Fig. 2a). BvNPs were found to have a particle size with the diameter of 301.6 nm and a polydispersity index (PDI) value of 24.2%. The surface charge of BvNPs was found as -15.2 mV, as shown in (Fig. 2b). Repulsion between particles can be induced by negative charge dispersion, effectively preventing the BvNPs from aggregating. (Fig. 2c) shows the peaks of BvNPs observed using XRD analysis. The

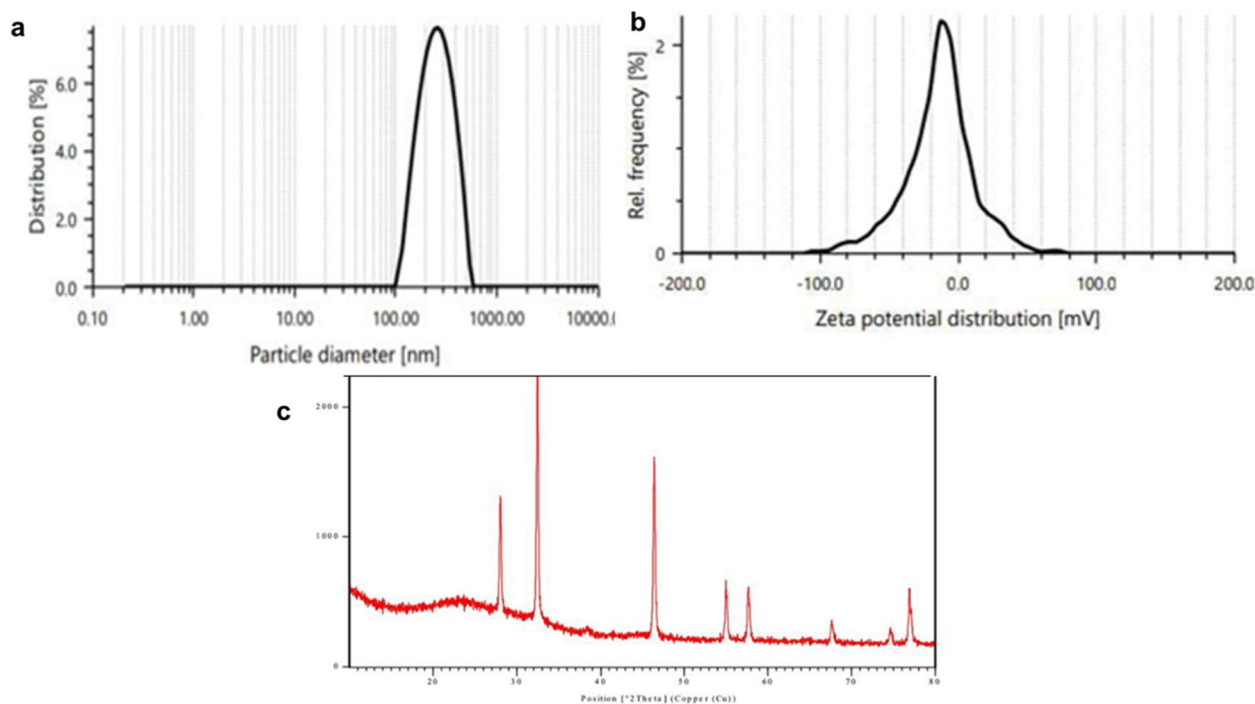


Fig. 2 Characterization of BvNPs: (a) DLS analysis of BvNPs depicts the particle diameter of 301.6 nm (b) Zeta potential analysis shows the surface charge of BvNPs -15.2 mV. (c) XRD diffractogram of BvNPs denotes the 2 Θ values of 57.63, 67.60, 76.88, respective to the (383), (158), (395) planes of silver nanoparticles

2 Θ values of 57.63, 67.60, 76.88 were respective to the (383), (158), (395) planes of silver nanoparticles. The peaks confirm the crystalline structure of BvNPs. These findings are respective with the previous studies of silver nanoparticles synthesized from *Bauhinia variegata* (Soliman et al. 2024).

Toxicity study of BvNPs in *Danio rerio* embryos

The survival rate of *D. rerio* embryos at 24 h, 48 h, 72 h and 96 h was observed as 78%, 67%, 56%, 44% respectively upon the treatment with 50 $\mu\text{g/ml}$ of BvNPs. Mortality rate and morphological malformations in *D. rerio* embryos were compared to the control which indicate the degree of cytotoxicity of BvNPs in the embryo as seen in (Fig. 3a). No morphological alterations were seen in the *D. rerio* embryo treated with BvNPs (Fig. 3b). All the embryos including control and treatment were maintained at room temperature.

All BvNPs concentrations caused noticeable development in the tested embryos, confirming that the BvNps were not toxic. Numerous developmental abnormalities brought on during embryogenesis by heavy metals exposure can ultimately reduce the survival rate. These abnormalities include developmental malformations, delayed or premature hatching and higher mortality rate among the embryos. On comparing the toxicity study of platinum-based nanomaterial synthesized from *Allium sativum* (Kumar et al. 2024) BvNPs, however, did not exhibit any anomalies during treatment. The toxicity study of

BvNPs in *Danio rerio* embryos indicates that BvNPs capped with phytocompounds did not exhibit observable toxicity under the tested conditions.

