

Green Synthesis Of Silica Nanocomposites With Coal Fly Ash Using Curry Leaves: A Review

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Abstract:

The production of coal fly ash from thermal power plants increases day-by-day due to coal being used, it has now emerged as one of the greatest environmental challenges facing many countries, particularly in areas like Korba, which belongs to Chhattisgarh. Fly ash, due to its high silica content, could be used for synthesizing Nano-silica but at the same time, fly ash pollution leads to environmental and health concerns due to air, soil, and water contamination. Therefore, this paper aims to review the green synthesis of Nano silica composites from fly ash using curry leaf (*Murraya koenigii*).

Green technology has received much interest as it does not make use of any poisonous substances and causes less harm to the environment. The curry leaf extract is known for the existence of phytochemicals like flavonoids, phenols, alkaloids, and antioxidants which involved in stabilization processes while forming silica nanoparticles. The present paper covers silica extraction, green synthesis technique, and characterization method using XRD, SEM, TEM, FTIR, and BET analysis.

The uses of silica nanocomposites consist of environmental remediation, catalytic applications, agriculture, antimicrobial activity, and biomedicine. The conversion of waste material to wealth promotes the concepts of sustainable development and green chemistry by using industrial waste materials.

Background: Korba, located in Chhattisgarh, generates huge quantities of fly ash due to its coal-fired thermal power plants, resulting in environmental pollution and disposal issues. As fly ash is abundant in silica, silica nanocomposites can be obtained from fly ash by using green methods of synthesis. Green chemistry through curry leaves extract provides a more sustainable approach than the traditional chemical process since the plant holds bioactive components that plays a role in the production of silica nanoparticles. The technique transforms waste materials into usable nanocomposites, thereby promoting green chemistry and sustainable development.

Materials and Methods: The fly ash that was employed in the experiments conducted during this work was sourced from thermal power plants burning coal and was the major source of raw material for the preparation of silica. The fly ash was first dried, sieved, and purified to remove the impurities in it along with the carbon particles. In this regard, it was reacted with a solution of sodium hydroxide (NaOH) at controlled heat conditions that dissolves the silica to form of sodium silicate. Further, the solution of sodium silicate was allowed to precipitate through the addition of hydrochloric acid (HCl) to form silica gel. Then, repeatedly washing is done using distil water to remove residual salts and impurities. The prepared silica gel dried and calcinated at elevated temperatures to produce pure silica nanocomposites.

Freshly harvested curry leaves (*Murraya koenigii*) were sourced locally, washed, shade dried, and boiled in distilled water to obtain plant extracts. These plant extracts were enriched with various phytochemicals such as flavonoids, tannins, alkaloids, polyphenols, and other antioxidants and were act as a reducing agent for green silica nanocomposites preparation. Analysis of prepared materials included XRD, TEM, SEM, BET surface analysis, FTIR, and UV-Visible spectroscopy.

Results: The formation of silica nanocomposites via coal fly ash is a sustainable technique for turning industrial wastes into useful nanomaterials. The green synthesis technique using plant extracts has emerged as a safe alternative to the traditional synthesis techniques in that it utilizes fewer amounts of hazardous chemicals. Such silica nanomaterials find wide usage in various industries including environmental restoration, catalytic processes, agriculture, and even in biomedicine thanks to their unique characteristics. More research is still needed for synthesis of plant-based nanocomposites and their production in mass.

Key Word: Green Synthesis, Nano composites, Silica Nano composites, Fly Ash, *Murraya koenigii*

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I. Introduction

Rapid industrial growth, urbanization, and increasing energy demands have caused a significant rise in industrial waste generation across the world. Among these wastes, coal-based thermal power plants producing fly

ash were environmental issue because of its large quantity and improper disposal practices (Ahmaruzzaman, 2010). Fly ash is a powder material. It is formed by the burning of coal. It is generally stored in ash ponds or dumped in landfills leads to several environmental problems. These problem includes air pollution, soil degradation, groundwater contamination, and ecological imbalance (Yao et al., 2015). In India, as major source of electricity is thermal power plants yields tons of fly ash every year (Pandey & Singh, 2010). Korba as industrial hub large number of coal-based power plants and industries located there. The continuous accumulation of fly ash makes serious environmental as well as public health concerns. So sustainable waste management very crucial (CPCB, 2021).

