Journal of Chemical Health Risks

www.jchr.org

JCHR (2026) 16(2), 2123-2134 | ISSN:2251-6727

Biosynthesis of Mesoporous Silica Nanoparticles Using *Adansonia digitata* for *in vitro* Anticancer, Antidiabetic and Drug Release Applications

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(Received: 16 January 2026 Revised: 25 February 2026 Accepted: 17 March 2026)

KEYWORDS
Mesoporous Silica Nanoparticles, *Adansonia digitata*, Drug Release, Anticancer Activity, Good Health And Well-Being

ABSTRACT:
In the present work, mesoporous silica nanoparticles were synthesized using *Adansonia digitata* leaf extract through a green approach. The use of the plant extract helped limit the use of harsh chemicals and also improved the biological nature of the material. The formation of the nanoparticles was confirmed by SEM and FTIR studies. SEM images showed nanosized particles with irregular to near spherical shapes and a rough surface appearance. FTIR analysis revealed the presence of hydroxyl and organic functional groups along with characteristic silica bands, indicating that plant-derived compounds were present on the nanoparticle surface. During biological studies, the nanoparticles showed a noticeable reduction in the growth of MCF-7 breast cancer cells with increasing concentration. The IC_{50} value was calculated to be close to 25 µg/mL, suggesting a moderate cytotoxic effect. In addition, the nanoparticles exhibited good free radical scavenging activity, showing more than 60 percent inhibition at higher concentrations, although the activity was slightly lower when compared to the standard compound. In the inflammation study, the nanoparticles showed a clear increase in inhibition with increasing concentration and at higher doses the effect was close to the standard drug. The antidiabetic study indicated moderate inhibition of α-amylase, with nearly 50% inhibition at 75 µg/mL, while the standard drug showed stronger activity. Drug release experiments showed an initial faster release followed by a slower release over time, with almost complete release within 24 hours. Taken together, the results indicate that *Adansonia digitata* extract based mesoporous silica nanoparticles show multiple biological effects along with controlled release behavior. Further animal studies are needed, but the findings suggest that this system may be useful for combined therapeutic applications.

1. Introduction

Cancer and diabetes are among the most challenging long term disorders faced by modern health systems. Their burden is rising in both developed and developing regions and the cost of treatment remains high for many patients. Cancer therapy often suffers from low selectivity and strong side effects while diabetes management demands sustained and controlled drug availability over long periods. Because of these limits there is strong interest in new material based systems that can deliver drugs in a safer and more effective manner while also offering added biological benefits such as antioxidant and anti-inflammatory activity [1]. Nanotechnology has opened new ways to deliver drugs using very small carrier systems that work at a very fine level. One material that has gained attention is mesoporous silica. It has open spaces inside it and a stable nature which makes it useful for holding drugs and releasing them slowly over time. Mesoporous silica is also seen as suitable for biological use because it works well with cells and its surface can be changed

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JCHR (2026) 16(2), 2123-2134 | ISSN:2251-6727

easily [2]. Because of this it has been studied widely for cancer treatment and also for problems related to metabolism such as diabetes. In recent years more interest has been shown in combining nanomaterials with natural plant sources. Plant extracts contain many active substances like polyphenols flavonoids and organic acids. These compounds are known to show antioxidant, anti-inflammatory and anticancer effects. When plant extracts are used during nanoparticle preparation the use of harmful chemicals is reduced and biological activity is added at the same time. This plant based approach follows environmentally friendly ideas and is generally seen as suitable for medical use [3]. *Adansonia digitata* which is commonly known as baobab has been used for many years in traditional medicine. Different parts of the plant are used to manage inflammation infections blood sugar imbalance and problems linked with oxidative stress. The fruit pulp leaves and bark contain vitamin C phenolic compounds and dietary fiber. Several studies have reported its antioxidant nature and its role in reducing inflammation and helping with glucose regulation [4]. Because of these properties *Adansonia digitata* is considered a useful biological source for developing multifunctional therapeutic materials.

When *Adansonia digitata* extract is used during the synthesis of mesoporous silica nanoparticles it provides both physical and biological benefits. The extract can act as a natural stabilizing agent during particle formation. Some plant derived compounds may remain on the surface after synthesis. This leads to a combined system where the silica structure provides stability and drug loading ability while the plant compounds contribute biological effects [5]. Such a system may improve therapeutic performance without making the formulation complicated. In cancer treatment controlled drug delivery is important to reduce damage to healthy tissues. Tumor regions often show a slightly acidic environment when compared to normal tissues. This difference can help promote drug release at the tumor site. When combined with antioxidant and anti-inflammatory components from Adansonia digitata the system may help reduce oxidative stress and inflammatory signals that support tumor growth [6]. This combined effect may improve treatment response. In a similar way diabetes management can also benefit from controlled drug release. Many commonly used antidiabetic drugs show changes in blood levels which may reduce effectiveness or lead to unwanted side effects. A mesoporous silica based delivery system can release drugs gradually over time helping to maintain stable glucose control. In addition the antioxidant properties of *Adansonia digitata* may protect pancreatic cells from oxidative damage which is known to play a role in diabetes progression [7]. Thus a single nanoplatform can address both drug delivery and disease related oxidative stress. Oxidative stress and inflammation are common factors linking cancer and diabetes. Excess reactive oxygen species can damage DNA proteins and lipids leading to cellular dysfunction. Chronic inflammation further worsens this damage and promotes disease progression. Antioxidant and anti-inflammatory agents can interrupt these harmful pathways. Plant based compounds are especially valuable because they often act through multiple mechanisms and show lower toxicity. Incorporating such compounds into a nanocarrier system allows them to be delivered more efficiently to target tissues [8].