Multipotent application of BvNPs

Antioxidant activity of BvNPs

The antioxidant activity of BvNPs was assessed using the DPPH radical scavenging assay and was found to be comparable to that of the standard antioxidant, ascorbic acid, which efficiently scavenges free radicals. In this assay, BvNPs exhibited scavenging percentages of 20.60%, 34.13%, 42.22%, 51.32%, and 60.17% at concentrations of 12.5, 25, 50, 75, and 100 $\mu\text{g/ml}$, respectively. Under the same experimental conditions, ascorbic acid (used as positive control at same concentrations in the same solvent and incubation conditions) showed antioxidant activity of 58.65%, 68%, 71.17%, 76.99%, and 80.78% for 12.5, 25, 50, 75, and 100 $\mu\text{g/ml}$, respectively (Fig. 4a). These results indicate a dose-dependent increase in antioxidant activity of BvNPs. Similar antioxidant effects of silver nanoparticles have been reported (Madhumitha et al. 2023)

Evaluation of anti-inflammatory properties of BvNPs

BvNPs anti-inflammatory properties were evaluated and compared with those of the standard drug diclofenac sodium using the protein denaturation inhibition assay. Both BvNPs and diclofenac sodium showed an increase in the percentage inhibition of protein denaturation

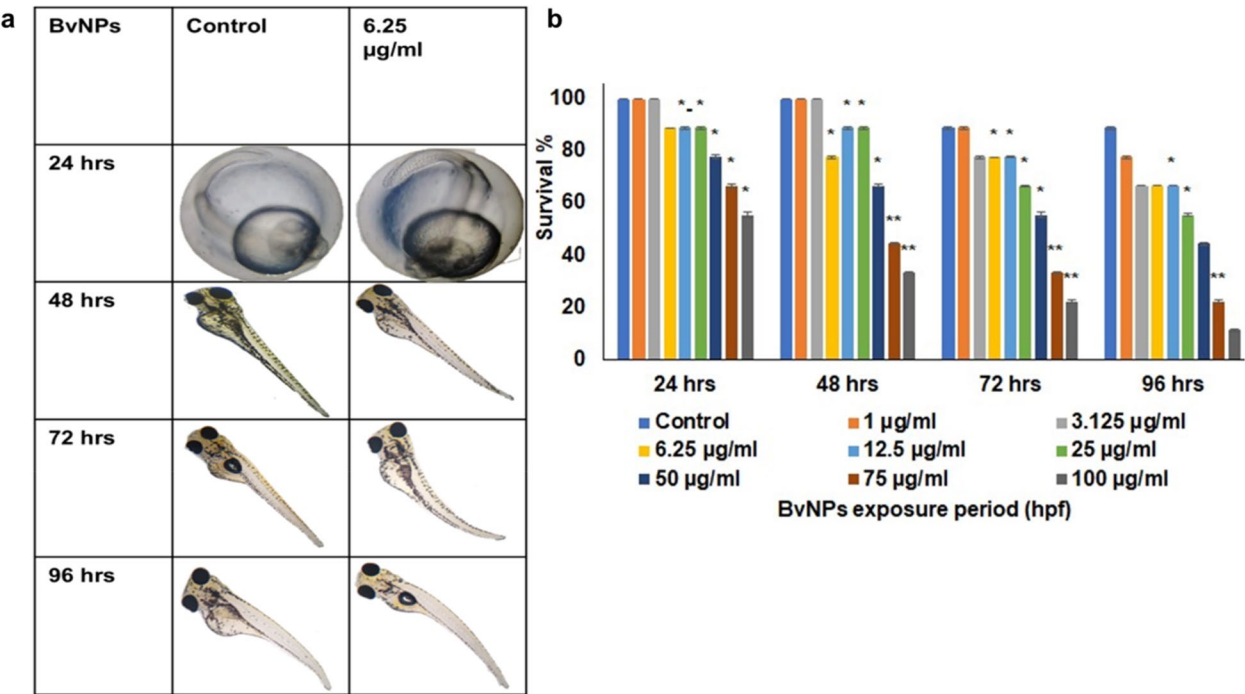


Fig. 3 Toxicity studies of BvNPs in Zebrafish embryos: (a) Morphological observations of BvNPs treated *Danio rerio* embryos (b) Survival rate of *Danio rerio* embryos upon treatment with BvNPs

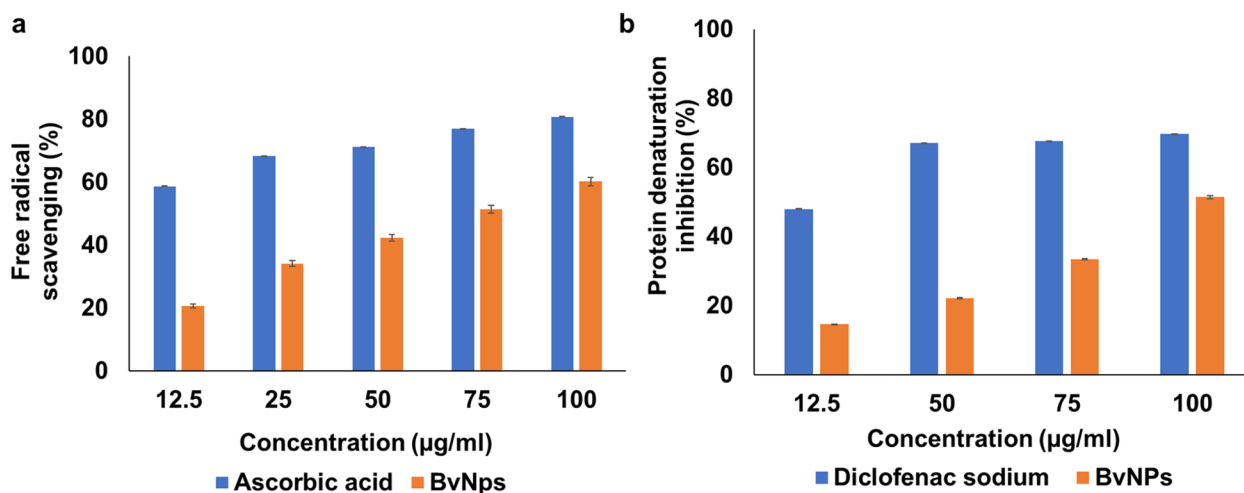


Fig. 4 **a** Anti-oxidant activity of BvNPs **(b)** Anti-inflammatory activity of BvNPs

