Journal of Climate Change
ISSN 2395-7611 Volume 12 (2026) No. 2. pp. 198–221

https://doi.org/10.70917/jcc-2026-012

Article

Sequential Valorization of *Musa balbisiana var elavazhai* peel into Biogenic Metallic nanoparticles and Starch-based biocomposite

Hiba Habeeb [1,*] and John E. Thoppil [1]

[1] Cell & Molecular Biology Division, Department of Botany, University of Calicut, Malappuram, Kerala, India-673635.
* Correspondence author: hiba.vavahaby@gmail.com

Abstract: Fruit-derived nanofactories are futuristic industries for sustainable development with a promising greener outlook. The forward thinking to embrace them as valuable nexus for nanoparticle phytosyntheis by intertwining circular economy and zero waste culture; in turn integrates green chemistry and sustainability principles via transforming fruit waste into cutting-edge nanomaterials. This study adopts an integrated peel valorization approach for total biomass valorization of fruit peels of *Musa balbisiana* var *elavazhai* by waste to value conversion pathway. Its aqueous extract is utilized as a universal bioreductant for green synthesis of Ag and Au nanoparticle, while its post extraction solid residue is repurposed into sustainable biocomposite films. The bio-agumented AgNPs (AgNP-MB) were spherical with a particle size of 22.42 nm (FE-SEM), monodisperse with a PDI of 0.407 (DLS), crystalline with an average crystal size of 20.74 nm (XRD) and showcased SPR peak at 432 nm (UV-Vis). FTIR analysis depicted the potential phytochemicals that acted as capping and reducing agents during AgNP biosynthesis. They were effective in degrading water-soluble organic dyes (MO & MB) with an efficiency of 97% and 85% via pseudo first-order kinetics. This integrated zero waste model advocates the generic value of fruit peels, by linking high performance nanocatalysis with sustainable material fabrication for environmental remediation.

Keywords: Biogenic Ag/Au nanoparticles; Peel Valorization; Starch based biocomposite film; Dye degradation; Green synthesis; Musa peel

1. Highlights

- Integrated peel valorization approach demonstrated the complete valorization of *Musa balbisiana* var *elavazhai* fruit peels
- The aqueous fruit peel extract functioned as a universal bioreductant for phytofabrication of Ag and Au nanoparticles
- The biogenic AgNPs showcased superior catalytic efficiency with a mass-normalized activity parameter of 1592.09 $s^{-1}g^{-1}$
- The reductive degradation of methyl orange recorded a maximum Turnover Frequency (TOF) of 1.44 min^{-1}
- A zero-waste loop was completed by repurposing of Biodegradable biocomposite film from the post extraction solid residue.

2. Introduction

Our planet earth is endowed with an immense diversity of flora and fauna, which sustains the balance of nature by amalgamating with each other *via* ecosystem services. Ecosystem services widely benefit human life by cherishing them. But we 'humans' often devastate their existence by turning nature into a landfill for waste dumping. Waste generated from our daily life is never properly recycled; thus, it creates a threat to sustainability of nature by creating environmental hazards. Hence, the advancing scientific literacy has resulted in nascent technology of zero waste either by its valorization or by bioactive extraction from them. Valorization involves carving out value added products from useless products. This term is being widely employed for proper utilization of food waste. Food waste, a by-product of numerous manufacturing, farming, household, and other food sector activities, is constantly increasing because of the rise in westernization in daily life operations. Several experiments have revealed that various types of food waste from fruits, vegetables, cereals, and other food processing sectors may contain bioactive compounds and nutraceuticals, which have a wide range of applications in the treatment of a variety of ailments. According to Parfitt et al. (2010), the food processing sector constitutes about 20% of the 14 million metric tons of waste generated annually. Later Ajila et al. (2012) justified it by stating that a major proportion (25-30%) of waste is generated from the fruit and vegetable industries. It comprises pomace, peel, rind, vine, pod, shell, seeds etc. Reports state that household operations generate up to 42 percent of food waste, with the food industry losing 39 percent and the food service industry losing 14% (ready-to-eat food, catering, and restaurants), while 5% is lost during delivery (Kumar et al., 2017). Food waste is expected to reach 126 Megatonnes by 2024 if no preventive measures or activities are implemented. As a result, encouraging its use in nanoparticle biosynthesis and related fields could be a critical step towards long-term development. Furthermore, bioactives isolated from food waste extracts can be combined with biosynthesized nanoparticles and incorporated in nutraceutical and functional foods, making drug delivery and nourishment of mother earth's fellow mates much safer.

The incorporation of nanotechnology into food waste recycling is athought-breaking approach being discussed among upcoming scientists. On behalf of this, kitchen waste, and agri- food wastes are being transformed as bioresources with immense potential for nanoparticle biosynthesis and related areas. The development of functional foods by utilizing bioactives from food waste has been a nascent approach toward sustainability. By inculcating the notion of zero waste, complete valorization of food waste into value added products can be optimized.

3. Major role play of fruit peels

Fruits are a remarkable treasure of nature. It is often embraced as nature's candies that can add flavor to our lives by enriching our nutritional requirements. Despite being enriched with sweetness, its parts, such as peels, rind, and seeds are endowed with immense potentiality to be embraced as reserves for innovative studies. They are elementary foods that enhance life expectancy and quality. Fruits are a whole package of phytoconsituents that act as an elixir of life by dampening the threats of lifestyle diseases affecting our vital organs. Because they are delicate, seasonal and with lesser shelf life, their effective use is made *via* its transformation into food products such as pulp, and puree. These often result in the generation of huge piles of wastes, of which more than 30% accounts from fruit and vegetables (Rodríguez et al., 2008).

In a 2000kcal diet, people are recommended mainly with fruits and vegetables as 4 -5 servings per day for lowering the threats of lifestyle diseases. Unfortunately, this proportion is not followed (Saini et al., 2019). Consumption of healthy food endowed with prebiotic and functional food ingredients has become a major concern among adults. Thus, the launching of nanoemulsion-based delivery systems has been a promising approach. In 2014, Khaled et al., reported that anti-microbial and antioxidant activity of nanoencapsulated essential oils are enhanced compared to normal. Lipophilic anti-microbials present in nanoemulsions are often found to exhibit enhanced bactericidal effect (Salvia-Trujillo et al., 2015). Nevertheless, bioactive compounds are also employed commercially in biocomposite, biodegradable polymer, packaging, edible films, coating, and so on.

Fruits peels are a treasure of bioactives enriched with antioxidant properties. These bioactives are exploited in different sectors of the food industry as preservative, anti-microbial, antioxidant, natural coloring agents. They can also be incorporated into our daily food *via* nanoemulsions. Green extraction technology is being employed for bioactive extraction due to its higher attributes. The bioactive potency of fruit and vegetable wastes makes their role play active as functional foods and nutraceuticals in the food and health sector.

Active packaging enhances food product quality and shelf life. It comprises gas scavengers, carbon dioxide emitters, and moisture absorbers. In 2018, Luchese et al. created a UV light protecting packaging film from cassava starch and blueberry pomace. Likewise, Ali et al. (2019) developed a hydroxypropyl high-amylase starch film by incorporating pomegranate peel as an antimicrobial agent and filler. In 2021, Shukor et al. produced a biodegradable, antimicrobial packaging film from jackfruit peel and tapioca starch, which retarded fungal growth on cherry tomatoes stored at 25^0C for 7 days.

The freshness of food throughout long storage time is checked with the help of pH indicators. A pH indicator made from sweet potato peel and starch was used to ensure freshness of chicken flesh was fresh for consumption. This film comprised of sweet potato peel anthocyanin exhibited remarkable color change with respect to the degree of spoilage of chicken (Sohany et al., 2021). As per Halăsz et al. (2018), the pomace extract of black chokeberry acts as a pH- sensing dye for chitosan films. The properties of biopolymers are improvised in film matrix on usage of fruit peels and pomace as fillers. In 2019, De faria Arquelau synthesized an edible film from the banana peel powder of "Prata banana". Fruit waste by-products may be food based such as fiber, pectin, and flour, or non-food based, such bioadsorbents. In 2018, Laysandra et al. created a composite adsorbent to wash off crystal violet by mixing acid-activated bentonite and sarsaponin with durian skin. Fish based gelatine films were produced from mango peel that can be used in food packaging (Adilah et al., 2018).