While fly ash is normally considered an industrial waste, but it consists of useful mineral such as Al_2O_3 , Fe_2O_3 , Calcium Oxide, silica (SiO_2), and other trace components (Blissett & Rowson, 2012). Amid these silica has expanded scientific importance for of its varied applications in nanotechnology, electronics, catalysis, adsorption, environmental clean-ups, sensors, and biomedical engineering (Imoisili et al., 2022). Silica nanocomposites exhibits exceptional properties like high surface capacity, porosity, thermal stability, biocompatibility, and adjustable surface chemistry, eventually suitable for many innovative technological applications (Rovani et al., 2018).

Conventionally, silica nanocomposites are produced using costly chemical materials such as tetraethyl orthosilicate (TEOS) and sodium silicate through hazardous processes (Stöber et al., 1968). These traditional methods increase manufacture costs and environmental hazards, decreasing their sustainability. To overcome these scientists are focusing on green synthesis methods which are safer, eco-friendly, and cost-effective. Green nanotechnology uses natural and distinct biological materials like plant extracts as well as agricultural waste to synthesise nanoparticle (Ahmed et al., 2016). Among these methods, plant-based synthesis become more and more popular as it is simple, economical, and suitable for large-scale production (Singh et al., 2018).

Plant extracts comprise natural compounds like terpenoids, proteins, tannins, alkaloids, flavonoids, phenolic compounds, and other antioxidants helps in the creation and stabilization process of nanoparticles (Mittal et al., 2013). Among medicinal plants, *Murraya koenigii*, commonly known as curry leaves, has attracted significant attention because of its unique phytochemical composition and medicinal value. Curry leaves have alkaloids, flavonoids, phenols, glycosides, and essential oils which show antioxidant, antimicrobial, anti-inflammatory, and reducing properties (Nayak et al., 2020). Due to these properties, curry leaves can efficiently assist the synthesis nanoparticle without the use of harmful chemicals. Additionally, curry leaves are extensively available in Chhattisgarh, India for its sustainable and low-cost application for green nanotechnology.

Silica nanocomposites synthesis from coal fly ash using curry leaf extract as an innovative approach combines industrial waste use with green chemistry principles. This eco-friendly technique helps in reducing environmental pollution side by side producing valuable nanomaterials with sustainable improved properties (Barani et al., 2024). Fly ash-derived silica nanocomposites prepared by biological methods shows vital applications in wastewater treatment, agriculture, antimicrobial coatings, food packaging, drug delivery, heavy metal removal, catalysis, and biomedical engineering (Ruiz et al., 2021). Current studies show that nanocomposites can be used in remove dyes and toxic pollutants from contaminated water, as antibiotics due to porous assembly and high surface area (Houghton et al., 2025).

In agriculture, silica nanocomposites can be used as sustainable Nano fertilizers that improve nutrient delivery and plant growth (Singh et al., 2024). Based on recent research plant-based green synthesis may reduce environmental toxicity and upkeep sustainable nanomaterial production (Rani et al., 2025). Studies published between 2021 and 2026 have progressively focused on producing silica from industrial waste and use of plant extracts for eco-friendly nanoparticle production (Imoisili et al., 2024).

Recent studies show only a few review studies related to eco-friendly synthesis of fly ash-derived silica nanocomposites using curry leaf extract were available. Thus, this review study targets to provide a detailed outline of synthesis of silica nanocomposites using coal fly ash, via green synthesis assisted curry leaf extract, its characterization techniques, the ecological and industrial uses of silica nanocomposites. Distinct emphasis is given to the sustainable fly ash management in industrial regions such as Korba, where better-quality waste management and resource recovery techniques are essential for sustainable development.

II. Material And Methods

Study Area and Collection of Raw Materials

In this study, Fly ash collected from various coal-based thermal power plants in Korba, Chhattisgarh is major industrial and thermal power areas of India. The region is known for its thermal power plants, which generate large amount of coal fly ash. Fresh fly ash is collected in sanitized polyethene containers directly from precipitator units and disposal sites. Afterward these samples were carefully transported to the laboratory and kept in dry conditions to avoid contamination and moisture absorption (Ahmaruzzaman, 2010).

