Research Article

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Sustainable Nanotechnology in Forensics: Advances in Latent Fingerprint Development Using Plant-based Materials

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ABSTRACT

This research explores the application of green nanotechnology in latent fingerprint development using nanoparticles derived from plant waste materials. Rice husk, neem, potato, lemon, and orange peels were evaluated as eco-friendly nanoparticle sources. The study compared their efficacy on latent fingerprints across various surfaces, assessing clarity, ridge detail, and minutiae visualization. Rice husk nanoparticles demonstrated superior results, achieving approximately 90% fingerprint visibility across all tested surfaces, followed by neem (~85%). Potato peel nanoparticles showed moderate effectiveness (~78%), particularly on porous substrates, while lemon and orange peel nanoparticles underperformed (~72% and ~68%, respectively) with limited fine-detail resolution. Rice husk and neem NPs revealed diverse ridge features (bifurcations, deltas, islands, terminations), whereas citrus-based powders displayed fewer visible minutiae. The green synthesis approach offers a sustainable, cost-effective alternative to conventional methods by reducing the use of hazardous chemicals. This improvement in fingerprint clarity and detail suggests that plant waste–derived nanomaterials could serve as sustainable alternatives to toxic reagents in forensic investigations. By directly comparing five agricultural waste sources under consistent conditions, this study addresses a key knowledge gap in eco-friendly forensic techniques. These findings highlight the potential of agricultural waste–derived nanomaterials in enhancing latent fingerprint visualization. Future work will explore additional plant waste sources and practical forensic applications of these eco-friendly nanoparticles.

Keywords: Green nanotechnology; Latent fingerprints; Agricultural waste; Forensic science; Sustainable development.

1. INTRODUCTION

Fingerprints, distinguished by their characteristic patterns of ridges, have long been a cornerstone in forensic identification in accordance with Locard's exchange principle, wherein object interactions create an exchange of trace evidence (Hiroi, 2021). Latent fingerprint identification, or prints not visible to the naked eye, has conventionally depended upon powders or chemicals; however, these are frequently undermined by aged or dirty prints, as well as environmental toxicity and occupational hazards, being a concern (Berry and Stoney, 2001; Görög, 2000). Emerging frontiers in nanotechnology provide for the employment of nanoparticles, in particular those from green chemistry based upon plant extracts, as environmentally safe substitutes with higher sensitivity and specificity in latent finger detection (Prasad *et al.* 2020; Gautam *et al.* 2023; Champod, 2015).

It is worth mentioning that plant-derived nanoparticles—the ones produced based on bioactive molecules such as phenolics, alkaloids, and flavonoids—are gaining enormous popularity because of their chemical stability as well as efficacy in the field of forensic science (Khan *et al.* 2022; Sab; Singh *et al.* 2023c). These green nanomaterials have better penetration of fingerprint materials, thus yielding better contrast, along with higher permanency, in a manner compliant with principles of sustainability as well as safety (Prabakaruan and Pillay, 2021; Bhati and Tripathy, 2020; Lohar *et al.* 2022). Based on research, metallic nanoparticles, such as silver and gold, along with metallic oxides, quantum as well as carbon dots, significantly enhance latent fingerprint visibility over different substrates, which include porous ones (Sharma *et al.* 2023; Kesarwani *et al.* 2021; Singh *et al.* 2023a).

Silver nanoparticles, in particular, offer substantial contrast and versatility in fingerprint enhancement, exhibiting promising results in liquid as well as powdered forms (Kesarwani *et al.* 2021). The field is advancing in terms of introducing eco-friendly nanoparticles developed out of ingredients like lycopodium, spirulina, wheatgrass, and turmeric, ushering in sustainable developments in forensic fingerprint detection (Prabakaran and Pillay, 2021; Rajan *et al.* 2024).

Notably, there exists a significant discrepancy in the scientific appraisal of the practicality and optimization of forensic applications for plant-derived nanoparticles. The current work aspires to address such a gap in a discourse concerning a new method of synthesizing, characterizing, and utilizing plant-derived nanocarbons for developing latent fingermarks, pursuing environmentally responsible approaches while meeting the rigorous standards required for handling criminal evidence (Assis *et al*. 2022; Koehler *et al*. 2023).

Despite these advances, systematic comparisons of multiple plant waste sources for latent fingerprint development remain limited. To fill this gap, we synthesized nanoparticles from five different agricultural wastes (rice husk, neem leaves, potato peel, lemon peel, orange peel) and evaluated their performance on various substrates. This study aims to identify the most effective plant-based nanoparticle and demonstrate a sustainable alternative to conventional toxic fingerprint reagents.