Colorful fruits and vegetables are the store house of edible pigments, which mainly comprise their innate phytochemicals. Fruits and vegetables wastes are widely exploited for the commercial production of natural pigments that can act as substitutes for synthetic pigments. The immense biotherapeutic potential of these pigments makes them promising candidates for fabrication as functional food ingredients. In 2020, Albuquerque et al. reported that freeze-dried jaboticaba peel powder can be used as the best source for extraction of anthocyanins with help of three different hydroalcoholic acid mixtures and an ultrasonic bath. According to Rodriguez et al. (2016), the aqueous extract of red dragon fruit contains approximately 30mg of betalains per 100g of dried peel. Carotenoids are often present in vegetables than fruits. Among fruits, it is extracted from orange and pomegranate peel *via* ultrasonic assisted extraction technique (Goula et al., 2017; Murador et al., 2019). Chlorophyll isolated from avocado peel is used as a demanding reserve in fortified food formulations (Wang et al., 2010). Being susceptible to damage, shelf-life of these pigments are increased by microencapsulating or nanoencapsulating them in a coating of biopolymers. It is done mostly by spray drying, which preserves their color and bioactivity more effectively than other methods (Robert et al., 2010).

According to Drago L. (2019), the occurrence of colon cancer can be reduced by the consumption of more dietary fiber and probiotics, which in turn eliminates constipation issues. Hence, fruit peels are supplemented with probiotics for elevating its bioactive potency. Probiotic yogurt produced from pineapple peel exhibited higher antioxidant, anticancer, and antibacterial effects against *E. coli* (Sah et al., 2015). Sugar and fat-free yogurt was produced from the peel powder of pineapple, passion fruit, and orange (Dias et al., 2021). Despite these vibrant potentialities, fruits and its peel advocates immense usage as adsorbents of industrial pollutants by transforming into biogenic metal nanoparticles. This could lead to empowering of technologies to deal with adversities that pop up due to increased pollution and drastic climatic change globally. By upbringing the initiative of incorporating those nanoparticles as efficient biocatalysts for degrading synthetic dyes, waste water can be rejuvenated into usable form and in turn ensure proper availability of healthy and pure water for fulfilling the needs of the growing population. By this study, the authors promotes the usage of biogenic silver nanoparticles as excellent water restorative agents for ensuring maximum recovery of wastewater from industrial effluents in a systematic manner.

Being an herbaceous tree of wet tropical biomes of Southern India, endemic to Kerala, *Musa balbisiana* Colla is embraced as a source of food and medicine. Its fruits are enriched with diverse arena of secondary metabolites that endow notable pharmacological properties to them (Swargiary et al., 2021).The unexplored wild banana variety(*Musa balbisiana* var *elavazhai* A. Joe, Sreejith & M. Sabu) endemic to Kerala represents a unique, yet scientifically overlooked and underlooked, reservoir of bioactive compounds. In the modern tapestry of material science, green nanotechnology role plays as the scientific 'broom and mop' for carving a restorative framework by sweeping away the hazardous foot prints of conventional synthesis and mopping up the risks of persistent pollutants. This initiative restructures agricultural waste as functional tools by replacing toxic ingredients with renewable plant derived recipes. By employing agricultural leftovers like fruits and vegetable waste into greener means of nanoparticle fabrication as powerful ingredient besides endemic plants often bypasses the hazards induced by age old methods of nanosynthesis. This in turn reduces the emissions of green house gases as these wastes are diverted from being into landfills for endless anaerobic decomposition and related methane release. The conversion of the residual biomass into bicomposite films significantly drops our dependence of one time use plastics and serves as a safer alternative for a sustainable environment that promotes zero waste, lower climatic issues and circular economy (Saxena et al., 2025).

Despite the proliferation of green nanotechnology, numerous studies remain limited by a 'linear' approach that focuses solely on nanoparticle synthesis while neglecting the resulting biomass waste. To address this gap and enhance the novelty of green catalysis, this study showcases an integrated peel valorization approach by employing an unexplored wild banana variety. Unlike common cultivars, this neglected genotype is hypothesized to delineate a lurking natural reserve of bioactives and fibres, rendering an unequalled chemistry for multiproduct valorization. This work demonstrates a zero-waste pathway where the aqueous extract enacts as universal bioreductant for Ag and Au nanoparticle while remaining solid residue is transformed into sustainable biocomposite films. Furthermore, to dive beyond qualitative findings and portray generic scientific value, the catalytic efficacy of synthesized AgNPs is also evaluated using standardized metrics (Activity parameter (K) and Turnover frequency (TOF)) to unwind its catalytic prodigy for the decomposition of organic dyes, in analogy to other phytoextracts. Hence, it can be stated that the central hypothesis of this study is the creation of a scalable model of zero-waste loop by amalgamating high performance nanocatalysis with biodegradable material fabrication for reframing the perception of total biomass valorization strategy via unveiling nominal worthiness of indigenous flora in transition towards a global waste-to-wealth economy. In a nutshell, it can be justified that this approach of integrated valorization loop matches closely with the core tenets of green engineering by shrinking over waste production and uplifting efficacy of biomaterial fabricated from single source of biomass (Hiba and Thoppil, 2022).

4. Methodology

4.1. Experimental

All reagents and solvents were of analytical grade and were used without any further modifications. Silver nitrate ($AgNO_3$), Tetrachloroauric acid ($AuCl_4$), Methylene Blue (MB), Methyl orange (MO), Sodium Borohydride ($NaBH_4$), Glacial acetic acid, Glycerol, Corn starch, Sodium hydroxide was purchased from Spectrochem Company. The ripened fruits of *Musa balbisiana* var *elavazhai* A. Joe, Sreejith & M. Sabu were collected from local residential areas of Kozhikode, Kerala, India. The peels were handled according to institutional waste management guidelines. Double distilled water was used for preparation of plant extract. Our methodology follows a peel-based bioproduct valorization framework that houses fruit peels of this wild banana as primary feedstock and diverts waste from extraction as essential feedstock for biocomposite fabrication.

4.2. Preparation of the Aqueous Extract and Residue

The fruit peels of fully ripened *Musa balbisiana* var *elavazhai* A. Joe, Sreejith & M. Sabu were removed from the pulp, rinsed in distilled water, chopped, and left to air dry in shade for 7-10 days. Once dried, the peels were ground to a fine powder in a blender. The aqueous extract of dried peels of wild banana was prepared by mixing and heating 5g of this powder in 100ml of distilled water in an Erlenmeyer's flask at 60^0C for 1 hour. The resultant mixture was filtered using Whattman No.1 Filter paper, and the filtrate was stored at 4^0C.The insoluble residue was collected for valorization into biocomposite films.

4.3. Phytofabrication of Ag and Au Nanoparticles

Green synthesis of silver nanoparticles (AgNPs) was performed by mixing and boiling 10ml of aqueous extract of fruit peels with 90ml of freshly prepared 0.005M Silver nitrate ($AgNO_3$) in a water bath (Labline) at 60^0C for 10-15 minutes at a pH of 13.The choice of alkaline pH depends on the phytochemical profile of *Musa balbisiana* peels due to needed for deprotonation of phenoilc hydroxyl groups instantly into active phenoxide ions which speeds up reduction kinetics of silver nanoparticle formation by dropping its reduction potential. The resultant biogenic AgNPs are more stable due to zero agglomeration and higher negative charge on former. While bio-synthesis of gold nanoparticles (AuNPs) was achieved by vortexing and heating of aqueous extract of fruit peels with freshly prepared 0.001 M tetrachloroauric acid ($AuCl_4$) in equal proportions for about 5-10 minutes. Further, both the reaction mixture was incubated in dark for 24hrs for completion of the entire synthesis. The color change from pale yellow to dark reddish brown solution indicated the formation of colloidal AgNPs where as color change from pale yellow to ruby red solution displayed the formation of colloidal

AuNPs. The resultant solutions were centrifuged using an ultra-centrifuge (Thermo Scientific, SorvallWx + Ultraseries centrifuge) at 13,000 rpm for 15minutes.After centrifugation, the obtained nanoparticles were washed in distilled water followed by distilled ethanol to ensure the complete separation of the nanoparticles in their purified form as nanopellets. The obtained nanopellets were further dried in a controlled temperature in a hot air oven. The physicochemical characterization of biosynthesized Ag and Au nanoparticles was further carried out.

The biological synthesis of AgNPs and AuNPs were conducted following the validated experimental protocol in our earlier studies (Covilakam et al., 2025; Habeeb & Thoppil, 2023; Naser and Thoppil, 2023) with slight modifications.