Fly ash samples dried at $105^{\circ}C$ in a hot air oven for 24 hours to remove moisture content. Dried samples were crushed using mortar and pestle then sieved through a fine mesh of 100–200 μm to get uniform particle size.

Impurities like unburned carbon particles, stones, and metallic materials were manually removed before silica extraction (Blissett & Rowson, 2012).

Fresh curry leaves (*Murraya koenigii*) were collected at different locations around Korba like local gardens and agricultural areas. Healthy curry leaves were sorted for the preparation of plant extract. In all over experiment process distilled water was used to lessen the contamination from dissolved minerals and other impurities.

Chemicals and Reagents

For silica extraction and nanoparticle synthesis chemicals of analytical-grade solution, hydrochloric acid (HCl) solution, sodium hydroxide (NaOH), ethanol, and distil water were used. During the experimental procedure all glassware and laboratory equipment were washed properly and cleaned with distilled water before use (Imoisili et al., 2022).

Curry Leaf Extract preparation

The extract of curry leaf was prepared using a green synthesis method (Ahmed et al., 2016). Fresh and healthy curry leaves were washed in tap water and distilled water subsequently to remove dirt and other surface impurities. At room temperature leaves were dried for about 5–7 days in shade preserving vital phytochemicals like flavonoids and other phenolic compounds. Subsequently, leaves were crushed into powder using a laboratory grinder.

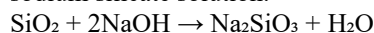
For extract preparation around 20–25 gm of curry leaf powder added to 200 mL of distilled water and heated at temperature of 70–80°C for nearly 30 minutes with constant stirring. The process of heating helped to release bioactive compounds from the plant material into the solution. Cooling of extract is done unless reached to room temperature filtered using Whatman No. 1 filter paper to separate solid particles. This prepared extract stored at 4°C for further experiments.

Curry leaves comprise of significant phytochemicals like alkaloids, terpenoids, glycosides, flavonoids, tannins, proteins, along with some supplementary phenolic compounds. These compounds play the role of reduction, stabilization, and capping in synthesis of silica nanoparticle, also improves nanoparticles stability and biocompatibility (Nayak et al., 2020).

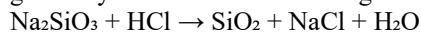
Extraction of Silica nanocomposites using Fly Ash

Silica extracted from fly ash using the alkaline extraction and acid precipitation method, is usually used for silica retrieval from industrial waste materials (Rovani et al., 2018). In the process around 50 gm of purified fly ash added to 250–300 mL of 2–3 M sodium hydroxide solution in a borosilicate glass beaker. Heating this mixture at 90–100°C for 2–4 hours with constant stirring in magnetic stirrer.

In alkaline treatment, silica particles present in fly ash reacts with sodium hydroxide to form soluble sodium silicate solution.



Eventually, the mixture was filtered in order to separate insoluble residues from the sodium silicate solution. The filtrate containing sodium silicate cooled to room temperature, and then hydrochloric acid was added gradually with continuous stirring until the pH reached around 7–8 and silica gel is formed.



This silica gel was kept for 12–24 hours to improve particle growth and structural stability. After aging, the gel washed repetitively with distil water till neutral pH – 7 was achieved and other salts and impurities removed. The purified gel dried at 100–110°C then, calcination at 600–700°C in a muffle furnace for 3–5 hours (Imoisili et al., 2022). Research shows that alkaline extraction followed by acid precipitation is one of the operational and economical methods for producing silica from coal fly ash (Chambioso et al., 2025).



Figure – 1 AI-assisted flow diagram of fly ash-derived silica nanoparticle extraction using chemical digestion and precipitation techniques, created and modified by the authors.

Green Synthesis of Silica Nanocomposites

Green synthesis of silica nanocomposites was supported using extract from *Murraya koenigii* as a natural stabilizing and coating agent. About 1 g of synthesized silica nanoparticles was mixed with distilled water and dispersed properly using magnetic stirring and ultra-sonication to obtain a uniform suspension. After this, a suitable amount of curry leaf extract was added slowly while continuous stirring was maintained.