2. Methods

Preparation of Adansonia digitata Extract

Adansonia digitata leaves were collected and washed well with tap water to clear away dirt and unwanted material. After cleaning the leaves were spread in a shaded place and allowed to dry naturally at room conditions until they were completely dry. After drying the material was crushed manually and powdered using a clean grinder to obtain a fine texture. About 10 g of the powdered material was placed into a beaker filled with distilled water. The mixture was heated slowly at a mild temperature to allow the bioactive compounds to leach into the solvent. After heating the extract was left undisturbed to cool naturally. The cooled mixture was filtered through Whatman filter paper to remove solid residues. The obtained clear extract was collected and preserved at 4 °C for further use in the synthesis of nanoparticles [9].

Preparation of MS/Nps

Mesoporous silica nanoparticles (MS/Nps) were prepared by following a sol gel based procedure with defined quantities. Initially 50 mL of sodium silicate solution was taken in a clean beaker as the silica source. To this solution 10 mL of the previously prepared

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Adansonia digitata leaf extract was added slowly drop wise under constant stirring. The stirring was maintained at room temperature to allow proper mixing. To make the mixture alkaline, 1 M sodium hydroxide solution was added slowly until the pH reaches close to 10. The mixture was then stirred continuously for about 6 hours, during which a pale white solid gradually appeared. The formed solid was separated by centrifugation at 8000 rpm for 10 minutes. After separation, the solid was washed several times with distilled water and then with ethanol to remove remaining impurities. Finally, the material was dried in a hot air oven at 60 °C for 12 hours. The dried nanoparticle powder was stored in air tight containers for further studies. Different working concentrations were freshly prepared using distilled water before biological analysis [10].

Infrared Study (FTIR)

Fourier-transform infrared spectroscopy (Nicolet 5700, Thermo Scientific) was used to clarify the *Adansonia digitata* MSNps. The KBr pellet method was used to prepare the samples, which were then analyzed over 500-4000 cm-1. The observed vibration bands confirmed that the nanoparticles were formed successfully and that plant-based compounds were present on their surface [11].

Surface Morphology using SEM

Adansonia digitata mesoporous silica nanoparticles were observed using SEM (JEOL JSM5600LV, Japan). The samples were first spread on polycarbonate sheets and then dried using a CO_2 critical point drying method to remove any remaining moisture. Before taking images, the samples were coated with a thin layer of gold to improve conductivity. The SEM images made it possible to see the general shape, size range and surface appearance of the particles, giving a clear idea about their overall formation [12].

In vitro Cell Culture

Human breast cancer MCF 7 cell line was procured from National Center for Cell Sciences Pune India. The cells were grown in Dulbecco's Modified Eagle's Medium which was enriched with required nutrients for proper cell survival. The culture medium contained L glutamine at a concentration of 2 mM sodium bicarbonate 1.5 g per liter sodium pyruvate 1 mM and glucose 4.5 g per liter along with 10 percent fetal bovine serum obtained from Gibco USA. Since MCF 7 cells require hormonal support insulin was added to the medium at a final concentration of 10 µg per mL to enhance cell growth. To avoid microbial contamination penicillin 100 IU per mL and streptomycin 100 µg per mL were included in the medium. The cells were maintained in a humidified incubator at 37 oC with 5 percent CO_2 atmosphere and were sub cultured regularly for experimental use [13].

Cytotoxicity Evaluation (MTT Assay)

Nanoparticle-induced cytotoxicity was quantified via MTT assay. Cells seeded (1×10^4/well)in 96-well plates were exposed to graded nanoparticle concentrations for 48 hours. Post incubation with MTT (0.5 µg/ml, PBS) formazan crystals were solubilized and absorbance was measured at 570 nm [14, 15]. Cell viability percentages were derived accordingly.

Cell viability(%)=((OD of treated sample)/(OD of control)) x 100

Antioxidant Assay

The antioxidant potential of the extracts was evaluated using the DPPH free radical scavenging method. For this assay, a fresh 0.1 mM solution of DPPH was prepared in methanol and protected from light to avoid degradation. Different concentrations of the plant extracts were made and each was mixed in equal proportion with the DPPH solution. The reaction mixtures were then allowed to stand at room temperature in the dark for about 30 minutes. After incubation, the change in absorbance was recorded at 517 nm using a UV-Visible spectrophotometer. Ascorbic acid was used as the standard reference compound. The ability of the extracts to scavenge DPPH radicals was expressed as percentage inhibition and calculated using the following formula:

% Inhibition= (A0-A1)/A0 × 100

Where A_0 denotes the absorbance of the control sample containing only the DPPH solution and A_1 refers to the absorbance of the solution mixed with the plant extract. The IC_{50} value-representing the concentration required to neutralize 50% of DPPH radicals was calculated to compare antioxidant efficiency among the extracts. All

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assays were carried out in triplicate and the results were expressed as mean ± standard deviation[16].