4.4. Fabrication of Residue-derived Biocomposite films

The insoluble residue obtained post extraction was repurposed to produce a sustainable material such as biodegradable biocomposite film as per Kharb et al. (2023) with slight modifications according to wild banana peel residue. During the synthesis of waste derived biocomposite films, blending of dried, finely ground solid residue (2.5g) with other raw materials and double distilled water (50 ml) was done in a 250 ml beaker. Other raw materials employed were corn starch (2.5g), glacial acetic acid (2.5 ml), plasticizer (glycerol-2.5ml) respectively. The resultant mixture was further heated with constant stirring using a glass rod until a uniform gelatinous consistency is achieved. The final film forming solution is cast onto sterilized petriplates and dried in hot air oven. Once dried, the biocomposite films are peeled from the plates and stored in air tight zip lock packets for further analyses. The biocomposite films were further characterized by XRD and FE-SEM analyses to inspect over its structural integrity, surface topography and fiber distribution.

4.5. Characterization of biogenic nanoparticles and biocomposite films

The optical and structural attributes of these functional products derived from fruit peels of *Musa balbisiana* var *elavazhai* via integrated peel valorization approach was examined by employing a bunch of analytical techniques. UV-Vis spectral analysis (JascoV-750 spectrophotometer) was performed in 200-800 nm range at a resolution of 1nm to scan over their Surface Plasmon Resonance (SPR) peaks, validating the fruitful synthesis of both biogenic Ag and Au nanoparticles. The crystalline phases of both metallic nanoparticles and structural arrangement of the biocomposite films were assessed via X-ray Diffraction (XRD) studies. The diffraction patterns were recorded in 2θ/θ scanning mode on a 'Malvern-Panalytical X'pert3 Powder X-ray Diffractometer' operated at 45 kV and with a current of 30 mA current with Cu/Kα radiation (λ= 1.540598 A^0 in the range of 20-80^0 in 2θ angles. The average particle size (crystal size) of the nanoparticles was calculated using Scherrer equation: were D is the crystal size, k is the geometric factor (0.89), λ is wavelength of X- ray beam (1.54), β is the angular full width at half maximum (FWHM) at the diffracted X-ray at an angle theta (θ).

$$D = \frac{k\lambda}{\beta cos\theta} \quad (1)$$

The Scanning electron microscope (SEM) analysis was utilized to depict the surface morphology of all three functional products (AgNPs, AuNPs and biocomposite film) via FE-SEM examination (Geminisem 300, with magnification of 12. −2,000,000., acceleration voltage 0.02–30 kV, and The Inlens BSE resolution 1.2 n mat 1 kV). The particle size, shape of both metallic nanoparticle and homogeneity of fibre-strach integration in films were studied.

Finally, certain high-resolution tests such as FTIR (Fourier transform infrared spectroscopy) and DLS (Dynamic light Scattering) analyses were carried out in biogenic AgNPs to embrace its use as primary catalysts by scrutinizing over its hydrodynamic diameter, size, polydisperity and phytochemical capping agents. FTIR analysis (Jasco FT/IR 4190) was done after sample preparation using standard KBr pellet technique at a wavelength range of 4000-400 cm-^{1} at 1 cm^{-1} resolution. Diluted samples of colloidal Ag and Au nanoparticle solution were employed for DLS screening using a Zetasizer nanoparticle analyzer (Nano ZS90 (ZEN1690)).The FTIR data of biogenic AgNPs is treated as representative profile of bio-organic functional groups responsible for reduction due the usage of same aqueous extract for fabrication of both Ag and Au nanoparticles. All the synthesis and analyses of biogenic Ag and Au nanoparticle and resulting biocomposite film formation requiring replicas were performed in triplicates.

4.6. Catalytic degradation of the organic dyes

The reduction of organic dyes, such as Methylene Blue (MB) and Methyl Orange (MO) with $NaBH_4$ were employed to study the catalytic efficacy of biogenic AgNPs. The procedure was performed according to Cyril *et al.,* (2019) with slight modifications. The reaction is performed in a quartz cuvette. Around 200µl of freshly prepared $NaBH_4$ solution (200mM) is added to 70µl of 2mM dye solution in the cuvette. Further, 20µl of AgNP solution was added to the former and made up to 3.3ml with double distilled water. Variations in the concentration of the respective organic dyes were measured in a real sample at regular intervals by recording the UV-VIS spectral data. A control (aqueous solution of each dye) was also prepared without the addition of AgNP and $NaBH_4$ and its absorbance was noted. The experiment was carried out in triplicates. The percentage degradation of organic dyes was determined using the following equation:-

$$Degradation\ efficiency\ (\%) = \frac{A_0 - A_t}{A_0} \times 100 \quad (2)$$

Here, A_0 is the initial adsorption and A_t is the adsorption at time t.

The pseudo-first-order rate constant for this degradation is calculated as given below:-

$$-kt = \ln \frac{A_t}{A_0} \quad (3)$$

Here, A_0 represents the initial concentration, A_t represents the concentration at time t, and k represents the pseudo-first-order rate constant.

All experiments concerning nanoparticle synthesis and catalytic degradation were done in strict independent triplicates.

4.7. Statistical analysis

The results obtained for the catalytic degradation of organic dyes were statistically analyzed using Duncan's multiple range tests at a 5% probability level. Data were subjected to one-way ANOVA using the SPSS software 16.0. Pearson's correlation analysis was performed to evaluate the relationships between the most important variables. The data are averages from three independent experiments, each with three replicates. The data represent mean ± standard error.

5. Results and Discussion

The phytofabrication of AgNPs and AuNPs from the fruits peels of *Musa balbisiana* var *elavazhai* A. Joe, Sreejith & M. Sabu was conducted using contemporary approach based on the classical tenets of green chemistry. The rapid synthesis of biogenic AgNPs and biogenic AuNPs were assured by optimizing certain conditions as ideal for their fabrication. The incubation time (24h), temperature (60^0C), metal ion [$AgNO_3$, $AuCl_4$] concentration (0.005M, 0.001 M), pH of reaction mixture (13), stoichiometric ratio of silver nitrate: aqueous extract(1:9) and stoichiometric ratio of gold chloride: aqueous extract (1:1) were optimized. The use of highly alkaline pH like 13 in this study is a deliberate choice for enabling maximal deprotonation of phenolic hydroxyl groups present in Musa balbisiana peels as it pertains to their higher activity. This in turn ensures the formation of smaller nanoparticle with higher efficiency and colloidal stability due to its enhanced reducing kinetics leading to rapid silver ion nucleation without agglomeration (Ovais et al., 2018; Githala et al., 2022; Fahim et al., 2024; Ko Ko et al., 2025).

The reduction of metal salt solutions (silver nitrate and tetrachloroauric acid) followed by the addition of plant extract led to the formation of biogenic silver and gold nanoparticles, which were further characterized by color change, UV-VIS spectra, XRD and SEM analyses. FTIR and DLS analyses were performed on biogenic AgNPs and were treated as primary representative profile of bio-organic functional groups responsible for reduction due the inclusion of same extract for biosynthesis.

5.1. UV-VIS spectral analysis

As the aqueous fruit peel extract of *Musa balbisiana* var *elavazhai* reacts with 0.005M silver nitrate solution in basic medium at 60^0C, an evident color change from pale yellow to dark reddish brown (Fig. 1) appears, embracing the formation of colloidal AgNPs. Similarly, on interaction of same aqueous extract with 0.001 M Tetrachloroauric acid, the formation of colloidal AuNPs were affirmed by a notable color change from pale yellow to ruby red (Fig. 2). These colloidal solutions of AgNPs and AuNPs were subjected to UV-VIS spectral analysis at a wavelength range of 200-800nm. The obtained spectral data depicted a broad peak at 432nm (Fig. 3) for biogenic AgNPs and a broad peak at 555 nm (Fig. 4) for biogenic AuNPs. The dark reddish-brown color and ruby red color depicts their surface plasmon resonance (SPR) properties. No notable characteristic peak was observed in the UV-Vis spectrum of aqueous peel extract. This clearly indicates that the red shift in UV-VIS spectra of AgNPs and AuNPs is due to the ultrafast fabrication of nanoparticles aided by the capping agents of peel extract and instant color change, respectively. The presence of a primary absorbance in UV region for aqueous peel extract confirms the existence of constituent phytochemicals as natural capping and stabilizing agents of biogenic AuNPs. The red shift justifies the transformation of precursor solution to reddish brown and ruby red colloid as a cardinal indicator of reduction of Au^{3+} to Au^0 and Ag^+ to Ag^0. The occurrence of dual peaks in phytofabricated gold nanoparticles accounts for the long-term stability offered by biological corona to these against clumping. On comparison to AuNPs, AgNPs yield lower wavelength peaks due its varying dielectric constants and electron oscillations at higher frequencies.