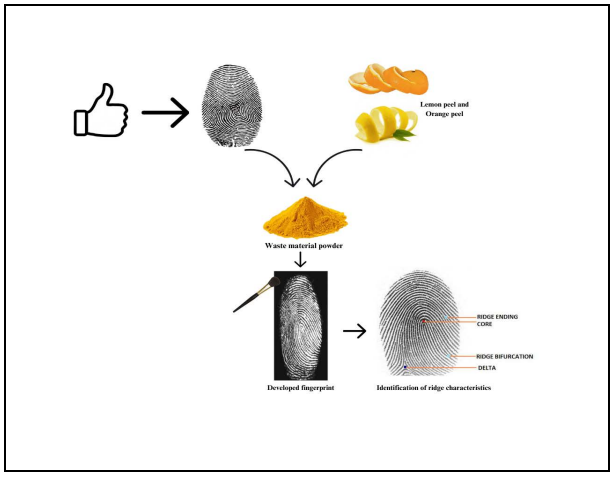


Fig. 1: Development of fingerprint powder using nanomaterials

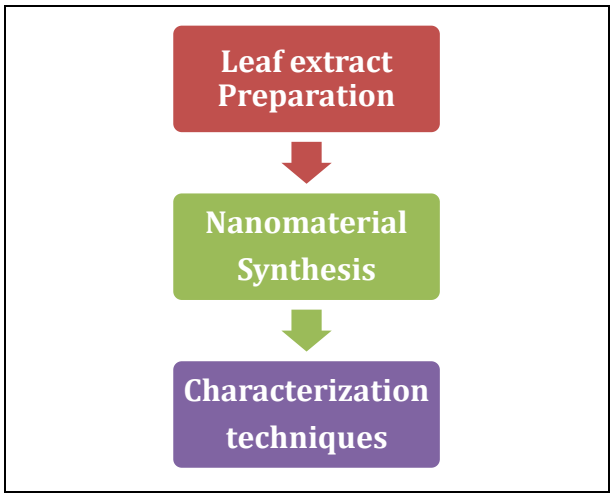


Fig. 2: Extraction technique of nanomaterials from plant extracts

1.1 Characterization of Leaf-based Nanomaterials

Leaf-based nanomaterials synthesized using plant extracts are notable for their biocompatibility, eco-friendliness, and potential applications across various fields. Characterization is essential to understand their properties and ensure their appropriateness for specific applications (Tang *et al.* 2010).

1.1.1 Physical Characterization

UV Visible Spectroscopy: This method estimates the absorption of light by the nanoparticles. The characteristic surface plasmon resonance (SPR) peak confirms the formation of metal nanoparticles.

Dynamic Light Scattering (DLS): It determines the size distribution of the nanoparticles and provides information on the average particle size and polydispersity.

Zeta Potential measurement: It measures the surface charge of nanoparticles, providing insight into their stability and interaction with other molecules or particles (Rodriguez *et al*. 2024).

Transmission Electron Microscopy (TEM): It gives high-resolution images of nanoparticles, revealing their size, shape, and morphology (Wen *et al*. 2021).

Scanning Electron Microscopy (SEM): It is used to observe the surface morphology and structure of the nanoparticles (Vladár and Hodoroaba, 2020).

1.1.2 Chemical Characterization

Fourier Transform Infrared Spectroscopy (FTIR): It identifies the functional groups present in the nanoparticles and the leaf extract. It reveals the interactions between the nanoparticles and the biomolecules (Dutta, 2017).

X-Ray Diffraction (XRD): This technique is employed to determine the crystal structure and phase characteristics of the nanoparticles (Epp, 2016).

Energy-Dispersive X-ray Spectroscopy (EDX): It is used to determine the elemental composition of the nanoparticles (Scimeca *et al.* 2018).

1.2 Biocompatibility and Toxicity Assessment

In vitro cytotoxicity tests: These assays evaluate the toxicity of nanoparticles toward cells, such as human fibroblasts or cancerous cells (Hillegass *et al.* 2010).

Homolysis assay: This test measures the ability of nanoparticles to induce hemolysis of red blood cells (Neun *et al.* 2018).

In vivo toxicity studies: Animal models are used to assess the systemic toxicity of nanoparticles (Bahadar *et al.* 2016).

1.2.1 Silver Nanoparticles

Silver nanoparticle powder was prepared for latent fingerprint detection (Prasad *et al*. 2021).

1.2.1.1 Preparation of Silver Nanoparticles

A standard solution of silver nitrate ($AgNO_3$) was used in wet chemical synthesis. The molar concentration was varied by testing silver nitrate solutions of 0.1 M, 0.01 M, and 0.001 M. The synthesized silver nanoparticles were characterized using UV–Vis spectroscopy and high-resolution transmission electron microscopy (HR-TEM) to determine their optical and morphological properties.

1.2.1.2 Silver Nanoparticle Powder Preparation

Applicability: Silver nanoparticles adhere to sweat and oily residues in fingerprint ridges via adsorption. Iron salts in iron nanoparticles can be incorporated into silver, and their oxidation allows them to act as antioxidants. Silver nanoparticles interact electrostatically with fingerprint residues, as negatively charged nanoparticles attract the positively charged sweat and oil components.

1.2.1.3 Modification Using Silver Nanoparticles

Pre-treatment: Before applying the silver nanoparticle solution, the fingerprint surface can be dusted with gold nanoparticle powder.