Table 2 Determination of MIC and MBC of BvNPs in *E.kobei*, *E.clocae*, *K.oxytoca*, *E.bugandensis*, *E. chuandaensis*, *E.huanxiensis* strains

S. No	Bacterial strains	MIC(µg/ml)	MBC(µg/ml)
1	<i>E. kobei</i>	1.56	12.50
2	<i>E. clocae</i>	3.13	25
3	<i>K. oxytoca</i>	6.25	6.25
4	<i>E. bugandaensis</i>	3.13	12.50
5	<i>E. chuandaensis</i>	3.13	3.13
6	<i>E. huaxiensis</i>	1.56	6.25

that was dependent on concentration. At 12.5, 50, 75, and 100 µg/ml of concentrations, diclofenac sodium was determined to have 47.93%, 66.9%, 67.54%, and 69.63% activity. At the concentration of 12.5, 50, 75 and 100 µg/ml the anti-inflammatory level of BvNPs were determined to have 14.6%, 22.13%, 33.45% and 51% of protein denaturation inhibition activity (Fig. 4b). While diclofenac sodium consistently exhibits higher inhibitory percentages across all doses, the results indicate that BvNPs demonstrated a strong anti-inflammatory impact, which may be attributed to their bioactive components. In a previous study (Raju et al. 2024), the anti-inflammatory activity of silver nanoparticles synthesized from *Azadirachta indica* (neem) and *Swertia chirata* (kirita) was evaluated using BSA as the standard. At concentrations of 10, 20, 30, 40, and 50 µl, the nanoparticles exhibited anti-inflammatory activities of 35%, 50%, 55%, 60%, and 70%, respectively (Raju et al. 2024).

Efficacy of BvNPs in controlling the growth and biofilm in food borne pathogens

Minimum inhibitory concentration of BvNPs in *E.kobei* was 1.5625 µg/ml, *E.clocae* was 3.125 µg/ml, *K.oxytoca* was 6.25 µg/ml, *E. bugandensis* was 3.125 µg/ml, *E. chuandaensis* was 3.125 µg/ml, *E. huaxiensis* was

1.5626 µg/ml represented in (Table 2). After a 24-h treatment, the minimum bactericidal concentration of BvNPs in *E.kobei* was 12.5 µg/ml, *E.clocae* was 25 µg/ml, *K. oxytoca* was 6.25 µg/ml, *E.bugandensis* was 12.5 µg/ml, *E. chuandaensis* was 3.125 µg/ml, *E. huaxiensis* was 6.25 µg/ml represented in (Table 2).

After 24 h of treatment with BvNPs and ampicillin, growth percentage was significantly lower for BvNPs treated cells. Following treatment with BvNPs and ampicillin at their respective MICs, the percentage of growth in *E. kobei* was 18%, *E.clocae* was 15%, *K.oxytoca* was 47%, *E.bugandensis* was 34%, *E.chuandaensis* was 29%, *E.huanxiensis* was 46% (Fig. 5a). Similarly, the bacterial growth for ampicillin treated strains were found as 67.80%, 80.77%, 63.33%, 76.56%, 73.70%, 70.58% for *E.kobei*, *E.clocae*, *K.oxytoca*, *E. bugandensis*, *E. chuandaensis*, *E.huaxiensis* respectively. BvNPs treatment has a dose-dependent impact in tested bacterial strains. On comparing the results of (Ranjani et al. 2022) minimum inhibitory concentration of *E.kobei* and *K.oxytoca* were 25 µg/ml and 12.5 µg/ml respectively and the minimum bactericidal concentration of *E.kobei* and *K.oxytoca* were 25 µg/ml for both strains. The growth rate of bacterial strains falls when BvNPs concentration rises. BvNPs antibacterial activity in food borne pathogens was demonstrated by observing the growth. These findings indicated that BvNPs are more effective than antibiotics in strongly preventing and killing the food borne pathogens. By determining the MIC and MBC in tested *E.kobei*, *E.clocae*, *K.oxytoca*, *E.bugandensis*, *E.chuandaensis*, *E.huanxiensis*, BvNPs was more effective than ampicillin, where synergism of phytochemicals and silver ions plays a crucial role. By targeting many sites, the phytochemicals and silver ions work together to prevent bacterial growth and ultimately kill the bacterial cells. By comparing the MIC and MBC values of BvNPs,