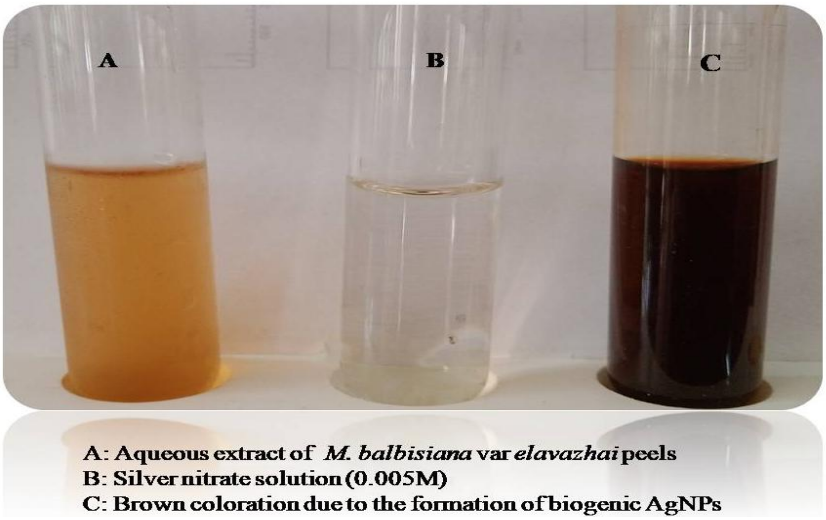

Figure 1. a, *Musa balbisiana* var *elavazhai* peel aqueous extract; b, 0.005M silver nitrate ($AgNO_3$) solution; c, Dark reddish-brown solution indicating the formation of silver nanoparticles.

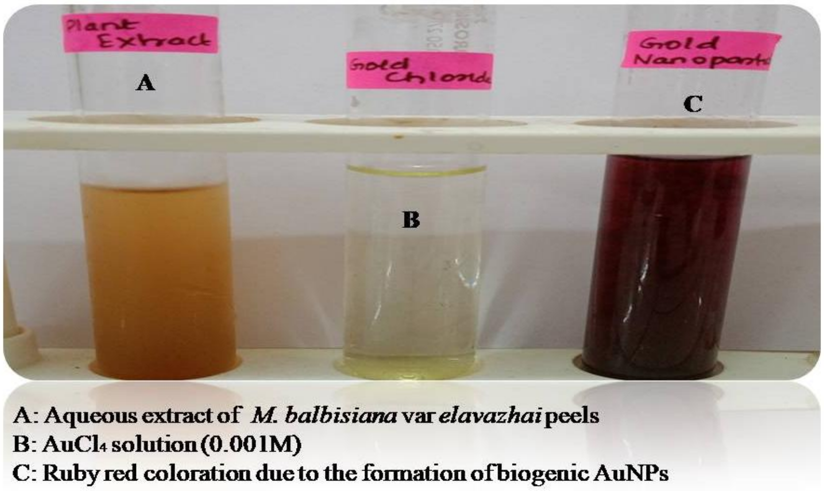

Figure 2. a, *Musa balbisiana* var *elavazhai* peel aqueous extract; b, 0.001M tetrachloroauric acid ($AuCl_4$) solution; c, Ruby redsolution indicating the formation of gold nanoparticle

UV-VIS spectroscopy is a widely used method for ensuring the phytofabrication of metal nanoparticles along with the detection of its optical characteristics (Abdelhalim et al., 2012). It reveals the surface plasmon resonance property of the respective metals used for nanoparticle fabrication. In a nutshell, it delineates the interplay of peel extract with silver salt solution ($AgNO_3$) *via* its bioreduction into its metal form (Ag). The remarkable absorbance peak in the lamba range of 200-800 nm showcases silver metal's surface plasmon resonance character (SPR). SPR plays a role in visible color change during the synthesis. When light falls over the nanoparticle surface, its conduction electrons oscillate as a resonance, which ascertains with the formation of AgNP by sparking over the interaction between the positive and negative charges of its surfaces and a significant absorbance band in the visible region (Ashour et al., 2014; Al hamza Hasoon et al., 2024).The SPR peak at 432nm very well correlates with the work of Kifle et al. (2025) where silver ions are instantly reduced by Musa peel metabolites.

Biogenic gold nanoparticle formed showcased prominent localized surface Plasmon resonance (LSPR) at 555nm which corresponds to the effective phytofabrication of gold ions into stable nanoparticle, guarded by the synergetic effect of thick phytochemical halo aided by Musa extract (Shaikh & Das, 2025). This remarkable SPR peak within visible range portrays as an optical fingerprint of organic metal interlude via promoting a minor red shiftideal for bio-stabilized AuNPs with respect to their synthetic counterparts (Bharadwaj et al., 2021). This respective SPR peak aligns with the biosynthesis of AuNPs from *Althaea officinalis* by Adiraju et al. (2025) where gold chloride reacted with aqueous extract in 1:10 ratio.

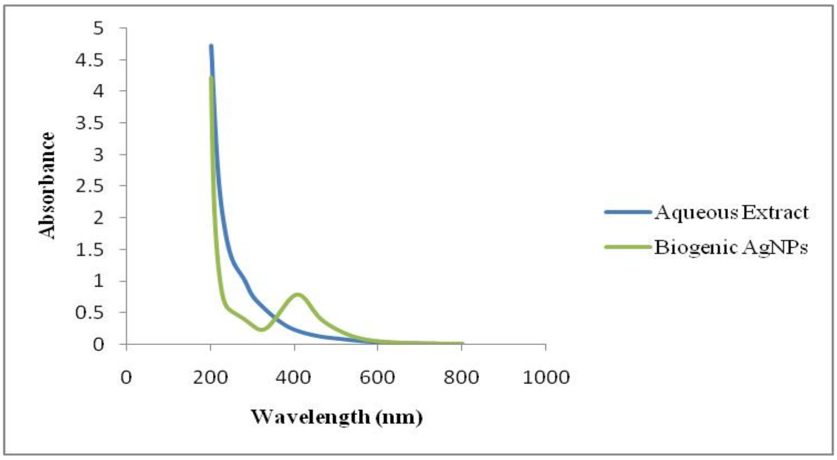

Figure 3. UV-VIS spectra of aqueous peel extract of *Musa balbisiana* var *elavazhai* and silver nanoparticles biosynthesized from the peel extract.

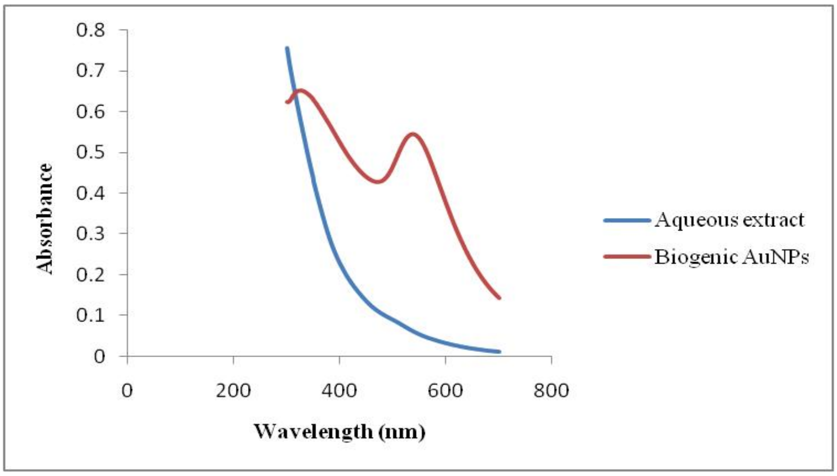

Figure 4.UV-VIS spectra of aqueous peel extract of *Musa balbisiana* var *elavazhai* and gold nanoparticles biosynthesized from the peel extract

5.2. Fabrication of Starch based Biocomposite films

Biodegradable plastics or biocomposites are eco-friendly films crafted from renewable resources of nature to reduce the usage of normal plastics. They targets to revert ecological imbalance by inculcating the notion of sustainability via impressive industry level elevation into utilization of renewable feedstock like agricultural wastes for wiping out the endless chains of traditional plastic pollution. This suppresses the upcoming threats of global warming by downgrading the release of greenhouses gases into the atmosphere. Bioplastic upholds several definitions in our scientific industry but the proclamation of European Bioplastics sounded more realistic. They delineated any material as bioplastic when it endorses biodegradability and bio- based raw material (Shamsuddin et al., 2017; Kharb & Saharan, 2022).