Assessment of Inflammation Inhibitory Potential

The inflammation-reducing ability of the extracts was examined using the protein denaturation method. The reaction mixture was prepared to a final volume of 5 mL, consisting of 0.2 mL bovine serum albumin (BSA) 2.8 mL phosphate-buffered saline (PBS, pH 6.4) and 2 mL of the extract at different concentrations. For the control, distilled water was used in place of the extract. All samples were first incubated at 37°C for 15 minutes and then heated at 70°C for 5 minutes to induce protein denaturation. Once cooled back to room temperature, the absorbance was recorded at 660 nm using a suitable blank. Diclofenac sodium was used as the standard drug and treated under the same experimental conditions.[17, 18].

% Inhibition-(Absorbance of Control-Absorbance of the sample)/(Absorbance of Control) x 100

Evaluation of α-Amylase Inhibition Activity

The α-amylase inhibitory activity of *Adansonia digitata* extract-based mesoporous silica nanoparticles was evaluated using an In vitro enzyme inhibition assay. The reaction mixture was prepared by adding 500 mL of 0.006 M sodium chloride, 0.02 M monosodium phosphate buffer and porcine pancreatic α-amylase enzyme (0.5 µg/mL) to a 1% starch solution made in 0.02 M sodium phosphate buffer. This mixture was allowed to incubate at 25°C for 10 minutes. After incubation, different concentrations of the synthesized mesoporous silica nanoparticles (25, 50, 75 µg/mL) were added to the reaction mixture. After a few seconds, 1.0 mL of dinitrosalicylic acid (DNSA) reagent was added to stop the enzymatic reaction. The mixture was then heated for 5 minutes, followed by an additional incubation for 10 minutes at 25°C and finally kept at room temperature (29 ± 2°C). The absorbance was measured at 540 nm using a UV-visible spectrophotometer (Systronics, India) after diluting the mixture with 10 mL of distilled water. The enzyme solution without nanoparticles was used as the control. The IC_{50} value was calculated to determine the inhibitory efficiency.

% α- amylase inhibition = At- Ac/Ac × 100

Where, At = absorbance of test sample; Ac = absorbance of control [19,20].

Enzyme Mediated Drug Release Study

For the release study, each nanoparticle formulation was dispersed in 10 mL of phosphate-buffered saline, followed by the addition of 1 mL of chitinase solution. The samples were incubated at 37°C under constant shaking at 100 rpm. At predetermined time intervals of 1, 3, 5 and 24 hours, 1 mL of the supernatant was withdrawn and centrifuged at 9,000 rpm for 5 minutes [20, 21]. An equal volume of fresh buffer was added back to maintain the total volume. The cumulative percentage of extract released from the nanoparticles was calculated using the following equation:

(Drug Released at Time (t)/ Total Drug Content)× 100

3. Results and Discussion

Surface Morphology

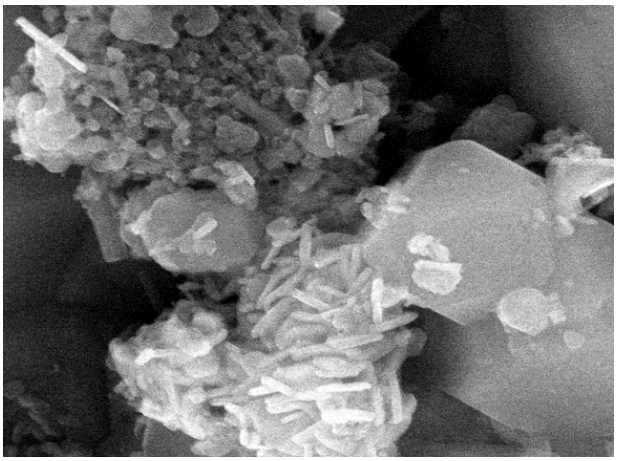

Fig 1. SEM *Adansonia digitata MSNps,* displaying irregularly shaped, nanoscale sheets with varying sizes and orientations, typical of graphene oxide structures

The Surface morphology of *Adansonia digitata* mediated MSNps (Figure 1) shows that the particles are formed in a clustered manner rather than being completely isolated. Most of the nanoparticles appear irregular to near spherical in shape with some plate like and rod type structures attached on the surface. This kind of mixed morphology is commonly seen in plant based synthesis where different phytochemicals take part in reduction and stabilization at the same time. The surface of the particles looks rough and uneven which