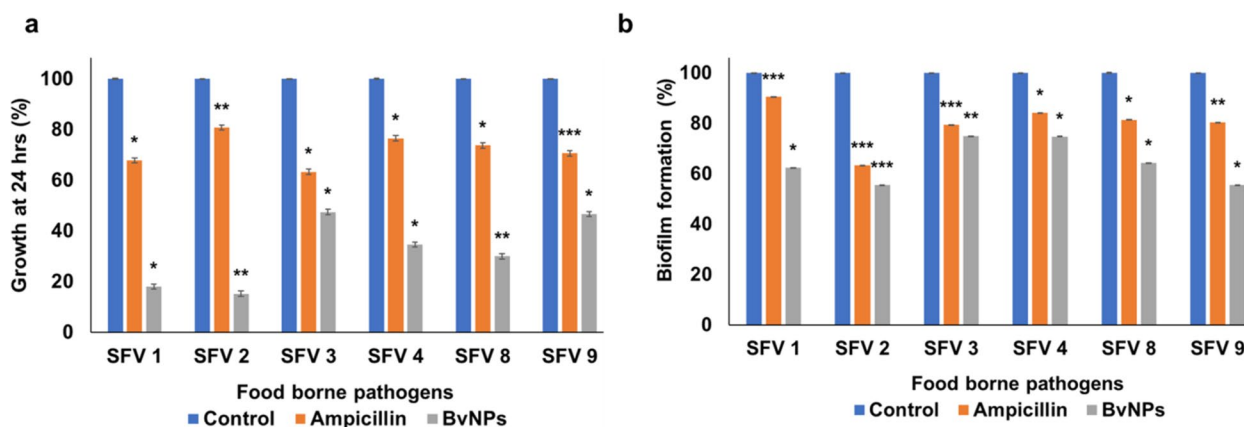


Fig. 5 Antibacterial activity of BvNPs in food borne pathogens: (a) Growth of food borne pathogens treated with BvNPs and compared with ampicillin treatment and control at 24 h (b) Percentage of biofilm formation in food borne pathogens treated with BvNPs and compared with ampicillin treatment and control. Error bars representing means $\pm$ standard deviation. * Denotes T-test (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$)

the tolerance levels for *E.kobei*, *E.clocae*, *K.oxytoca*, *E.bugandensis*, *E.chuandaensis*, *E.huanxiensis* were determined as 0.125, 0.125, 1, 0.25, 1, 0.2516 respectively. So, the tolerance of 0.125 depicts bactericidal property. Hence, the BvNPs proved to have bactericidal potential. AgNPs were shown to have high capacity to damage bacterial cell membrane by producing reactive oxygen species (ROS) interfering with replication, and killing bacterial cell. The spherical BvNPs can readily enter the bacterial cell and interfere with its normal activity. BvNPs have a larger surface area than volume, which makes them more effective at presenting biological membranes.

Silver nanoparticles may inhibit the formation of biofilms by penetrating the bacterial cell wall, suppressing the production of exo-polyasaccharide layers and interfering with cell adhesion. AgNPs interfere with a bacterial communication system that regulates biofilm formation. Silver nanoparticles release silver ions that have broad spectrum of antimicrobial activity by killing bacteria and preventing biofilm formation. Upon treatment with BvNPs, the percentage of biofilm formation was reduced to 62%, 55%, 74%, 64%, 55% in *E. kobei*, *E. clocae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, *E. huanxiensis* respectively (Fig. 5b). Then upon treatment with ampicillin the percentage of biofilm formation were found as 90.43%, 63.26%, 79.41%, 84.13%, 81.39%, 80.35% for *E. kobei*, *E. clocae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, *E. huaxiensis* respectively. Based upon the findings of nanoparticles synthesized from *Colletotrichum siamense* (Ranjani et al. 2022) *E. kobei* and *K. oxytoca* showed 50% reduction in biofilm formation when treated with silver nanoparticles.

Action mechanism of BvNPs in food borne pathogens

Protein leakage in *E. kobei*, *E. clocae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, and *E. huanxiensis* cells were measured following treatment with BvNPs and

ampicillin and compared with the corresponding control (Fig. 6a). In ampicillin-treated cells, protein leakage was 21.2 ± 0.3 , 20.5 ± 0.4 , 20.9 ± 0.3 , 21.6 ± 0.2 , 21.2 ± 0.3 , and 21.6 ± 0.3 $\mu\text{g}/\text{mg}$, respectively. Following BvNPs treatment, protein leakage increased to 22.1 ± 0.4 , 22.4 ± 0.3 , 21.8 ± 0.3 , 22.0 ± 0.2 , 22.8 ± 0.3 , and 22.8 ± 0.3 $\mu\text{g}/\text{mg}$, respectively. Compared with the control and ampicillin treatments, BvNPs induced a progressive increase in protein leakage, with values of 18.8 ± 0.2 , 18.4 ± 0.3 , 18.8 ± 0.2 , 21.2 ± 0.3 , 19.6 ± 0.3 , and 20.8 ± 0.3 $\mu\text{g}/\text{mg}$, respectively (Fig. 6a). BvNPs cause the cell wall to develop pits and cause the cell's proteins to leak out. The permeability of bacterial cell walls is increased by the BvNPs, which makes more protein to seep out of the cells and results in cell death (Wypij et al. 2021). The Ag⁺ ion can also arrest and disturb the structure of proteins by binding to amino groups thiol present in the cell wall. BvNPs cause the release of numerous intracellular proteins and enzymes in addition to the cell wall protein. One of the previous studies (Naik and Ramana Devi 2021) found that the protein leakage in *E.coli* and *S. aureus* were 92 $\mu\text{g}/\text{ml}$ and 81 $\mu\text{g}/\text{ml}$ after 8 h of treatment with their synthesized nanoparticles. Compared to ampicillin, BvNPs were more effective in inducing protein leakage in *Klebsiella* and *Enterobacter* strains. Two significant factors contributing to cell death are the nanoparticles size and their high surface-to-volume ratio. Nanometer-sized, spherically shaped BvNPs can readily damage cells and cause the release of proteins (More et al. 2023).