The physicochemical characterization techniques like XRD and FE-SEM was employed to assess the phase composition and structural integrity of biocomposite synthesized from solid residue of peels collected post extraction. The FE-SEM image has showcased a dense, heterogeneous surface morphology with high degree of roughness, interlocking ridges and micro-fibrous textures. This composite film display a complex lignocelluloses network comprising of hemicelluloses, lignin and cellulose left behind as precursors after extraction. The roughness of film upholds the occurrence of lignocelluloses fibers from wild banana peel residue as intercalated within the cornstarch-glycerol matrix. The lack of fissures or voids or cracks pinpoints towards its cohesiveness and seamless nature. Strong interfacial bonding, chemical cross linking and gelatinization between polysaccharide chains were aided by glacial acetic acid and glycerol (plasticizer) such that flawless sea is created for anchoring of fibrous peel particles (filler). This composite bioplastic film matches wells with the mango peel film produced by Kharb & Saharan in 2025. The crystallinity of biocomposite film was found to evaluate as semi-crystalline by XRD analysis with three distinct Bragg reflections at 2θ values of 17.215, 20.129and 21.710 degrees. The initial peak at 17.215^0 depicts B-type starch crystallinity with (110) lattice plane of Cellulose I from wild banana peel fiber (Fig. 5). While peak at 20.129^0 represents the interplay of amylase chains with glycerol and acetic acid during gelatinization of cornstarch matix by advocating V-type crystallinity. The band at 21.710^0 affirms the amalgamation of ordered lignocelluloses fragments into starch matrix. The amorphous nature of bioplastic film is treated as invaluable asset for flexibility and transparency of these films (TaraziRiess et al., 2022; Podgorbunskikh et al., 2023; Photinam et al., 2024).

The peaks at 2θ values of 20 and 21 degrees correspond to van der waals region or amorphous phase as observed in sapodilla peel derived bioplastic (Kharb & Saharan, 2025). Glycerol being the plasticizer here has enhanced crystillinity of film by incorporating of Hydrogen bonds for aiding in reorientation of polymer chains (Goncalvesa et al., 2019).

Figure 5.Image of biocomposite film synthesized from soild residue collected post extract of fruit peels of *M. balbisiana* var *elavazhai.*

5.3. XRD analysis

XRD analysis was employed to ensure its fabrication along with estimation of its average grain size and crystalline nature. It is read in the 2θ range of 20–80 degrees. For these biogenic AgNPs, four distinct Bragg reflection peaks at 2θ values of 38.22, 44.40, 64.63, and 77.58 degrees were obtained in the XRD diffractogram, which correspond to the (111), (200), (220), and (311) sets of lattice planes (Fig. 6) and were confirmed to be silver nanoparticles (AgNPs) with face-centred cubic crystal structures due to its homology with the standard powder diffraction card of the ICDD (PDF card No. 00-003-0921) (Khanal et al., 2022). Thus, it has been proven that these synthesised AgNPs are nanocrystalline. Furthermore, the crystalline sizes of the biosynthesized nanoparticles were estimated using the Scherrer formula. The XRD pattern of these biogenic AgNPs is well aligned to the crystalline geometry of AgNPs biosynthesized from aqueous extracts of *Lysiloma acapulcensis* and *Rubus ellipticus* (Garibo et al., 2020; Khanal et al., 2022). The average crystalline size of the silver nanoparticles was found to be 25.9nm. Thus, silver nanoparticles with well-defined dimensions can be synthesized by the reduction of metal ions, which may be due to the phytoconstituents' potential activity from aqueous fruit peel extract of *Musa balbisiana* var *elavazhai.* For biogenic gold nanoparticle, the XRD difrractogram revealed four distinct Bragg reflection peaks at 2θ values of 38.157, 44.331, 64.631, and 77.620 degrees corresponding to the (111), (200), (220), and (311) sets of lattice planes denoted by miller indices (Fig. 6). Due to its close resemblance with the standard power diffraction card of ICDD (PDF card No. 00-004-0784), it was confirmed to be gold nanoparticles (AuNPs) with face-centred cubic crystal structures (Doan et al., 2020). Hence, the biosynthesized AuNPs were found to nanocrystalline. The average crystalline size of the gold nanoparticles was approximately around 10 nm. The XRD pattern of these green AuNPs exhibited close similarity with the crystalline alignment of AuNPs produced from aqueous extracts of *Codnopsis pilosula* (Doan et al., 2020). The indistinguishable nature of Bragg's reflection peaks is accredited to the structural equivalence and analogous lattice constants of silver and gold often substantiated in scientific literature pertaining to green synthesis where plant extract behaves as common stabilizing agent (Banker et al., 2010; Ibrahim, 2015). Certain minor unassigned peaks recorded in biogenic AuNPs are in accordance with the crystallization of phytochemicals from wild banana peel extract assuring the proficient biocapping of metallic nuclei (Chang, 2025).

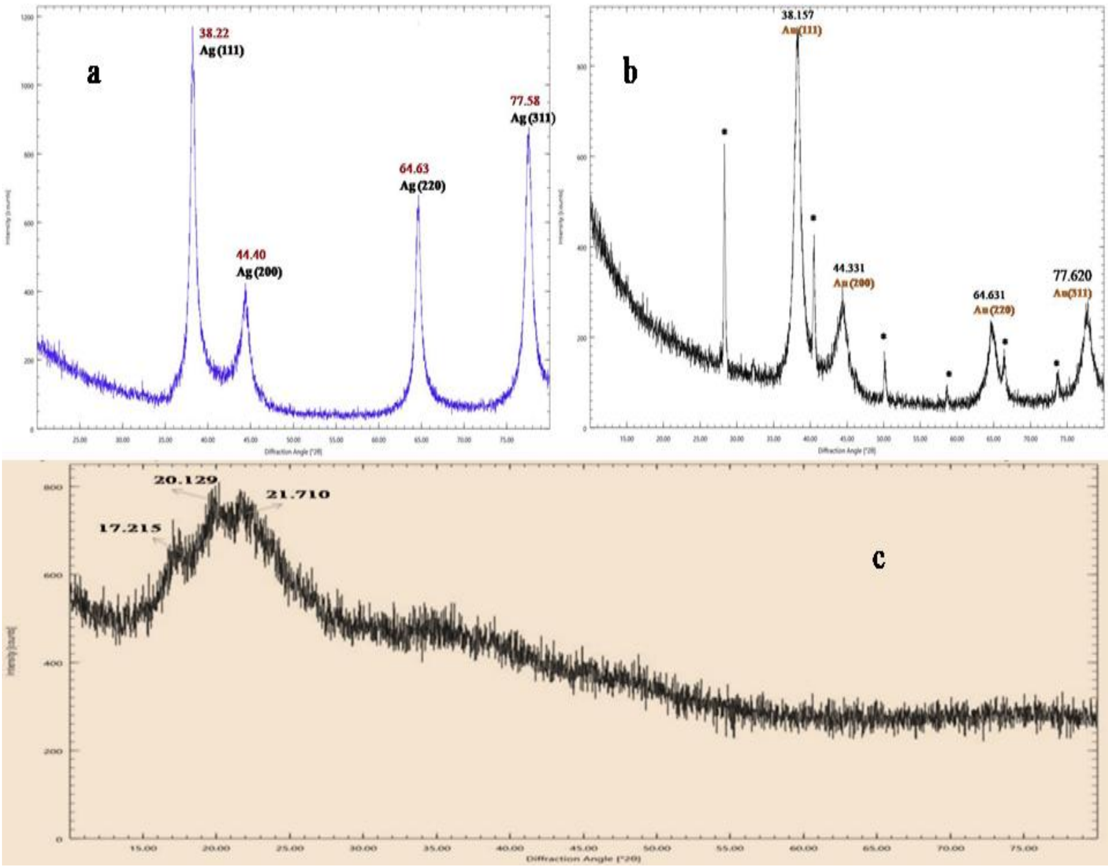

Figure 6. XRD diffractogram of silver nanoparticle (a), gold nanoparticles (b) and biocomposite film (c) biosynthesized from the fruit peels of *Musa balbisiana* var *elavazhai.*