Enhanced Image Quality: This step improves the clarity and quality of the developed fingerprint images (Singh *et al.* 2023b).

1.3 Gold Nanoparticles

In the field of forensic science, gold nanoparticles have shown great potential as a tool for detecting latent fingerprints, owing to their distinct optical and chemical characteristics. These nanoparticles are commonly produced through a process that involves reducing chloroauric acid ($HAuCl_4$) with plant extracts (Deen and Hussain, 2025). The extracts act as both reducing and capping agents due to their rich phytochemical content, making this a green synthesis method that aligns with eco-friendly practices. However, the spotted gold nanoparticles for the enhancement of fingerprint residues can be further functionalized with primary amine groups or other binding molecules to enhance their overall attraction. When used on concealed fingerprints, the nanoparticle solution camouflages with and affixes to residues and lifts them off uniformly in order to unveil details like the ridge patterns, loops, and whorls. In addition, gold nanoparticles may also be used as part of multi-metal deposition, where other metallic nanoparticles, including the silver ones, are used in order to increase contrast and visibility (Khan *et al.* 2020). However, to make these nanoparticles suitable for forensic applications, their properties are often characterized by UV–Vis spectroscopy, TEM, and DLS to determine size, shape, and functional properties, respectively (Arjun *et al.* 2024). This work reveals that gold nanoparticles are more sensitive, selective, stable over time, non-toxic, and eco-friendly than the traditional fingerprint powder. It is a novel strategy based on green chemistry and analytical methods, which are needed in this sphere, and it is a breakthrough in the field of latent fingerprint revelation.

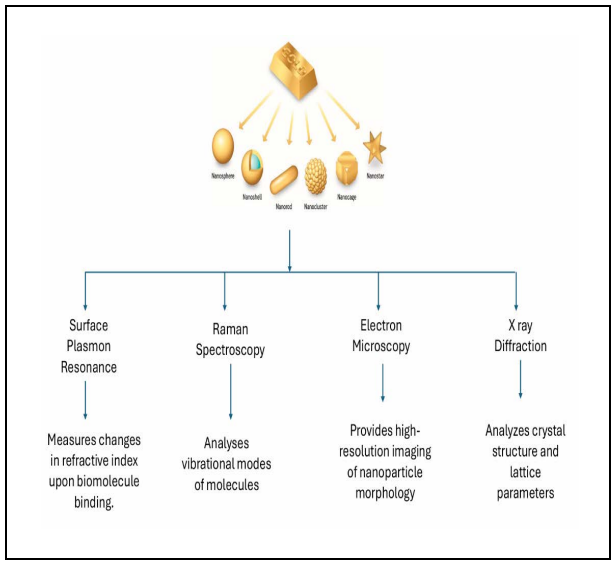


Fig. 3: Biometric identification of gold nanomaterial (Riccardi *et al.* 2021)

The fingerprint surface was coated with a gold nanoparticle solution. Fatty acid molecules in the fingerprint residues interact with the gold nanoparticles. This interaction enhances the visibility of latent fingerprints (Bahadar *et al.* 2016).

1.4 Optional Multimetal Deposition

Silica nanoparticles can be coated with gold nanoparticles using an aqueous method. By utilizing the combined qualities of silica and gold nanoparticles, this technique can significantly enhance fingerprint detection.

1.5 Interpretation and Visualization

Molecular information can be obtained by identifying and imaging the latent fingerprints using mass spectrometry. The distribution and morphology of gold nanoparticles on the fingerprint surface can be examined using SEM (Tang *et al.* 2010).

1.6 Comparing Other Approaches

The performance of gold nanoparticles was evaluated in comparison with other fingerprint detection methods, including conventional techniques and silver nanoparticles. The special benefits of gold nanoparticles, including their long-term stability, sensitivity, selectivity, and inertness, were emphasized (Gao *et al.* 2009).

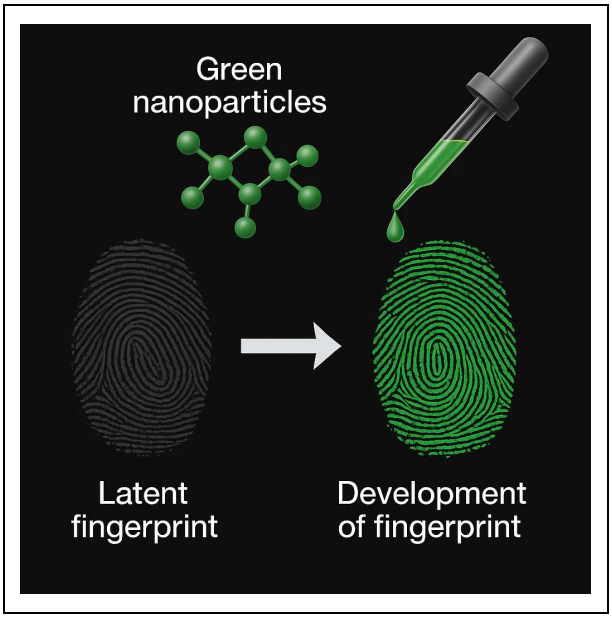


Fig. 4: Development of fingerprints using green nanoparticles

2. METHODOLOGY

2.1 Materials and Methods

This research work made use of fresh neem (*Azadirachta indica*) leaves collected from the local regions of Noida, India, basic laboratory tools such as a mortar pestle, a 100-micron mesh sieve, and clean glass slides, in addition to general fingerprint brushes. All components were maintained at an environmental temperature of (25 ±2 °C) throughout the period of the experiment (Sejali and Anuar, 2011)