Sugar leakage in *E. kobei*, *E. clocae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, and *E. huanxiensis* cells were measured following treatment with BvNPs and ampicillin and compared with the corresponding control (Fig. 6b). In ampicillin-treated cells, sugar leakage was 20.8 ± 0.3 , 21.6 ± 0.4 , 20.9 ± 0.3 , 21.5 ± 0.2 , 20.9 ± 0.3 , and 21.5 ± 0.3 $\mu\text{g}/\text{mg}$, respectively. Following BvNPs treatment, sugar leakage increased to 22.1 ± 0.4 , 22.9 ± 0.3 ,

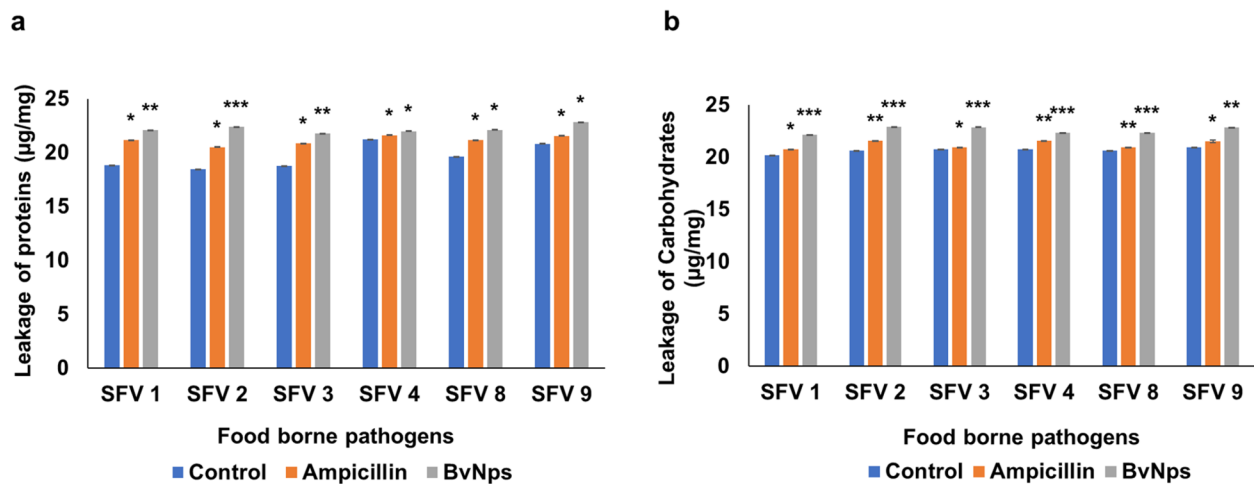


Fig. 6 Evaluating the mechanism of action of BvNPs in food borne pathogens: (a) Leakage of proteins (b) Leakage of sugars. Error bars representing means $\pm$ standard deviation. * Denotes T-test (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$)

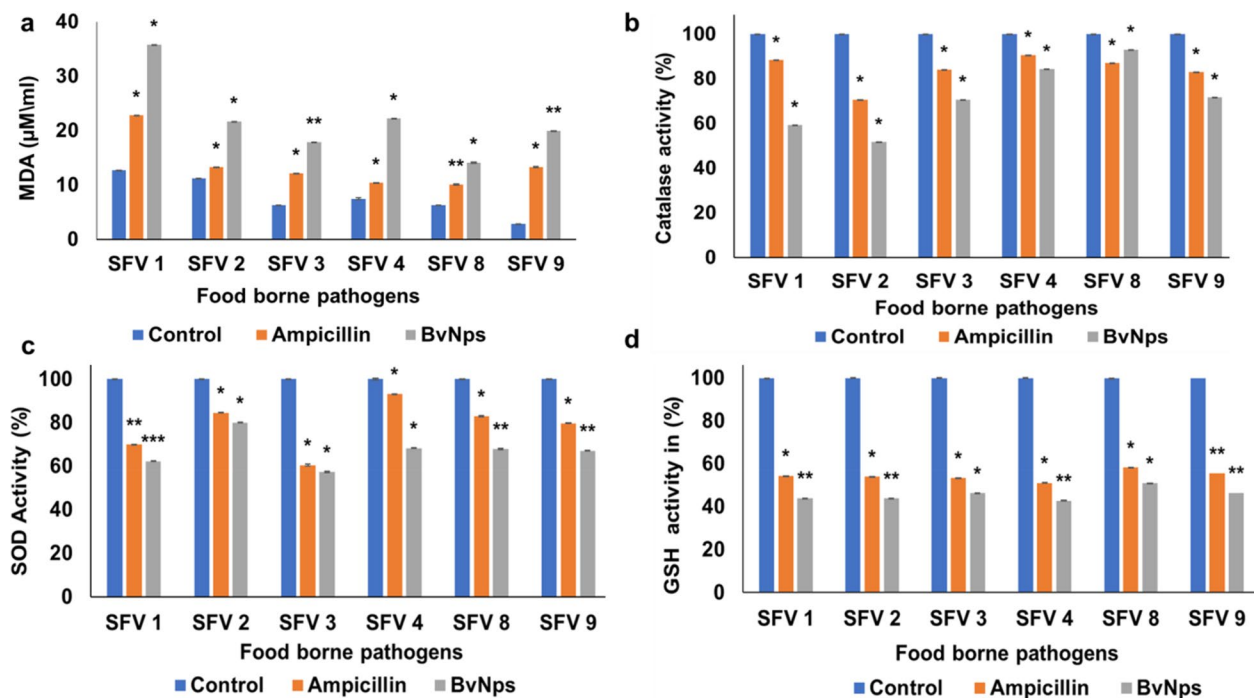


Fig. 7 Evaluating the level of oxidative stress induced by BvNPs in food borne pathogens: (a) Levels of MDA (d) CAT activity (b) SOD activity (f) GSH activity. Error bars representing means $\pm$ standard deviation. * Denotes T-test (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$)