The reaction mixture heated at 60–80°C for 2–3 hours to increase the interaction between silica nanoparticles and the essential phytochemicals contained in the curry leaf extract. Bio compounds like flavonoids, phenols, proteins, as well as alkaloids attached to the nanoparticles' surface acting as capping and stabilizing agents. These biomolecules assisted to prevent nanoparticle agglomeration in order to improve the stability of nanocomposites (Singh et al., 2018).

The preparation of silica nanocomposites was observed through many changes like turbidity and surface appearance of the suspension. The synthesized nanocomposites were separated by the centrifugation method and washed a number of times with distil water after that with ethanol to remove unwanted plant residues as well as unreacted substances. Finally, purified nanocomposite material synthesized was dried either at room temperature and placed in airtight containers used for further characterization and application. Researches shows that plant-based green synthesis methods offer environmentally friendly, low-cost, and sustainable approaches for nanoparticle fabrication (Barani et al., 2024; Rani et al., 2025).

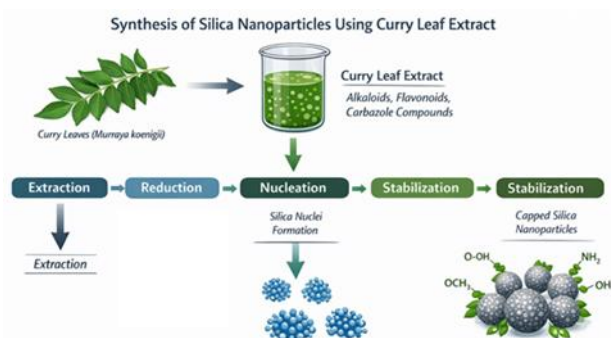


Figure – 2 AI-generated representation of green synthesis of fly ash-derived silica nanoparticles using curry leaf (*Murraya koenigii*) extract, created and edited by the authors.

Characterization of Silica Nanocomposites

Analytical spectroscopic techniques used to study the properties of the synthesized silica nanocomposites. To determine the crystallinity, phase composition, and structure X-ray diffraction analysis done. Scanning electron microscopy for surface morphology and particle aggregation, while transmission electron microscopy carried out for thorough information about size, shape, and distribution of the synthesized nanoparticle.

To study the interaction between silica nanoparticles and phytochemicals from *Murraya koenigii* extract, identification the functional groups present Fourier transform infrared spectroscopy (FTIR) analysis carried out. UV–Visible spectroscopy for optical properties, Brunauer–Emmett–Teller (BET) was done to estimate size of pore, porosity, and area of surface of the synthesized nanocomposites (Ruiz et al., 2021).

Recent researches on fly ash-derived silica nanoparticles stated the formation of Nano sized particles with high porous structure and extraordinary surface area, making them appropriate for environmental remediation and biomedical applications (Imoisili et al., 2024; Singh et al., 2024).

Comparative Review and Data Analysis

This review article included the analysis of published research articles, review papers, and experimental studies testified between 2001 and 2026 related to silica nanoparticles prepared from fly ash and plant-based green synthesis approaches. Comparative analysis was done on the basis of efficiency of silica extraction, nanoparticle size and structure, their morphology and surface properties, phytochemical interactions as well as environmental impact, and industrial applications.

Special consideration was given to eco-friendly nanotechnology techniques which use locally available coal fly ash and bio materials like curry leaves for sustainable nanoparticle synthesis. The reviewed studies show that combining coal fly ash and curry leaves extract with the approach of green synthesis provides an effective sustainable industrial development and environmental remediation.

III. Result And Discussion

The research studied from 2001 to 2026 show coal fly ash converted into silica nanoparticles and silica-based nanocomposites using environmentally friendly green synthesis techniques. This approach combines managing industrial waste with green nanotechnology. Also provides a sustainable method for reducing environmental pollution and remediation. In industrial regions like Korba, large amount of coal fly ash was produced. Converting this waste into nanomaterials provides both environmental remediation and economic well-being.