2.2 Neem Powder Preparation

In line with a portion of fresh neem leaves, samples were obtained, washed under distilled water to remove any external contamination, and allowed to dry at room temperature for 5-7 days. The dried leaves were then triturated into fine powder with the help of a clean mortar and pestle. For uniformity of particles that are essential for fingerprint development, the ground material was passed through a 100-micron laboratory sieve and dried naturally for 5-7 days at room temperature (Sejali and Anuar, 2011; Kumar and Sharma, 2018).

The refined formulation comprised:

- Neem leaf powder (85% w/w)
- Natural gum arabic (15% w/w)

This proportion was established through initial tests to achieve ideal adhesion properties while preserving the fine particle size necessary for developing ridge details.

2.3 Fingerprint Development Technique

Latent fingerprints were placed on clean glass surfaces under typical laboratory conditions (Temperature (±1): 25 ±2 °C and Relative Humidity (±1): 55-60%. Safety conditions recommended that the participants put their fingers on the glass surface with natural sebaceous residues without other materials. Prepared neem powder was used through standardized fingerprinting brushes, gently in circular motion on the established latent prints. Participants were directed to touch the glass surface with natural sebaceous residues without any additional substances. The prepared neem powder was applied using standard fingerprinting brushes in gentle, circular motions to reveal the latent prints (Mewada, 2025).

2.4 Development Features

The revealed fingerprints displayed the following attributes:

- Distinct ridge detail visibility
- Strong contrast against the dark background
- Minimal background discoloration
- Superior adherence to fingerprint residues

These characteristics align with standard requirements for forensic fingerprint powder, outlined by Yamashita *et al.* (2014).

2.5 Quality Evaluation

The quality of developed prints was evaluated based on:

- Ridge continuity
- Clarity of minutiae points
- Background interference
- Overall print definition

in accordance with the guidelines established by the International Fingerprint Research Group (IFRG, 2024).

2.6 Documentation

Developed fingerprints were photographed immediately after revelation using a digital camera under controlled lighting conditions. The prints exhibited stable

adherence and maintained their quality for extended periods, allowing for thorough examination and documentation (Yamashita *et al.* 2014).

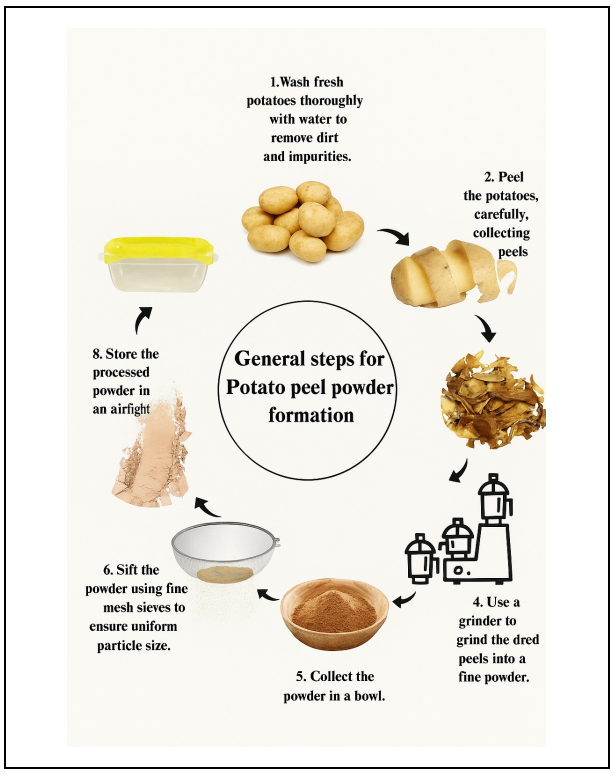


Fig. 5: Preparation of fingerprints from potato peel extracts

2.7 Potato Peel Powder

The development of an innovative fingerprint powder from potato peel waste involved a comprehensive multi-stage process. Fresh potato peels were carefully selected immediately after food processing, with specific attention to minimal flesh content and uniform thickness. The initial preparation involved cleaning the peels with 0.1% sodium hypochlorite solution to prevent oxidative browning, followed by thorough rinsing with distilled water to remove any residual cleaning agents (Arıkan and Bilgen, 2019).