22.9 ± 0.3 , 22.3 ± 0.3 , 22.3 ± 0.3 , and 22.8 ± 0.3 $\mu\text{g}/\text{mg}$, respectively (Fig. 6b). In *E. kobei*, *E. cloacae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, and *E. huanxiensis*, the sugar leakage progressively increases in the BvNPs treatment than with the control, ampicillin treatment. According to the research, ampicillin causes bacterial cells to release less sugar than BvNPs. The findings imply that BvNPs have the capacity to adhere to the cell wall, cause osmotic shock, penetrate the cell membrane and then trigger the release of sugar molecules. The present findings were consistent with previous research

demonstrating that AgNPs cause bacteria to significantly disrupt the membranes and seep out sugar molecules (Soundharajan and Srinivasan 2025).

Malondialdehyde is a biomarker that is produced in bacterial cells by lipid peroxidation. (Fig. 7a) illustrates how the cells treated with BvNPs may change their cellular protein and other substances that are connected to the synthesis of unsaturated aldehydes. The levels of malondialdehyde (MDA) were measured in *E. kobei*, *E. cloacae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, and *E. huanxiensis* cells following treatment with ampicillin and

BvNPs. In ampicillin-treated cells, MDA levels were 22.8, 13.3, 12.1, 10.4, 10.1, and 13.3 $\mu\text{M/ml}$, respectively. Following BvNPs treatment, MDA levels increased to 35.8, 21.6, 17.9, 22.2, 14.1, and 19.9 $\mu\text{M/ml}$, respectively. Polyunsaturated lipids are important for oxidative stress. In the bacterial strains, BvNPs treatment showed a greater release of MDA levels in comparison to control and ampicillin treatment. These results suggest that the treatment of ampicillin and BvNPs may both raise MDA levels, which could indicate the initiation of oxidative stress and lipid peroxidation. Similarly, as per previous studies (Basha et al. 2025) showed greater release of MDA levels in *E. faecalis* and *S. mutans* when treated with AgNPs. Enzymes with thiol groups and their disulfide bonds play a role in cellular metabolism, particularly in the respiratory cycle. Microorganisms experience cellular oxidative stress and reactive oxygen species (ROS) as a result of the silver ions rendering them inactive (Mikhailova 2020).

Silver ion-catalyzed H_2O_2 breakdown produces a free radical that increases ROS production and affects antioxidant activity. Catalase activity of bacterial strains treated with BvNPs and ampicillin were measured and compared to the control. Treatment of *E. kobei*, *E. cloacae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, and *E. huanxiensis* with ampicillin resulted in decreased catalase activity to 88.3%, 70.7%, 84.0%, 90.7%, 93.0%, and 83.0%, respectively. In contrast, BvNPs treatment further reduced H_2O_2 levels in *E. kobei*, *E. cloacae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, and *E. huanxiensis* to 59.3%, 51.7%, 70.0%, 84.3%, 87.0%, and 71.7%, respectively (Fig. 7b). These findings indicate that BvNPs may have a greater effect on catalase activity than antibiotic-treated cells and control, which could have an effect on the processes by which food borne pathogens respond to oxidative stress (Yuan et al. 2017; Wypij et al. 2021). AgNPs affect *Pseudomonas aeruginosa* catalase and peroxidase activities, according to previous report (Liao et al. 2019). Catalase deficiency may hinder DNA synthesis and other crucial molecules for cell viability (Liao et al. 2019).

SOD superoxide dismutase measurements in bacterial cells treated with ampicillin and BvNPs showed significant alterations as compared to the control. SOD levels were shown to drop after receiving ampicillin and BvNPs treatments as seen in (Fig. 7c). In *E. kobei*, *E. cloacae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, and *E. huanxiensis*, ampicillin treatment decreased SOD levels to 69.8%, 84.5%, 60.4%, 93.2%, 83.0%, and 79.0%, respectively. In contrast, BvNPs treatment reduced the SOD levels in these strains to 62.2%, 80.0%, 57.0%, 68.3%, 67.9%, and 67.0%, respectively. A study on nanoparticles synthesized from *Colletotrichum gloeosporioides* reported a decrease the SOD levels in *E. coli* strains following the treatment with nanoparticles, similar to the effects observed in BvNPs-treated cells. These findings

suggest that BvNPs can modulate enzyme activity, resulting in reduced SOD levels. Consequently, lower SOD activity may lead to an accumulation of reactive oxygen species (ROS), contributing to oxidative stress in comparison to untreated controls or cells treated with ampicillin (NajeerAhamed et al. 2023; Soundharajan and Srinivasan 2025; Yuan et al. 2017).