Physicochemical Properties of Fly Ash

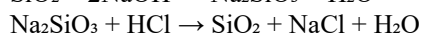
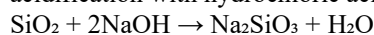
Characterization studies shows fly ash has an enormous amount of silica along with some Al_2O_3 , iron oxide, CaO , MgO , and additional trace minerals. The amount of silica content ranges from 40% to 65%, as per the variety of coal used and combustion condition in thermal power plants (Blissett & Rowson, 2012). The high amount of amorphous silica in fly ash gives it an appropriate raw material for silica nanocomposites synthesis.

Fly ash comprises both crystalline and amorphous phases as revealed from XRF and X-ray diffraction XRD. Minerals such as quartz and hematite were commonly recognized, though the amorphous silica phase played a significant role in silica extraction (Yao et al., 2015) from coal fly ash. Further SEM analysis indicated that particles of fly ash are mostly spherical with high porosity because of rapid cooling in the course of coal combustion. These porous assembly growths the chemical reactivity of fly ash during extraction.

Pre-treatment methods like drying, sieving, acid washing, and magnetic separation provides better-quality fly ash and silica recovery is very large. The removal of unburned carbon and metallic impurities increased the quality of the silica nanoparticles produced (Ahmaruzzaman, 2010).

Silica Extraction Efficiency

Alkaline extraction followed by acid precipitation is the most operative techniques for silica recovery from fly ash. In the process sodium hydroxide reacts with silica in fly ash to form sodium silicate then after acidification with hydrochloric acid forms silica.



According to some researchers' silica extraction lies between 60% and 90%, subject to factors like temperature, concentration of alkali used, pH of solution, and reaction time (Imoisili et al., 2022). Higher concentration of sodium hydroxide and elevated temperatures improved silica dissolution, while excess heating sometimes causes impurity formation and nanoparticle agglomeration.

Calcination temperature similarly affects nanoparticle quality. Calcination at 600°C – 700°C produced highly pure amorphous silica nanoparticles with improved thermal stability and high surface area (Rovani et al., 2018). However, very high temperatures reduced porosity due to crystallization of silica particles.

Role of Curry Leaf Extract in Green Synthesis

Extract from *Murraya koenigii* leaves played an essential role for green synthesis of silica nanocomposites. Curry leaves contain bioactive compounds like alkaloids, terpenoids, glycosides, flavonoids, polyphenolic acids, and other antioxidants plays as natural reducing, capping, and agents of stabilization for the synthesis of silica nanocomposites (Nayak et al., 2020).

The phytochemicals present in curry leaf extract interacted with silica nanoparticles to form stable nanocomposite structures. These natural compounds prevented nanoparticle aggregation to improved particle stability and dispersion. Green synthesized nanoparticles displayed smaller particle size and more uniform morphology as compared to chemically synthesized nanoparticles (Ahmed et al., 2016).

Additionally, plant-mediated synthesis reduces the use of toxic chemicals. Unlike ancient conventional methods that need harmful reducing agents and surfactants. Curry leaf-mediated synthesis offers a safer, cost effective, and sustainable eco-friendly alternative for nanoparticle synthesis.

Characterization for Structural and Morphological properties

X-Ray Diffraction (XRD)

XRD analysis confirm the formation of silica nanocomposites from fly ash. Furthermost studies reported broad diffraction peaks near $2\theta = 22^\circ$, specified the amorphous morphology of silica nanoparticles (Imoisili et al., 2022). Amorphous silica is highly appropriate for adsorption as well as catalytic applications due to its extraordinary surface activity and high porous assembly.

Some studies also reported weak crystalline peaks related to quartz and mullite because of residual fly ash minerals. Higher calcination temperatures promoted partial crystallization of silica structures.

Scanning Electron Microscopy (SEM)

Synthesized silica nanoparticles were irregular, and porous structures with some spherical shape confirmed by SEM analysis. Green synthesized nanoparticles showed lower agglomeration because phytochemicals from curry leaf extract stabilized the nanoparticle surface. The porous structure observed in SEM images is beneficial for adsorption and catalytic applications.