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suggests successful capping by bioactive compounds present in *Adansonia digitata* (Figure 1). In several regions the nanoparticles are closely packed and slightly agglomerated which may be due to drying during sample preparation or natural attraction between particles. Still the overall structure indicates formation of mesoporous silica nanoparticles with visible pores and layered texture. The variation in particle size can also be observed clearly (Figure 1). This size difference may be linked to non-uniform nucleation during synthesis which is expected in green synthesis routes. Overall the SEM image confirms the successful formation of MSNps using *Adansonia digitata* extract and supports its role as a natural reducing and stabilizing agent (Figure 1). The rough and uneven surface texture of the nanoparticles strongly suggests effective surface capping by bioactive compounds present in *A. digitata* leaf extract. Similar surface features have been reported for biosynthesized silica and metal oxide nanoparticles, where phytochemical adsorption not only stabilizes the nanoparticles but also contributes to enhanced surface functionality and biological activity [22].

FTIR analysis

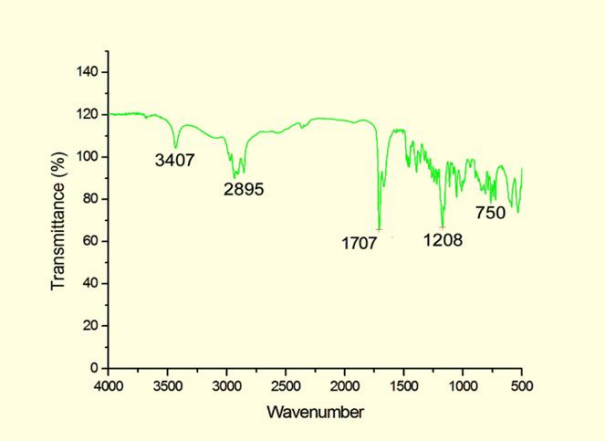

Figure 2. FTIR spectrum of *Adansonia digitata* extract mediated mesoporous silica nanoparticles showing characteristic peaks corresponding to hydroxyl groups, organic functional groupsand Si-O-Si vibrations, confirming successful green synthesis and silica framework formation.

The FTIR results of *Adansonia digitata* extract mediated mesoporous silica nanoparticles are presented in Figure 2. A broad band seen around 3400 cm^{-1} is related to O-H stretching, which may come from hydroxyl groups present in the plant compounds as well as silanol groups on the silica surface. This suggests that the plant extract interacted well with the nanoparticle surface. A weak signal observed near 2920 cm^{-1} corresponds to C-H stretching of aliphatic groups, indicating the presence of organic residues from the extract that may act as stabilizing agents. The band around 1630 cm-1 is mainly linked to bending of absorbed water molecules and may also involve C=O stretching from plant based compounds attached to the silica framework. A strong band in the range of 1080-1100 cm^{-1} is associated with Si-O-Si asymmetric stretching, confirming the formation of the silica structure. Additional bands observed near 800 cm^{-1} and 460 cm^{-1} are related to symmetric stretching and bending of Si-O-Si bonds. Overall, the FTIR pattern supports the successful formation of mesoporous silica nanoparticles using *Adansonia digitata* extract, which is in agreement with the SEM observations shown in Figure 1. Similar FTIR patterns characterized by broad O-H stretching vibrations (3200-3500 cm-1), aliphatic C-H stretching bands (2850-2950 cm^{-1}) and intense Si-O-Si asymmetric stretching peaks (1080-1100 cm-1) have been widely reported in plant-mediated synthesis of silica nanoparticles. These functional groups are mainly associated with phenolic hydroxyls, alcohols, carboxyl and other oxygen-containing biomolecules present in plant extracts, which play a crucial role in the reduction, surface capping and stabilization of the nanoparticles [23].

***In vitro* cytotoxicity by MTT assay of *Adansonia digitata MSNps* on MCF-7 cell line**

The cytotoxic activity of *Adansonia digitata* based mesoporous silica nanoparticles against MCF-7 cells was examined using the MTT assay and the findings are presented in Figure 3. The control cells that were not treated showed high viability, which indicates normal and healthy cell growth. With increasing nanoparticle concentration, a gradual reduction in cell viability was observed. Lower concentrations (5 and 10 µg/mL) caused only mild reduction in viability, while a clear decrease was seen at 25 and 50 µg/mL. At 100 µg/mL cell viability reduced to around 30 percent, indicating strong growth inhibition. The IC_{50} value was found to be close to 25 µg/mL, which indicates a moderate level of cytotoxic effect of the nanoparticles on MCF-7 breast

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cancer cells. In general, the results show that inhibition of cell growth increased with rising nanoparticle concentration. Comparable dose-dependent cytotoxic effects have also been reported in studies involving mesoporous silica-based nanoparticles against MCF-7 breast cancer cells. Similarly, bare and drug-loaded mesoporous silica nanoparticles have been reported to significantly reduce MCF-7 cell viability in a concentration-dependent manner, highlighting the intrinsic cytotoxic potential of silica nanostructures and the enhancement of therapeutic effects upon functionalization [24]. In addition, polydopamine-coated mesoporous silica nanoparticles loaded with umbelliprenin were shown to markedly inhibit MCF-7 cell proliferation through enhanced cellular internalization and induction of programmed cell death, supporting the role of surface modification in improving anticancer efficacy [25]. These studies provide a basis for interpreting the moderate IC_{50} observed in the present work, suggesting that both the mesoporous silica framework and associated phytochemical surface capping contribute synergistically to the cytotoxic response in breast cancer cells.