In addition to preventing oxidative stress in cells, thioredoxin and glutathione preserve the environment between the cells. Measurements of glutathione (GSH) levels were used to examine the effects of ROS production. BvNPs cause oxidative stress in cells, which results in a drop in GSH levels, and they also modify antioxidant mechanisms. GSH levels in cells treated with ampicillin were 54.4%, 54%, 53.33%, 51.06%, 58.2%, 55.43% respectively for strains *E. kobei*, *E. cloacae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, *E. huanxiensis* when compared to control represented in (Fig. 7d). GSH levels in strains of *E. kobei*, *E. cloacae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, *E. huanxiensis* treated with BvNPs were 44%, 43.8%, 46.2%, 42.7%, 51%, 46.46% respectively. These findings demonstrate that BvNPs treatment completely reduced the GSH levels (Fig. 7d). Compared to food borne pathogens treated with ampicillin, BvNPs treatment results in loss of cell survival and oxidative stress due to the reduction in GSH levels. Endophytic fungal based nanoparticles when treated with *E. coli* cells showed comparable outcomes (Kumar et al. 2024; NajeerAhamed et al. 2023). All of these results demonstrated how AgNPs disrupt homeostasis and disturb the antioxidant system of cells. According to previous report (Yuan et al. 2017), there was 80% and 70% decrease in levels of GSH in *Pseudomonas aeruginosa* and *Streptococcus aureus* in cells treated with AgNPs. Therefore, BvNPs also comparatively reduces the GSH levels in tested food borne pathogens. AgNPs on *in vitro* exposure causes lipid peroxidation, elevated ROS, decreased glutathione (GSH) levels. Increased ROS levels have been linked in certain instances to DNA damage, necrosis, and apoptosis.

Conclusion

The current study was focused on the synthesis of nanoparticles mediated by *Bauhinia Variegata* leaf extract to control food borne pathogens. The size, composition, stability, structure and the functional groups of the synthesized BvNPs were determined by various characterization techniques. Toxicity studies in *Danio rerio* embryos revealed that BvNPs were not toxic and did not cause any malformations in the tested embryos. BvNPs from *Bauhinia Variegata* leaf extract has a potential antibacterial and antibiofilm properties in various food borne pathogens namely *E. kobei*, *E. cloacae*, *K. oxytoca*, *E. bugandensis*, *E. chuandaensis*, *E. huanxiensis*. BvNPs can be employed in place of traditional antibiotics to prevent

the growth of these bacteria without causing any negative side effects. Studies on investigating the action mechanisms of BvNPs indicate that they induce oxidative stress and lipid peroxidation in treated bacterial cells, leading to increased MDA levels and the release of intracellular macromolecules, such as proteins and carbohydrates. Additionally, the treatment of BvNPs interfered with the antioxidant defense systems of bacteria, as demonstrated by changes in superoxide dismutase (SOD) activity, catalase activity and a reduction in glutathione reductase (GSH) levels. The current study implies that environmentally benign BvNPs have potential as antibacterial agents against a range of foodborne pathogens that can infect humans. In addition, these nanoparticles may be explored for applications in food preservation, by potentially reducing the reliance on chemical preservatives. BvNPs could also be incorporated with biopolymers and applied as thin coatings on packaging films, offering a sustainable alternative to conventional plastic and other non-biodegradable wrapping materials.

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Authors' contributions

SH conceived and designed research. MM and SR conducted experiments. SH analysed data. All authors wrote the manuscript. All authors read and approved the manuscript.

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Data availability

Data will be available on request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