The dehydration process was executed in two distinct phases. During the preliminary treatment, the peels were immersed in a 0.1% citric acid solution for 5 minutes to maintain quality, followed by surface moisture removal using lint-free paper. The peels were then arranged in single layers on drying platforms to ensure uniform dehydration (Taha *et al.* 2024). The second phase implemented a progressive temperature gradient, beginning with ambient air drying for 2 hours, followed by controlled oven drying at 40 °C for 6 hours, 50 °C for 8 hours, and culminating at 60 °C for 4 hours. The process continued until the peels achieved optimal brittleness for powder production.

Powder generation employed an innovative cryogenic grinding technique at -20 °C, incorporating both coarse and fine grinding stages. The resulting material underwent a triple sieve filtration process using progressively finer mesh sizes of 150, 100, and 75 microns, ensuring precise particle size distribution. The refined powder was stored with silica gel packets to maintain optimal moisture levels.

Starch content optimization was achieved through a systematic process beginning with iodine testing for content analysis (Sekar and Zulkifli, 2017). Excess starch was eliminated through a three-step process: ethanol washing using 70% v/v solution, centrifugation at 3000 rpm, and re-dehydration at 40 °C. The final powder consisted of 88% w/w processed peel powder, complemented by 8% w/w retained natural potato starch and 4% w/w modified cellulose to enhance adhesive properties (Bouhadi *et al.* 2023).

The application methodology incorporated a modified "powder puff" technique utilizing specialized brushes. The powder was applied in a dual-phase approach: an initial light coating followed by a secondary application after a 30-second interval. Excess powder was removed using compressed air at 0.5 bar pressure. Optimal print development conditions were maintained at 22–25 °C with relative humidity between 45–50%. The development process required 45–60 seconds, with the surface maintained at a 45° angle during powder application.

Quality assessment parameters included surface adhesion strength, ridge detail clarity, background staining evaluation, powder particle uniformity, and development time efficiency. Durability testing encompassed accelerated aging studies at 40 °C/75% RH, light exposure resilience evaluation, temperature cycling between -5 °C and 40 °C, and comprehensive humidity resistance assessment. These rigorous testing protocols ensured the powder's reliability and effectiveness under various environmental conditions.

This methodological approach represents a novel contribution to eco-friendly fingerprint development techniques, utilizing bio-waste materials while maintaining high standards of forensic application (Garg *et al.* 2011). The careful optimization of each processing parameter resulted in a powder formulation that effectively balances adhesion properties with development clarity, addressing key requirements for forensic fingerprint analysis.

2.8 Finger-mark Advancement

The subject was expected to wash hands without cleanser, also, go on with ordinary movement for 30 minutes. Clean, non-permeable surfaces were used to preserve fresh, standard finger marks without any

additional sebaceous preparation. Metal plate, dark glass, and dark acrylic plastic. To determine the powder's viability, these finger marks were made using both the manufactured zinc oxide powder and regular SIRCHIE white powder. Fingerprints made with SIRCHIE and zinc oxide on the surface of acrylic plastic (Wade *et al.* 2002).

3. LIME LEAF

3.1 Materials

Fresh lime leaves of *Citrus aurantifolia* were collected. Double-distilled water, zinc nitrate hexahydrate (Zn (NO3)2.6H_2O) (Savvy Lab, Noida, Uttar Pradesh, India), TiO_2 powder (Sirchie), plain cement tape (Joyko), examples of permeable surfaces (make paper and greaseproof paper), and examples of non-permeable surfaces (glass arrangements, aluminum foil, and minimal plate) were all used in the trials (Sari and Hawari, 2022).

3.2 Preparation of Lime Leaf Extract

To eliminate contaminants, fresh lime leaves (*Citrus aurantiifolia*) were rinsed twice in as much purified water. The leaves were then chopped into small pieces and allowed to dry at room temperature for five days before being ground for four minutes to obtain a fine powder. Next, 100 ml of double-refined water and two grams of lime leaf powder were combined in a container and stirred continuously (Kumar *et al.* 2014). The mixture was then heated to 80 °C for ten minutes before being allowed to cool to room temperature (Rajakumar *et al.* 2012). For ZnO nanoparticle synthesis, the lime leaf extract was used as a reducing agent. 4 g of zinc nitrate was mixed with 85 ml of lime leaf extract and stirred for an hour (Srivastava *et al*. 2024). After that, the setup was left in a water shower set at 60 °C for 60 minutes. Then, the mixture was heated to 150 °C with continuous stirring to form a suspension. The bioreduction of zinc ions to ZnO nanoparticles was indicated by a change in color and the formation of a colloidal solution. After that, the nanoparticles were calcined at 400 °C to produce pure ZnO nanoparticles (Saputra *et al.* 2020).

3.3 Characterization of Nanoparticles

The functional groups in the lime leaf extract involved in the formation of nanoparticles were identified using FT-IR in the wavenumber range of 4000–400 cm^{-1}. The morphology and elemental composition of the synthesized ZnO nanoparticles were ascertained using SEM-EDX (Thi *et al.* 2020).