5.4. FE-SEM imaging

The surface morphology and related aspects of the biogenic silver nanopellets were analyzed by FE-SEM imaging. During FE-SEM imaging, high-energy electron beams begin scanning the nanoparticle surface and then interact with its surface atoms, resulting in the production of signals that can portray about the surface topography and particle composition in detail. It mainly comprises of attributes surface morphology such as size and shape at micro and nanoscale levels (Fissan et al., 2014; Lin et al., 2014). The particle size was found to be 22.42 nm respectively (Fig 7). The biogenic AgNPs were spherical and crystalline. The particle size value varies among XRD, DLS and FE- SEM analysis due the distinctiveness in the nature of techniques and methods employed for sample preparation. In the case of biogenic gold nanoparticles biosynthesized from fruit peels of *Musa balbisiana* var *elavazhai*, the FE-SEM micrographs depicted quasi-spherical nanoparticle along with large anisotropic plate-like structures. The large flaky structures recorded sparkles out the presence of a bio-organic or phytochemical halo or cage around the gold metallic core. This protects irreversible clumping of nanoparticle via steric hindrance. This in turn confirms the reduction of gold ions has took place inside the pockets of fruit peel's phytochemical scaffold. This aspect acts as cardinal essence of the waste to value valorization pathway being advocated in this study (Sidhu et al., 2022; Albahri et al 2025).

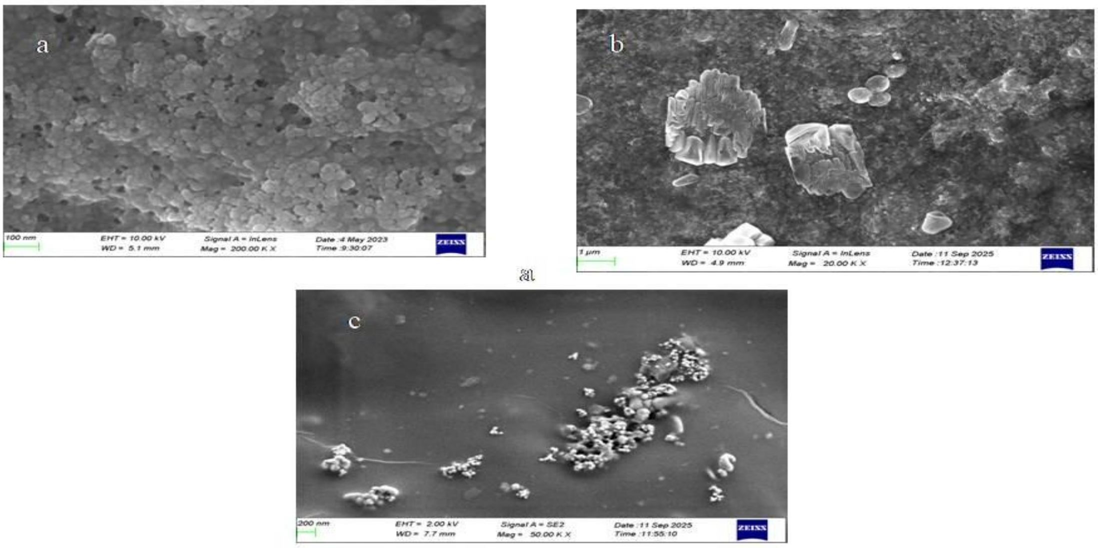

Figure 7. SEM images of silver nanoparticle (a), gold nanoparticles (b) and biocomposite film (c) biosynthesized from the fruit peels of *Musa balbisiana* var *elavazhai*.

The dynamic characterization of biogenic AuNPs draws insights into its structural integrity and optical performance by drawing a core tie between them. The primary confirmation of Au nanoparticle production was depicted by a localized SPR peak at 555nm while the secondary peaks at UV region around 320nm pinpoints towards the organic crystalline phases analyzed in XRD diffractogram. The unassigned XRD peaks at 2θ values of 28.15, 40.07 relates to the crystallization of phytochemicals in Musa peels, which is in turn corroborated by the orientation of quasi-spherical metallic nuclei as embedded within a sheet-like biological pattern leading to anisotropic conformation. The optical performance of biogenic AuNPs in UV-Vis spectroscopy functions as a core tie to the structural data recorded from XRD and FE-SEM analyses. A broad SPK band (555nm) is closely intertwined to the polydisperity and morphological alterations seen in SEM images. The wild banana peel extract advocates a core- shell mechanism for formation of biogenic AuNPs. This is substantiated by the similitude of Bragg reflection at (111) indices and widening of LSPR peak to polydisperity noted in FE-SEM images. The core shell framework is validated by the smaller crystalline size (10 nm) over the particle clusters observed in FE-SEM images. Hence, it can be relatively illustrated that the metallic FCC grid of AuNPs is strongly guarded by a crystalline bio-organic layer that imparts persistent colloidal stability versus irreversible agglomeration (Chang, 2025).

5.5. FTIR analysis

The roles of various phytochemicals in the fabrication of AgNPs were exhibited by their respective functional groups in its FTIR analysis. It depicts the intermolecular interaction by analysing the stretching and bending vibration of specific bonds. FTIR analysis of peel extract and its biogenic silver nanoparticles were employed to differentiate the remarkable functional groups in peel extract, which has enacted in the reduction of Ag^+ ions to Ag^0, capping, and optimal stabilization of the resultant AgNPs (Alam, 2022). The absorption peaks obtained for these biogenic AgNPs were 3739.3, 3652.52, 3435.56, 2918.73, 2847.38, 1629.55, 1016.3, 853.347, 694.248, 659.536, 639.287, 541.899 , and 417.513 cm^{-1} (Fig. 8). For the aqueous peel extract, the major peaks were 3412.42, 2917.77, 2850.27, 1733.69, 1610.27, 1383.68, 1240, 1198.54, 1104.05, 1065.48, 887.095, 762.709, and 665.321 cm^{-1} respectively. These results depict the role play of phytoconsituents from aqueous extract as capping and stabilizing agents for biogenesis of silver nanoparticles. FTIR spectroscopy is a biophysical technique employed for analyzing the biochemical constitution of bionanoparticle's surface pertaining to the detection of biomolecules involved in its bioreduction along with depiction of the local arena of capping agents on its surface, by recording their respective molecular vibrations (Habeeb and Thoppil, 2023).

The spectral band at 3739.3 and 3652.52 cm^{-1} is a characteristic of O – H stretching vibration type of alcohols and phenols. The peak at 3435.56 and 3412.42 cm^{-1} corresponds to N-H stretching of primary and secondary amines and amides along with O-H stretching of alcohols, phenols and carboxylic acids. The band at 2847.38, 2850.27, 2918.73, and 2917.77 cm-^{1} denotes O-H stretching of carboxylic acids, N-H stretching of amines and C-H stretching of aldehydes (aromatic compounds) respectively. The peak at 2850.27 cm^{-1}denotes methyl asymmetric C-H stretching of alkanes. The peak at 1629.55 and 1610.27 cm^{-1} represents C = C stretching of alkenes (aliphatic hydrocarbons), primary N –H bending of amides, C=N stretching of oximes and imines, N–H bending of primary and secondary amines and amides, C=N-OH stretching of oximes, and the asymmetric stretching of nitrate NO2. The peak at 1733.69 cm^{-1} showcases aliphatic C=O stretching of aldehydes and esters. The spectra at 1383.68 and 1335.46 cm-^{1} attributes to C-H NO_2 symmetric stretching of the aliphatic nitro compounds. The spectrum at 1383.68 cm-^{1} attributes C-H NO_2 symmetric stretching of aliphatic nitro compounds, S=O stretching of sulfoxides and methyl symmetrical bending of alkanes. The band at 1065.3cm^{1} corresponds to C-N stretching of amines and C-O stretching of alcohols, ethers, esters, anhydrides and carboxylic acids. The peaks at 1240, 1198.54 and 1104.05 cm^{-1} represents C-O stretching of carboxylic acids, anhydrides, alcohols, phenols and in plane C-H bending of aromatic compounds, respectively. The bands at 1065.48 and 1016.3 cm^{1} corresponds to aliphatic C-N stretching of amines and C-O stretching of alcohols, ethers, esters, anhydrides, and carboxylic acids, respectively. The peak site at 887.095, 853.347, and 762.709 cm-^{1} represents C-H bending of 1,2,4-trisubstituted and 1,3- disubstituted compounds and =C-H out-of-plane bending of the alkenes. The bands at 694.248, 665.321, 659.536, 639.287 cm-^{1} represents =C-H bending of alkynes. While spectral bands at 1016.3, 762.709, 694.248, 665.321, 659.536, 639.287, 541.899 and 417.513 cm-^{1} C-X stretching vibration of halogen compounds (X= Cl, Br, F, I)(Pavia et al., 2001; Suart, 2004).