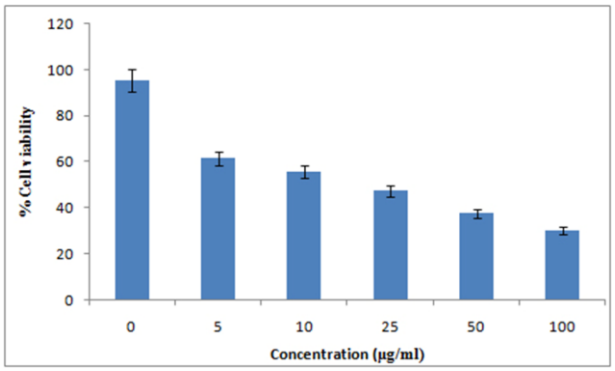

Figure 3. *In vitro* cytotoxic activity of *Adansonia digitata* extract mediated mesoporous silica nanoparticles against MCF-7 breast cancer cells assessed by MTT assay after 48 hours. Data are expressed as mean ± SD (n = 3).

In vitro DPPH assay

The antioxidant potential of *Adansonia digitata* based mesoporous silica nanoparticles was assessed by the DPPH radical scavenging method and the results are shown in Figure 4. The nanoparticles displayed higher radical scavenging activity as the concentration increased across the tested range. At 25 µg/mL, only low inhibition was observed when compared to ascorbic acid. With an increase to 50 µg/mL, the inhibition percentage increased noticeably and At this concentration the activity was nearly comparable to that of the standard. When the concentration reached 75 µg/mL, the nanoparticles showed a strong scavenging effect with inhibition exceeding 60 percent, whereas ascorbic acid produced a marginally higher response. These results indicate that the synthesized nanoparticles possess good antioxidant potential and their activity increases with concentration. Similar concentration-dependent DPPH radical scavenging activity has been reported for green-synthesized silica nanoparticles, where antioxidant behavior is mainly attributed to surface-bound phytochemicals such as phenolics and hydroxyl-containing compounds [26]**.** In that study, silica nanoparticles synthesized using *Tridax procumbens* leaf extract showed increased DPPH inhibition with rising concentration, reaching activity comparable to standard antioxidants. Likewise, bio-fabricated silica nanomaterials synthesized using plant residues demonstrated significant free-radical scavenging efficiency due to phytochemical capping [27]**.** The results of the present study are therefore in good agreement with these reports, confirming that *Adansonia digitata*-mediated mesoporous silica nanoparticles possess effective, dose-dependent antioxidant potential.

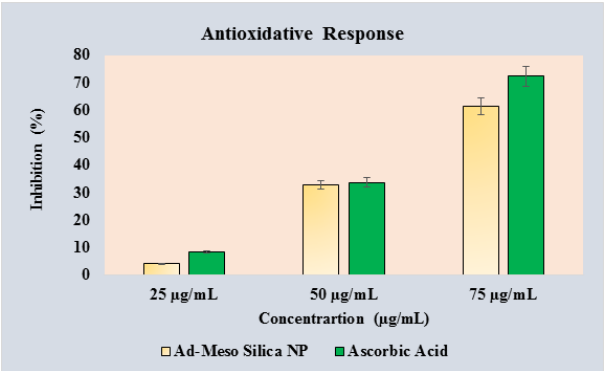

Figure 4. *In vitro* antioxidant activity of *Adansonia digitata* extract mediated mesoporous silica nanoparticles compared with ascorbic acid at different concentrations (25, 50and 75 µg/mL) using the DPPH radical scavenging assay. Values are expressed as mean ± SD (n = 3).

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In vitro anti-inflammatory activity

The anti-inflammatory activity of *Adansonia digitata* mediated mesoporous silica nanoparticles was evaluated using the protein denaturation assay and the results are shown in Figure 5. The nanoparticles exhibited a clear concentration dependent increase in inhibition percentage across the tested concentrations. At 25 µg/mL, only minimal inhibition was observed, indicating a weak response at lower concentration. When the concentration was increased to 50 µg/mL, a noticeable rise in inhibition was seen and the activity was comparable to that of the standard drug diclofenac sodium. At 75 µg/mL, the nanoparticles showed strong anti-inflammatory activity with inhibition close to 70 percent. This inhibition was higher than that observed for diclofenac sodium at the same dose. The findings indicate that the nanoparticles show good anti-inflammatory activity and the effect becomes stronger as the concentration increases. Comparable concentration-dependent anti-inflammatory effects have been documented for bio-fabricated nanoparticles using protein denaturation assays, where inhibition of protein unfolding reflects anti-inflammatory potential. Studies on green-synthesized silver and zinc oxide nanoparticles demonstrated dose-dependent inhibition of protein denaturation with increasing concentrations, showing activity approaching that of standard drugs such as diclofenac sodium in BSA and egg albumin assays, which has been attributed to surface-bound phytochemicals stabilizing protein structures and mitigating inflammatory responses [28]**.** Furthermore, reviews on plant-mediated green synthesis report that nanoparticles capped by plant phytochemicals often show enhanced anti-inflammatory activity compared with non-functionalized particles due to biomolecule interactions with inflammatory pathways [29]**.** These observations support the present findings, where *Adansonia digitata*-mediated mesoporous silica nanoparticles exhibited a clear concentration-dependent increase in protein denaturation inhibition, indicating effective anti-inflammatory potential.