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References

- Abdel-Tawab M, Werz O, Schubert-Zsilavecz M (2011) *Boswellia serrata*: an overall assessment of in vitro, preclinical, pharmacokinetic and clinical data. Clin Pharmacokinet 50:349–369
- Adeyemi JO, Oriola AO, Onwudiwe DC, Oyedele AO (2022) Plant extracts mediated metal-based nanoparticles: synthesis and biological applications. Biomolecules 12(5):627
- Ahmed S, Ikram S (2015) Silver nanoparticles: one pot green synthesis using *Terminalia arjuna* extract for biological application. J Nanomed Nanotechnol 6(4):1–6
- Ahn EY, Jin H, Park Y (2019) Assessing the antioxidant, cytotoxic, apoptotic and wound healing properties of silver nanoparticles green-synthesized by plant extracts. Mater Sci Eng C 101:204–216
- Almatroudi A (2020) Silver nanoparticles: synthesis, characterisation and biomedical applications. Open Life Sci 15(1):819–839
- Basha SBA, Soundhararajan R, Srinivasan H (2025) *Solanum virginianum* mediated green nanoparticles to control dental pathogens. Discov Appl Sci 7(1):67
- Biswas R, Alam M, Sarkar A, Haque MI, Hasan MM, Hoque M (2022) Application of nanotechnology in food: processing, preservation, packaging and safety assessment. Heliyon 8(11):e11795
- Fahimirad S, Ajallouei F, Ghorbanpour M (2019) Synthesis and therapeutic potential of silver nanomaterials derived from plant extracts. Ecotoxicol Environ Saf 168:260–278
- Ghasemi S, Dabirian S, Kariminejad F, Koochi DE, Nemattalab M, Majidmoghadam S, Yousefbeyk F (2024) Process optimization for green synthesis of silver nanoparticles using *Rubus discolor* leaves extract and its biological activities against multi-drug-resistant bacteria and cancer cells. Sci Rep 14(1):4130
- Gopinath V, MubarakAli D, Priyadarshini S, Priyadarshini NM, Thajuddin N, Velusamy P (2012) Biosynthesis of silver nanoparticles from *Tribulus terrestris* and its antimicrobial activity: a novel biological approach. Colloids Surf B Biointerfaces 96:69–74
- Haggag EG, Elshamy AM, Rabeh MA, Gabr NM, Salem M, Youssif KA, Haggag E, Elshamy A, Rabeh M, Gabr N, Youssif K, Samir A, Bin Muhsinah A, Alsayari A, Abdelmohsen UR (2019) Antiviral potential of green synthesized silver nanoparticles of *Lampranthuscoccineus* and *Malephora lutea*. Int J Nanomed 14:6217–6229
- Harborne JB (1998) Phytochemical methods: a guide to modern techniques of plant analysis, 3rd ed. Chapman & Hall, London, UK
- Kumar D, Soundhararajan R, Srinivasan H (2024) Screening the efficacy of platinum-based nanomaterial synthesized from *Allium sativum* to control plant pathogens. J Mater Sci Mater Eng 19(1):29
- Liao S, Zhang Y, Pan X, Zhu F, Jiang C, Liu Q, Cheng Z, Dai G, Wu G, Wang L, Chen L (2019) Antibacterial activity and mechanism of silver nanoparticles against multidrug-resistant *Pseudomonas aeruginosa*. Int J Nanomed 14:1469–1487
- Madhumitha H, Ranjani S, Karunyaa JR, Hemalatha S (2023) Clitoria Ternatea Floral Mediated Synthesis, Characterization, Antioxidant, and Cytotoxicity Evaluation of Silver Nanoparticles: Clitoria ternatea floral mediated SNP to control BC. Archives of Breast Cancer 222–231
- Mikhailova EO (2020) Silver nanoparticles: mechanism of action and probable bio-application. J Funct Biomater 11(4):84
- More PR, Pandit S, Filippis AD, Franci G, Mijakovic I, Galdiero M (2023) Silver nanoparticles: bactericidal and mechanistic approach against drug resistant pathogens. Microorganisms 11(2):369
- Nadaroglu H, Güngör AA, Ince S (2017) Synthesis of nanoparticles by green synthesis method. Int J Innov Res Rev 1(1):6–9
- Naik LS, Ramana Devi CV (2021) Phyto-fabricated silver nanoparticles inducing microbial cell death via reactive oxygen species-mediated membrane damage. IET Nanobiotechnol 15(5):492–504
- NajeerAhamed MJ, Soundharajan R, Srinivasan H (2023) Antibacterial, antibiofilm, and antivirulence effects of nanoparticles synthesized from *Colletotrichum gloeosporioides* in pathogenic *E. coli*. Microb Pathog 185:106420
- Nunes CDR, Barreto Arantes M, Menezes de Faria Pereira S, Leandro da Cruz L, de Souza Passos M, Pereira de Moraes L, Vieira IJC, Barros de Oliveira D (2020) Plants as sources of anti-inflammatory agents. Molecules 25(16):3726
- Patra JK, Das G, Fraceto LF, Campos EVR, Rodriguez-Torres MDP, Acosta-Torra LS, Acosta-Torres LS, Diaz-Torres LA, Grillo R, Swamy MK, Sharma S, Habtemariam S, Shin HS (2018) Nano based drug delivery systems: recent developments and future prospects. J Nanobiotechnology 16:1–33
- Raju R, Prasad AS, Kumar R (2024) Anti-inflammatory and antioxidant activity of Neem and Kirata-Induced silver nanoparticles against oral biofilm: an in vitro study. Cureus 16(8):e67708
- Ranjani S, Hemalatha S (2023) Influence of polyherbal nanoformulation on plant growth and biochemical constituents in legume seedlings. J Plant Growth Regul 42(11):7142–7150
- Ranjani S, Karunya JR, Hemalatha S (2022) Differential actions of nanoparticles and nanoemulsion synthesized from *Colletotrichum siamense* on food borne pathogen. LWT 155:112995
- Shahana S, Nikalje APG, Nikalje G (2017) A brief review on *Bauhinia variegata*: phytochemistry, antidiabetic and antioxidant potential. Am J Pharmtech Res 7:186–197

- Shi M, Liao P, Nile SH, Georgiev MI, Kai G (2021) Biotechnological exploration of transformed root culture for value-added products. *Trends Biotechnol* 39(2):137–149
- Soliman MK, Hashem AH, Al-Askar AA, Abdelgayed G, Salem SS (2024) Green synthesis of silver nanoparticles from *Bauhinia variegata* and their biological applications. *Green Process Synth* 13(1):20240099
- Soundharajan R, Srinivasan H (2025) *Camellia sinensis* mediated nanoparticles to control growth and biofilm in *Vibrio* sp. *Aquac Int* 33(3):1–19
- Wypij M, Jędrzejewski T, Trzcińska-Wencel J, Ostrowski M, Rai M, Golińska P (2021) Green synthesized silver nanoparticles: antibacterial and anticancer activities, biocompatibility, and analyses of surface-attached proteins. *Front Microbiol* 12:632505
- Yuan YG, Peng QL, Gurunathan S (2017) Effects of silver nanoparticles on multiple drug-resistant strains of *Staphylococcus aureus* and *Pseudomonas aeruginosa* from mastitis-infected goats: an alternative approach for antimicrobial therapy. *Int J Mol Sci* 18(3):569
- Zhang XF, Liu ZG, Shen W, Gurunathan S (2016) Silver nanoparticles: synthesis, characterization, properties, applications, and therapeutic approaches. *Int J Mol Sci* 17(9):1534

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