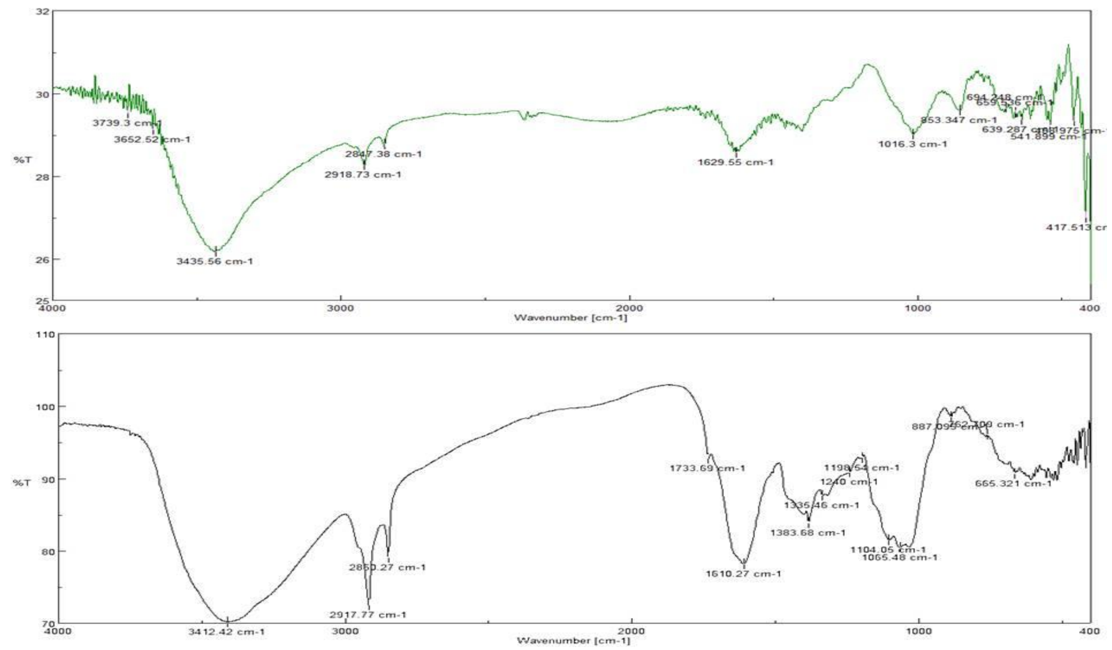

Figure 8.FTIR spectra of aqueous extract of *Musa balbisiana* var *elavazhai* fruit peels and resultant AgNPs from 400 to 4000 cm-[1]. The resemblance between the two spectra confirms that the synthesis and functionalization of AgNPs were carried out by the extract.

The major functional groups found in aqueous peel extract and biogenic AgNPs were alcohols, phenols, aromatic compounds, aliphatic hydrocarbons, azo compounds, amides, amines, aldehydes, esters, ethers, anhydrides, and carboxylic acids. FTIR spectral analysis of both peel extract and biogenic AgNPs have showcased the rapport of phytometabolites from peel extract are active agents for biofabrication of biogenic silver nanoparticles for a faster and more efficient synthesis.

5.6. DLS analysis

Dynamic light scattering (DLS) analysis is advocated for estimation of distribution of particle size by showcasing its qualitative properties. It determines the polydispersity index (PDI) and average hydrodynamic diameter of biogenic nanoparticles by estimating charismatic changes in the intensity of light scattering caused by Brownian movement of particles. PDI values normally lie between 0 (monodisperse) and 1 (polydisperse) (Nayak et al., 2016). It's dimensionless scaled value that denotes the transition in distribution of particles being monodisperse to polydisperse (Jasuja et al., 2014). The hydrodynamic diameter of nanoparticles is found to be higher than that of SEM images due to the capping of swollen phytochemicals over the AgNP surface as a hydrating layer (Anand et al., 2017; Saha et al., 2021). Due to the difference in the size distribution of synthesized AgNPs, 2 peaks were observed in the size distribution by intensity plot. The 2 peaks obtained were at 95.7 and 7.368 nm with an intensity of 95.7% and 4.3 %respectively. The Z- average (average particle size) of the phytofabricated AgNPs was 62.29, while its PDI was 0.407, indicating that the nanoparticles were monodisperse without any form of aggregation (Fig. 9). The surface of nanoparticles is often covered by a double electrical layer along with stabilizing and capping agent, which in turn embraces its hydrodynamic diameter as well. The latter is seen to be well correlated with nanoparticle size measurements *via* SEM analysis.

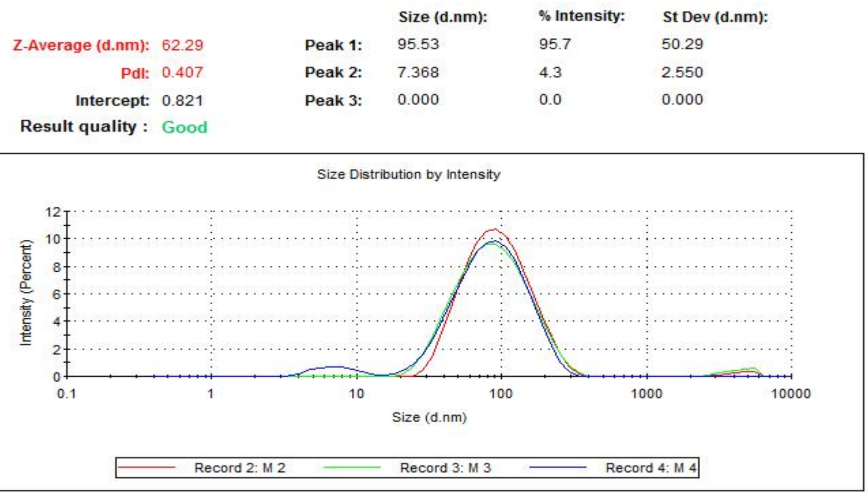

Figure 9. DLS imaging of silver nanoparticles biosynthesized from the fruit peel extract of *Musa balbisiana* var *elavazhai*

The screening of surface chemistry of biogenic AgNPs synthesized from fruit peel extract of *Musa balbisiana* var *elavazhai* was done to decide its impact on performance as a nanocatalyst. Its FTIR analysis acts as an ideal prototype for bio-organic interface across both metallic systems. The FTIR results confirmed that the respective aqueous extract has efficiently functionalized the surface of nanoparticle with functional groups of alcohols, phenols, aromatic compounds, aliphatic hydrocarbons, azo compounds, amides, amines, aldehydes, esters, ethers, anhydrides, and carboxylic acids as ligands. Despite of being the reducing agents of silver salt, these groups act as stabilizing shield for these nanoparticles too. The strength of this shield is validated by DLS results. DLS analysis has confirmed a stable and monomodial suspension of nanoparticles with its Z-average above 60 nm and PDI greater than 0.3. This unique PDI value (0.407) throws light over the complex multi-component bio-organic shell revealed by FTIR spectra. Recent papers justify such PDI values as typical for biological synthesis via showcasing the mixed aura of phytomolecules as encapsulating the metallic core (Arora et al., 2026). The presence of distinct phytochemical constituents as a non-uniform stabilizing shell around the nanoparticle by encapsulating the metallic core accounts for the altering hydrodynamic volume. This soft shell or bio-capping architecture enriched with alcohols, phenols, aromatic compounds, aliphatic hydrocarbons, azo compounds, amides, amines, aldehydes, esters, ethers, anhydrides, and carboxylic acids is crucial for catalytic degradation due its inherent ability to portray as the stabilizing junction that can bypass clumping of nanoparticle during the entire cycle (Kumar et al., 2023). The adsorption of pollutants onto nanoparticle surface is advanced by maximal exposure of active sites due to high surface to volume ratio and molecular bridges formed by organic functional groups for improved electron transfer frequency of entire catalytic cycle. This biogenic interface embraces sustained catalytic turnover and high degradation rates across silver nanoparticle by regulating the colloidal stability and hindering particle coalescence during the reaction (George et al., 2025). This valuable synergy and healthy rapport between chemically active surface layer and stable hydrodynamic profile underscores the marvelous catalytic efficacy denoted in Ag systems.