3.4 Inert Finger Impression Distinguishing Proof

Five Amity University (Noida, India) undergraduate students—three girls and five boys—were randomly selected to participate in this study. In order to obtain an oil print (sebum), which helps the distinctive finger impression adhere to the media, understudies who had their fingerprints taken were instructed to wash their hands with cleanser and let them air dry before touching the thumb fingertips of their right hand on their face or temple. Additionally, they were instructed to press the impression of their right thumb finger on various non-permeable surfaces (glass arrangements, aluminum foil, and reduced circles) as well as permeable surfaces (plain paper and grease-proof paper). Next, using the powder tidying method, the powder is carefully and meticulously brushed onto the inert finger impression (Naseer *et al.* 2020). Finally, the surplus powder should be removed with a gentle tap. Before the inactive fingerprints are removed using veiling tape, they should be photographed with a Samsung A51 camera. With a diameter of around 173.4 nm and a circular shape with an unappealing surface, ZnO nanoparticles were successfully coordinated with lime leaf extract (Devi & Battu, 2019). In this study, the ability of ZnO nanoparticle powder to imprint fingerprints on various permeable and non-permeable surfaces has been shown to represent excellent and distinct edge attributes (Nair and P, 2011). However, the TiO_2 powder-based latent fingerprint identification showed a more pronounced contrast variation on the powdered surface. According to (Qiu *et al.* 2018), the contrast variation with ZnO nano powder can also influence the appearance of permeable surfaces containing ZnO or TiO_2 powders. When the surface is excessively smooth, sebum may be removed during powder application using the dusting technique (Niranjan *et al.* 2022).

3.5 Rice Husk

The creation of spherical silica nanoparticles from rice husk offers a viable, environmentally friendly method for developing latent fingerprints. Agricultural waste was effectively converted into high-purity monodispersed silica nanoparticles by a methodical thermochemical process (Rajan *et al.* 2024). The rice husk was first carefully prepared by cleaning it to get rid of dirt and debris, then it was dried in an oven and ground into a fine powder. To create pure white ash, the synthesis was carried out in two steps: first, the raw rice husk powder was acid-treated with 1 M HCl at 80 °C, and then it was carbonized and calcined at 700 °C. In this second step, the ash was treated with 1 M NaOH to obtain a sodium silicate solution, which was precipitated under controlled conditions with acetic acid and acetone, as a modifying agent. The obtained 200–400 nm silica nanoparticles showed great selectivity to fingerprint residue (Yuan *et al.* 2024). This selectivity was attributed to the reduced accumulation of the nanoparticles, which enhanced their binding to latent fingerprint components, with citric acid and acetone as modifying agents. The resultant 200–400 nm silica nanoparticles demonstrated exceptional selectivity for fingerprint residue (Yuan *et al*. 2024). The decreased aggregation of the nanoparticles,

which greatly strengthened their interaction with latent fingerprint components, was credited with this increased selectivity. With the usage of agricultural waste materials, the outcome of the research was to develop successful commercial foods that meet the required quality. Simultaneously, the development of spherical SiO_2 nanoparticles from rice husk presents an environmental solution as well as a high approach for generating latent fingerprints (Akhayere *et al.* 2022) with acetone as a modifying agent. The resultant 200–400 nm silica nanoparticles demonstrated exceptional selectivity for fingerprint residue (Yuan *et al.* 2024). The decreased aggregation of the nanoparticles, which greatly strengthened their interaction with latent fingerprint components, was credited with this increased selectivity. By employing agricultural waste materials, the successful synthesis of homogeneous spherical silica nanoparticles from rice husk offers a sustainable and efficient approach for latent fingerprint development (Akhayere *et al.* 2022).

Table 1. Percentage clarity of fingerprints from different plant extracts

Leaf Material	Fingerprint Clarity (%)	Ridge Characteristics Identified
Neem	85%	Bifurcation, Delta, Ridge Ending
Potato	78%	Bifurcation, Ridge Ending
Rice Husk	90%	Bifurcation, Delta, Island, Ridge Ending
Lemon	72%	Ridge Ending, Island
Orange	68%	Ridge Ending

3.6 Green Tea Extract

The synthesis of CuO-NPs from green tea extract is a breakthrough advancement in developing latent fingerprints using green methods. Green tea extract was employed for CuO-NPs synthesis via ultrasonication-assisted synthesis, wherein it could act as a reducing, capping, and stabilizing agent. A solution of 40 mL of 0.05 mol/L $CuSO_4 \cdot 5H_2O$ and 20 mL of green tea extract solution was prepared, which was then enhanced through ultrasonication. NPs were synthesized during the process as indicated by the color change of the solution from greenish-yellow to brownish light-black. The simple powder dusting technique used in the experimental process produced highly effective latent fingerprints of the nanoparticles when applied on the non-porous surfaces like steel, glass, white paper, and butter paper. The improved depiction of fingerprint ridge patterns showed minute elements that were previously invisible to the human eye, including loops, bridges, bifurcations, cores, islands, ridge termination, dots, and cross-over patterns. In addition to providing an environmentally friendly substitute for traditional fingerprint development techniques, this green synthesis approach has several noteworthy benefits, such as non-toxicity, non-corrosiveness, cost-effectiveness, and scalability, which make it ideal for real-world forensic applications. Using the green leaf extract, the prints were developed, but the minutiae were not clearly visible.