Transmission Electron Microscopy (TEM)

Nanoscale with particle sizes from 20 to 100 nm depending on synthesis conditions as confirmed from TEM analysis. Uniform particle distribution and lower aggregation were commonly observed in samples leads to smaller nanoparticle size, increased area of surface to improve environmental and biomedical performance (Ruiz et al., 2021).

Fourier Transform Infrared Spectroscopy (FTIR)

Functional groups such as Si–O–Si and Si–OH vibrations established by FTIR analysis in silica. Peaks in phenolic compounds and flavonoids displays interaction between silica nanocomposites and different phytochemicals from *Murraya koenigii* extract (Singh et al., 2018). These show enhanced the nanoparticle stability and bio compatibility.

BET Surface Area Analysis

The synthesized silica nanocomposites possessed high surface area and mesoporous structure showed in BET analysis. Extraction and calcination conditions are responsible for surface properties. Due to high surface area and abundant porosity the silica nanocomposites are beneficial for adsorption, catalysis, and controlled drug delivery applications.

Environmental Applications

Studies shows there is a high usefulness of environmental application of fly ash-derived silica nanocomposites. The high porosity and adsorption capacity of silica nanocomposites are effective in removing pollutants from waste water systems.

Studies testified that silica nanocomposites are effective in elimination of toxic heavy metals like lead, cadmium, chromium, arsenic etc. from contaminated water (Ahmaruzzaman, 2010). Silica nanocomposites also effective in dye removal like methylene blue, rhodamine B, and different textile wastewater pollutants.

The high area of surface and active poly-functional groups increases the adsorption and surface mechanisms. These results show that silica nanocomposites are beneficial for sustainable water purification technologies.

Modern studies published between 2021 and 2026 further confirmed that fly ash-derived silica nanoparticles possess extraordinary adsorption capacity and mesoporous structure fit for environmental clean-ups applications (Imoisili et al., 2024; Idowu et al., 2026). Nanoparticles are effective in removing antibiotics and dyes from wastewater due to their highly active surface sites stated by Houghton et al. (2025).

Biomedical and Agricultural Applications

Green synthesized silica nanocomposites showed capable antimicrobial activity against different bacterial and fungal pathogens. This antimicrobial property was associated to both nanoscale silica properties and the bioactive compounds existing in curry leaves (Nayak et al., 2020). These properties make silica nanocomposites more useful in wound healing supplies, biomedical coatings, food packaging, and pharmaceutical applications.

In agriculture, silica nanoparticles give better-quality seed germination, nutrient uptake, and lessen environmental stress in plant resistance. Studies also stated that amine-functionalized silica nanocomposites derived from coal fly ash can give sustainable Nano fertilizers for nutrient delivery in controlled way and improvement in crop productivity (Singh et al., 2024).

Biocompatibility studies describes plant-mediated silica nanoparticles have lower toxicity as compared to chemically synthesized nanoparticles leads to suitability for biomedical uses like drug delivery and tissue engineering.

Sustainability with Waste-to-Wealth Approach

The reviewed studies support the converting industrial waste of fly ash into valuable nanomaterials through green synthesis methods. In a region such as Korba, where accumulation of fly ash is a chief environmental issue, utilization fly ash for silica nanoparticle manufacture can reduce waste removal problems and environmental pollution and remediation.

The curry leaf extract improves sustainability by using biological resources instead of toxic synthetic chemicals. This combined approach pays a path to green chemistry principles, strategies for circular economy and goals for sustainable development. Synthesis of silica nanocomposites from low-cost waste materials like fly ash creates opportunities for sustainable industrial growth.

Challenges and Future Perspectives

In spite of the progress, some challenges still remain for large-scale manufacture and commercialization of fly ash-derived silica nanocomposites. Variations in fly ash chemical composition from various thermal power plants also affect silica extraction efficiency and quality of nanoparticle.

Further Studies are necessary to boost synthesis conditions, uniformity in nanoparticle shape, size and morphology. Toxicity studies, lifecycle assessments, and industrial-scale evaluations are also essential before commercial use.

Overall, the combination of fly ash utilization and green nanotechnology delivers a promising and sustainable approach. It also aimed at environmental management and advanced nanomaterial production in industrial regions such as Korba.

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