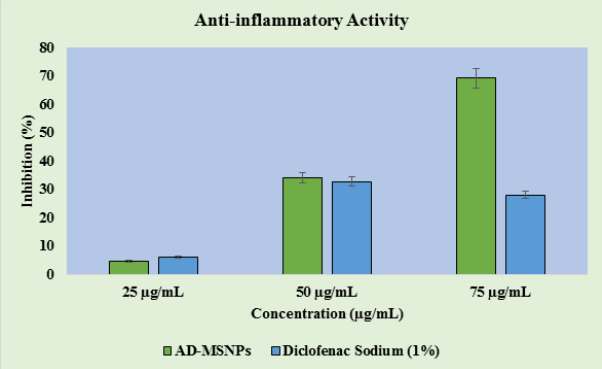

Figure 5 Anti-inflammatory effects of *Adansonia digitata* MSNps *Vs* Diclofenac Sodium (1%) at 25, 50and 75 µg/mL show dose-dependent inhibition. NPs achieve comparable efficacy to Diclofenac Sodium at higher concentrations, with significant differences noted at 50 µg/mL (+$p < 0.05$) and 75 µg/mL (±$p < 0.05$).

Enzyme Mediated Drug Release study

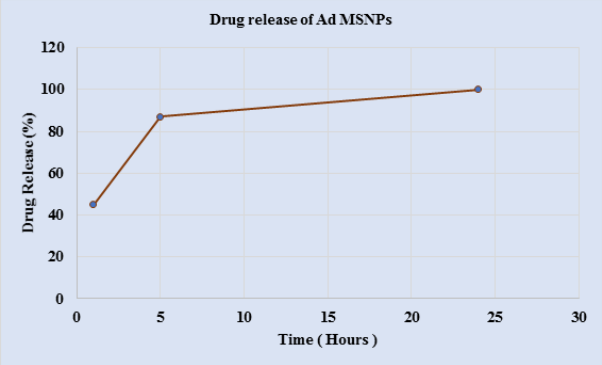

Figure 6. *In vitro* drug release profile of *Adansonia digitata* MSNPs showing a rapid initial release within 5 hours and sustained release up to 24 hours, approaching nearly 100% cumulative release.

The drug release from *Adansonia digitata* based silica nanoparticles was checked under controlled conditions and the results are shown in Figure 6. At the beginning, the drug was released faster during the first few hours and later the release slowed down gradually. Nearly 45% of the drug came out within the early hours, which may be because some drug was loosely present on the particle surface. Around 5 hours, the release increased quickly and reached about 85%, showing that the drug was moving out from inside the particles. After this point, the release became slower and almost complete release was seen by 24 hours. This type of release suggests that the particles can give an initial amount of

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drug followed by a longer release, which is useful for treatments that need steady drug availability. The biphasic drug release pattern observed in the present study, characterized by an initial burst release followed by sustained release up to 24 h, is a well-recognized behavior of mesoporous silica nanoparticles. Similar release profiles have been reported for drug-loaded MSNs, where the early rapid release is attributed to surface-adsorbed drug molecules, while the prolonged release results from diffusion of drug molecules from the mesoporous channels [30,31]. Enzyme-responsive and biologically triggered release from silica nanoparticles has also been shown to improve controlled drug availability at the target site, enhancing therapeutic efficiency. The present findings are therefore consistent with established MSN-based drug delivery systems and highlight the suitability of *Adansonia digitata*-mediated silica nanoparticles for sustained drug release applications.

α-Amylase Inhibition Activity

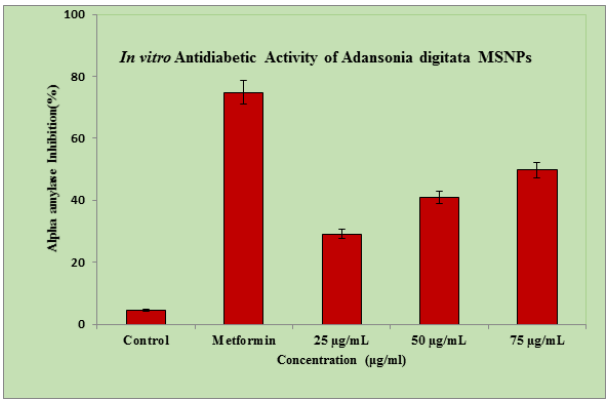

Figure 7. *In vitro* antidiabetic activity of *Adansonia digitata* extract mediated mesoporous silica nanoparticles measured by α-amylase inhibition assay at different concentrations (25, 50and 75 µg/mL). Metformin was used as the standard drug. Values are expressed as mean ± SD (n = 3).