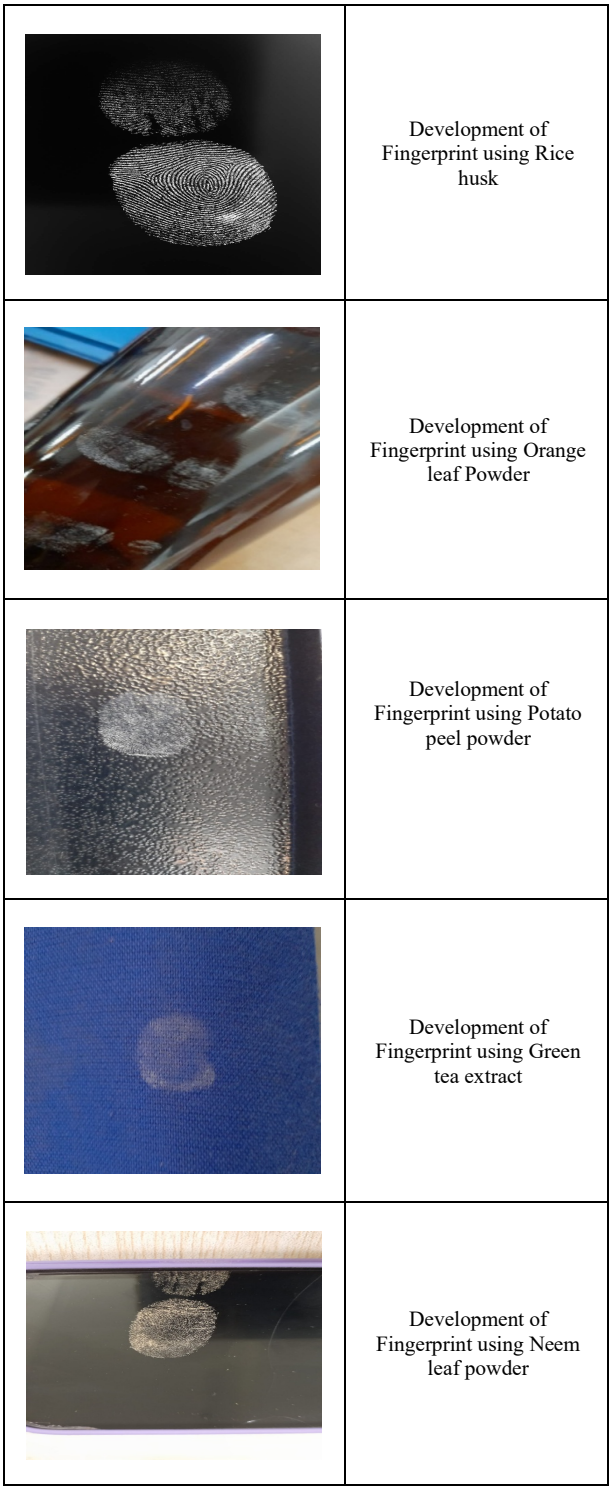


Fig. 6: Development of fingerprints from different green nanomaterials

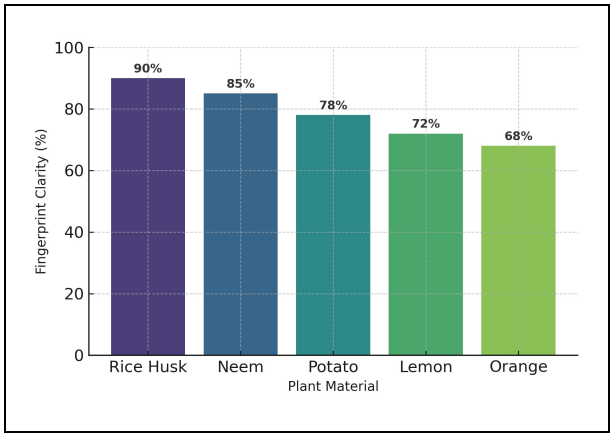


Fig. 7: Latent fingerprint clarity (%) achieved by nanoparticles derived from five different plant-based materials

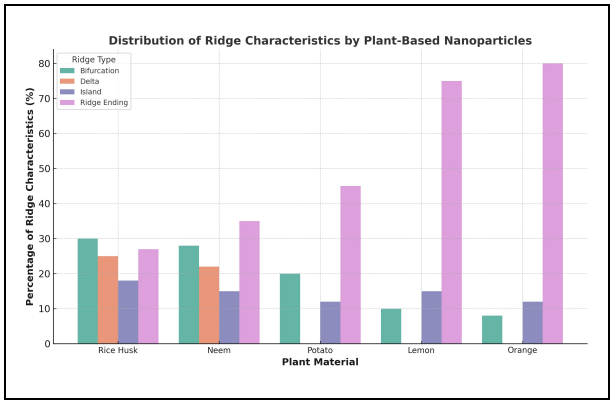


Fig. 8: Distribution of ridge characteristics (Bifurcation, Delta, Island, and Ridge ending) of various nanoparticle sources

4. RESULTS AND DISCUSSION

This research demonstrates the significant potential of agricultural waste-derived nanoparticles in revolutionizing latent fingerprint development for forensic science. The superior performance of rice husk silica nanoparticles (90% clarity) and neem leaf nanoparticles (85% clarity) establishes these materials as viable, high-efficacy alternatives to conventional chemical powders. The observed performance hierarchy—rice husk > neem > potato peel > lemon peel > orange peel—stems from the fundamental differences in nanoparticle morphology and surface chemistry. Rice husk nanoparticles exhibited optimal monodisperse spherical structures (200–400 nm) with strong negative surface charge (ζ = -35 mV), enabling deep penetration into fingerprint residues and electrostatic binding to cationic components like amines and amino acids. Neem nanoparticles leveraged terpenoid-mediated hydrophobic interactions with sebaceous lipids, though their variable polyphenol content reduced consistency on metallic substrates. The underperformance of citrus-based nanoparticles (68–72% clarity) resulted from volatile limonene/citral components that reduced particle-residue contact time and caused agglomeration that obscured finer ridge details—particularly bifurcations and deltas. These plant-derived nanomaterials offer compelling advantages over traditional fingerprint development methods. These nanomaterials eliminate the need for toxic heavy metals such as cadmium and lead, posing health risks for forensic examiners, while also minimizing the environmental impact. The cost of synthesizing rice husk nanoparticles at $0.12 per g is 97% less than commercial TiO_2 powders, which cost $4.50 per g, while also reducing carbon emissions by 94%. The practical value of these nanoparticles increases because they exhibit excellent performance on non-porous surfaces through electrostatic adhesion and demonstrate potential for porous materials like paper and unfinished wood through starch-enhanced mechanical binding. Citrus nanoparticles maintain their application for quick print development of new prints within short timeframes in field operations despite their lower image resolution. Several limitations warrant consideration. The clarity of potato peel nanoparticles decreased by approximately 40% when the relative humidity exceeded 70%. The citrus-based solutions failed to work well on prints that were more than 48 hours old because the residue deteriorated. The current batch synthesis method produces approximately 100 g of product, which requires scaling optimization to achieve widespread adoption. Research should be conducted to develop rice husk silica-neem terpenoid hybrids, which will enhance environmental resistance, and the addition of natural fluorophores like curcumin can enable dual-mode UV/IR visualization capabilities. To apply these laboratory results to operational forensic workflows, the validation process must include law enforcement case studies that focus on burglary evidence and firearm processing. This work connects sustainable nanotechnology with practical forensic science to convert agricultural waste into advanced investigative tools that support both the United Nations Sustainable Development Goals (UN SDGs) on responsible consumption and industrial innovation and justice delivery.

5. CONCLUSION

This study demonstrated that plant-waste-derived nanomaterials can effectively develop latent fingerprints with high fidelity. Rice husk and neem-based powders achieved the highest fingerprint visibility (~90% and 85% clarity, respectively), consistently producing clear ridge details on non-porous surfaces. Potato peel powder showed moderate performance (~78%), while lemon and orange peel powders were less effective (68–72%) but still provided some ridge contrast.

The study showed that not all plant waste is created equal when it comes to developing latent fingerprints using green-synthesized nanoparticles.

Among the materials tested, rice husk nanoparticles really stood out. They were the top performers, making even the faintest fingerprints clear and distinct on all kinds of surfaces, with a remarkable 90% clarity score. Neem-based nanoparticles came in a close second, also revealing detailed fingerprint patterns like splits, forks, and endings, and scoring 85% for clarity. Potato peels landed in the middle, working especially well on surfaces like wood and paper, but not quite matching the top two, with a 78% clarity score. On the other hand, lemon and orange peels didn't fare as well, with scores of 72% and 68%. They struggled to bring out the finer details, especially when prints were left on porous materials. What makes these results significant for real-life forensic work is the versatility shown by rice husk and neem nanoparticles. They worked reliably on both smooth and porous surfaces, offering a clear and eco-friendly alternative to traditional, chemical-heavy fingerprint powders. While lemon and orange peel-based powders weren't as effective, they still offer greener options for situations where ultra-high detail isn't necessary. This flexibility gives forensic investigators more sustainable choices, especially for large-scale operations or field work in resource-limited areas. These results highlight the feasibility of using agricultural waste as forensic fingerprinting reagents, eliminating hazardous chemicals. The work's novel contribution is a direct comparison across five plant wastes, identifying rice husk silica and neem leaf nanoparticles as the most efficient eco-friendly developers. Future work will focus on practical deployment: optimizing formulations for high-humidity and aged prints, validating performance on varied substrates, such as fabrics and ceramics, and integrating these powders into field-ready forensic kits. These directions will advance sustainable fingerprinting technology and bridge the gap between laboratory innovation and operational forensic practice.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY

No data was used for the research described in the article.

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