The antidiabetic activity of *Adansonia digitata* based silica nanoparticles was examined *In vitro* using the α-amylase inhibition method and the results are presented in Figure 7. The control samples, which did not contain nanoparticles, showed almost no inhibition, indicating that the enzyme was working normally under the test conditions. Metformin used as the standard drug exhibited strong inhibition, validating the assay conditions. The nanoparticles showed a concentration dependent increase in α-amylase inhibition. At 25 µg/mL, moderate inhibition was observed, which increased further at 50 µg/mL. At the highest tested concentration of 75 µg per mL the inhibition reached close to 50 percent which shows effective suppression of the enzyme. Even though the activity was lower when compared to metformin the results still suggest that the nanoparticles have clear antidiabetic potential and may help in controlling carbohydrate digestion. Concentration-dependent α-amylase inhibition similar to the present findings has been widely reported as a standard indicator of antidiabetic potential. The α-amylase inhibition assay is a well-established in vitro method for screening agents that can delay carbohydrate digestion and reduce post-prandial hyperglycemia [32]. Several studies have shown that materials containing plant-derived polyphenols and hydroxyl-rich compounds exhibit dose-dependent α-amylase inhibition due to enzyme-inhibitor interactions at the active site [33]. The observed inhibitory effect of *Adansonia digitata*-mediated mesoporous silica nanoparticles is therefore consistent with established antidiabetic screening models.

Morphological and apoptotic changes

The morphological changes induced by Adansonia digitata-mediated mesoporous silica nanoparticles in MCF-7 cells are shown in Figure 8. Control cells (Figure 8A and Figure 9A) exhibited normal spindle-shaped morphology with intact cell membranes and good adherence to the culture surface, indicating healthy cell growth. In contrast, cells treated with the nanoparticles at the IC_{50} concentration showed clear morphological alterations (Figure 8B and Figure 9B). The treated cells appeared shrunken with loss of normal shape, reduced adherence, and an increased number of floating cells. Membrane blebbing and cell condensation were also observed, which are typical features associated with apoptotic cell death. These visible changes were in agreement with the cytotoxic effects observed in the MTT assay. Fluorescent staining further confirmed the progression of cell death. The untreated control cells mainly exhibited green fluorescence (Figure 9A), indicating viable cells with intact membranes, whereas nanoparticle-treated cells showed increased orange and red fluorescence (Figure 9B), suggesting membrane and nuclear damage. This

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distinct change in fluorescence pattern indicates apoptotic cell death rather than necrosis.

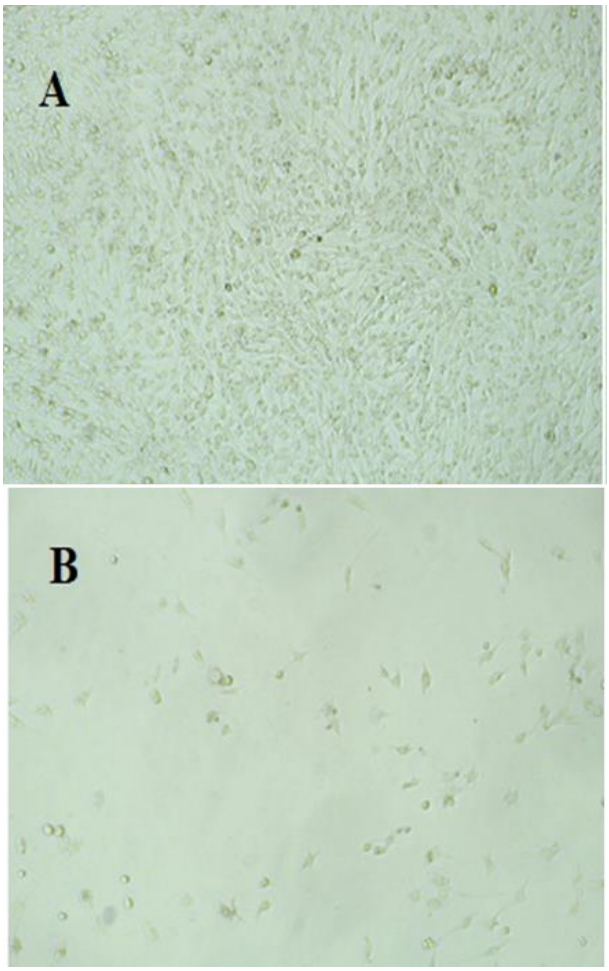

Figure 8. Morphological changes in MCF-7 breast cancer cells treated with *Adansonia digitata* mediated mesoporous silica nanoparticles. (A)Control cells showing normal morphology with intact cell structure and good adherence. (B)Cells treated with nanoparticles at IC_{50} concentration (22 µg/mL) showing cell shrinkage, loss of adherence, membrane blebbingand increased floating cells. Images were captured using an inverted phase contrast microscope at 10× magnification.

Overall, the microscopic observations are consistent with the concentration-dependent cytotoxic effects of the nanoparticles on breast cancer cells. The morphological alterations and fluorescence staining patterns observed in treated MCF-7 cells are classical indicators of apoptosis. Acridine orange/ethidium bromide (AO/EtBr) dual staining is a well-established technique for distinguishing viable, apoptotic, and necrotic cells based on membrane integrity and chromatin condensation [34]**.** Cell shrinkage, membrane blebbing, nuclear condensation, and the shift from green to orange/red fluorescence are hallmark features of programmed cell death [35]**.** The present observations therefore strongly confirm apoptosis-mediated cytotoxicity induced by *Adansonia digitata*-mediated mesoporous silica nanoparticles.

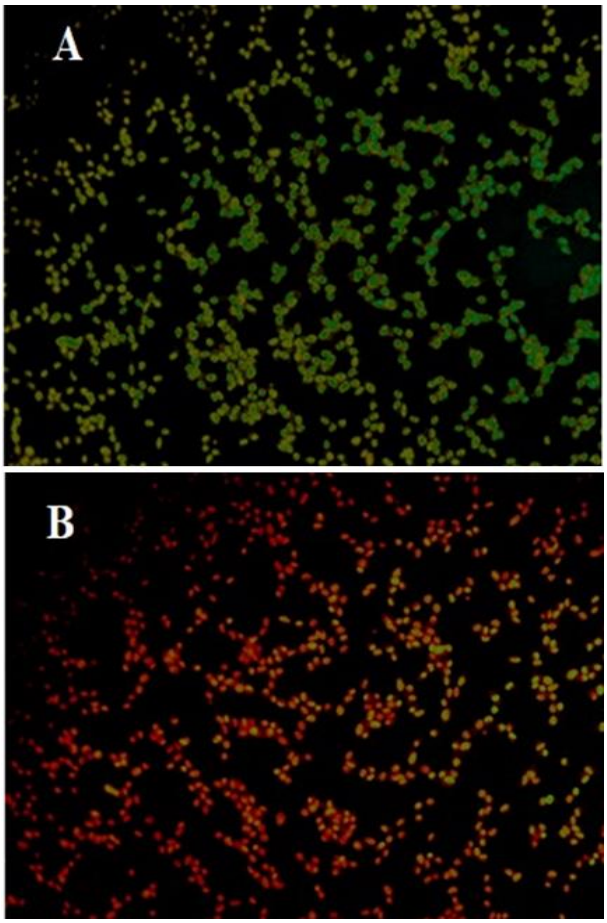

Figure 9. Fluorescence microscopy images showing apoptotic changes in MCF-7 cells after treatment with *Adansonia digitata* mediated mesoporous silica nanoparticles. (A)Control cells showing predominant green fluorescence indicating viable cells. (B)Treated cells showing increased orange and red fluorescence, indicating loss of membrane integrity and apoptotic cell death. Images were captured using a fluorescent microscope at 10× magnification.

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JCHR (2026) 16(2), 2123-2134 | ISSN:2251-6727

4. Conclusion

In the present work mesoporous silica nanoparticles were developed using *Adansonia digitata* extract through a green preparation method. The use of plant extract helped reduce chemical usage and also improved the biological nature of the material. Structural examination showed that the particles had suitable surface features which were confirmed through SEM and FTIR studies. Biological testing revealed that the nanoparticles slowed down the growth of MCF-7 breast cancer cells as the concentration increased. Along with this the particles showed antioxidant anti-inflammatory and antidiabetic activity at measurable levels. The drug release experiment showed that the loaded material was released in a controlled manner over time which supports its possible role as a delivery system. In some of the biological tests the activity was lower than that of standard drugs. Still the overall response showed that the nanoparticles were active in more than one biological aspect. This indicates that plant based mesoporous silica nanoparticles may be useful for combined therapeutic purposes. More work is still needed mainly detailed mechanism studies and animal level testing to confirm safety and long term effects. Overall this study adds useful information toward the development of eco-friendly nanomaterial that may find future use in biomedical applications.

Funding Statement

There is no funding.

Data Availability

Data will be made available on request

CRediT authorship contribution statement

Vimal S: Investigation, Methodology, Writing - original draft & editing, Supervision. **Pavithra R**: Investigation, Supervision, Writing - review & editing. **Mohamed Faiz Farook Mohamed Aboobucker:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Rubina Mary A**: Conceptualization, Methodology, Writing - review & Software**. Balaji MB**: Conceptualization, Methodology, Investigation, Writing - review & editing. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval

Ethical approval was not required for this research.

Consent to participate

All participants gave their consent to participate.

Consent for publication

The manuscript has never been published in other journals.

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