5.7. Determination of concentration of biogenic silver nanoparticles

The equation developed by Kalishwaralal et al. (2010) was used to determine the concentration of biogenic AgNPs.

$$N = \frac{\pi \rho D^3}{6M} N_A \tag{4}$$

where π = 3.14, ρ is Density of fcc silver (10.5 g/cm^3), D is the average diameter of nanoparticles (22.42nm= 2.242×10^{-6} cm), M is the atomic mass of silver (107.868 g/mol), and NA is the number of atoms per mole (Avogadro's number =6.023×10^{23} particles/mol).

Assuming 100% conversion of all silver ions to silver nanoparticles, the value obtained for N =345775.930

Finally, the molar concentration of the synthesized AgNP solution is calculated using the following formula:

$$C = \frac{N_T}{N V N_A} \tag{5}$$

where C is the molar concentration of the nanoparticle solution, N_T is the total number of silver atoms added ($AgNO_3$ = 0.005M), N is the number of silver atoms per nanoparticle (from formula 1), V is the volume of the reaction solution in L, N_A is the Avogadro's number.

Finally, the concentration of biogenic AgNPs was estimated as C = 0.00072301M/L = 0.723mM= 7.23 x 10^5nM. Further, it can be analyzed that, 20µl of biogenic AgNP solution used in reductive degradation contained1.56 µg of AgNPs.

5.8. Catalytic degradation of the organic dyes

Recent advancements in scientific world have led to the increased usage of biogenic nanoparticles as catalysts for the degradation of environmental pollutants that harm our nature. Nanoparticles widely known to exhibit catalytic activity against organic dyes, such as methylene blue, methyl orange, azo violet, and congo red. The catalytic degradation of organic pollutants is identified by its faster discoloration from its standard form to colorless ones.

The catalytic activity of biogenic AgNPs derived from aqueous fruit peel extract of *M. balbisiana* var *elavazhai* was examined *via* the reduction of Methyl Orange (MO) and Methylene Blue (MB) in the presence of excess $NaBH_4$ using time dependent UV-Vis absorption spectra. When 20µl of AgNP and 200µl of $NaBH_4$ is added to the dye solutions (MO & MB), a significant decrease in the peak intensity was observed at 464 nm and 664 nm. This was visually showcased by the gradual fading of their respective orange and blue colored dye solutions into colorless forms (Fig 10&Fig 11) along with the lowering of the absorbance of their relative absorption peaks. The reaction was completed at a faster pace upon the addition of nanocatalyst. Biogenic AgNPs took around 5 minutes and 10 minutes for complete degradation of MO and MB suspensions (Table 1). The dyes degraded at a slower rate under the absence of AgNP as a catalyst. The control chosen for degradation studies were dye solution only without AgNPs and NaBH4 which showcased negligible effect and can be correlated to UV-Vis spectra of peel extract too as no peaks were recorded. This directly pinpoints the observed catalytic efficacy to be solely driven by respective biogenic AgNPs only.

The surface of silver nanoparticles is made more susceptible to oxidation by lowering its reduction potential under the influence of a strong nucleophile (BH4-). Once the surface is activated, both borate and ions from organic dyes co-adsorb and initiate electron transfer by catalysing the underlying reaction.

The entire degradation showcases a pseudo-first-order kinetics model for the decoloration of organic dyes by AgNP as nanocatalysts. Using the Langmuir-Hinshelwood model of heterogenous catalysis, a graph of ln (A_t) *vs* time'*t*' was plotted. The plot exhibited linearity with ln(A) as a function of time, where A is the absorbance at time t. Pseudo-first order rate constant was determined. Because the concentration of $NaBH_4$ is much higher than that of the azo dye, the kinetics of the entire process was monitored to be pseudo first order (Cyril et al., 2020). The catalytic efficiency of newly biofabricate AgNPs is assessed by calculating the activity parameter (K). Activity parameter (K) is defined as the ratio of the rate constant to the total weight of added catalyst. It measures the intrinsic efficiency of a nanocatalyst for catalytic degradation. According to this model, the surface-mediated electron transfer from the reducing agent causes the decoloration of the dye molecules. Thus, the pseudo-first-order rate constant can be ironically interpreted as a synergistic effect of surface catalytic activity and adsorption affinity, respectively (Raj et al., 2020).In this study, AgNP-MB act as the best nanocatalyst for MO than MB with K as 9.26 $s^{-1}g^{-1}$ and 1.37 $s^{-1}g^{-1}$ respectively.

Metal nanoparticles act as green catalysts due to the large surface-to-volume ratio of metal ions, which in turn ensures the effective bonding of reactants to their binding sites (Narayan et al., 2019). Methyl orange is an anionic organic dye with azo and diethylamine groups. In the presence of AgNP, $NaBH_4$ rapidly reduces methyl orange azo dye (-N=N-) to colorless amines (-NH-NH-) in a fast paced manner by fluctuating the absorbance intensity at its λ max (464 nm) (Muthu & Priya, 2017). The addition of nanoparticles as a nanocatalyst to the reaction solution leads to the process of electron shuttling between the acceptor (MO) and the reducing agent($NaBH_4$). Methyelne Blue (MB) is a cationic thiazine dye. During the catalytic reaction, an electron transfer occurs from $NaBH_4$ to the dye *via* the role play of BH_4^- ions, from the former as a nucleophile and the latter as an electrophile *via* AgNPs. On the adsorption of excess BH_4^- to Ag surface, the Fermi level of the metal spikes up due to the enhance in electron density, which promotes the electron transfer to the dye molecules, which subsequently leading to its reduction into leucomethylene blue (LMB) (Pal et al., 1997). The catalytic activity appears to be enhanced duringthe potential difference between the metal particle and the dye molecule (Azad et al., 2022). Thus, it can be concluded that AgNPs dual play as a redox catalyst and electron transfer mediator by creating an electron relay effect (Gupta et al., 2011).This effect contributes to the blue spectral shift of the SPR band of AgNPs (Pardhan et al., 2002).

Our research work has clearly elaborated the usage of AgNP-MB as an effective nanocatalyst for the degradation of toxic dyes like methylene blue and methyl orange, which are discarded into our water bodies by various textile and related industries. This, in turn, pinpoints the former's remarkable scope as agents to wipe out pollutants from wastewater by ensuring its proper treatment without causing any hazard to the environment. Previous literature studies have opened up the employability of biogenic AgNPs as dye degrading catalysts for several carcinogenic dyes due to their remarkable efficiency. Rajasekar et al. (2021) efficiently used biogenic AgNPs derived from the floral extract of *Heterotheca subaxillaris* for degrading methyl orange in the presence of $NaBH_4$ by pseudo first order kinetics with a rate constant of $2.1x\ 10^{-3}s^{-1}$. Biogenic AgNPs derived from *Sterculia acuminata* seed extract were successful in reducing Methylene blue and methyl orange at a faster pace of 3 minutes by following pseudo-first-order kinetics. These AgNPs were considered to be best catalyst for Methylene blue at an approximate 100% degradation with a rate constant of $0.00286cm^{-1}$ (Bogireddy et al., 2015). In 2016, Varadavenkatesan et al. portrayed AgNPs biosynthesized from leaf extract of *Mussaenda erythrophylla* was a promising catalyst agent for the reduction of methyl orange with the help of sodium borohydride within a time span of 45 minutes. *Saussurea costus* root extact derived AgNPs exhibited an efficiency of 91% in degrading methylene blue after 80 minutes by following first-order kinetics. It also showcased 72.88% removal of methyl orange dye after 135 minutes by following second order kinetics respectively (Hijazi et al., 2024).

The FTIR results clearly depict overplay of certain functional groups on the efficient catalytic power of green AgNPs. It includes hydroxyl and carbonyl groups that act as reducing, capping and stabilising agents of those nanoparticles (Khatun et al., 2022; Alharbi et al., 2023). These infers into the involvement of flavonoid and phenolics in the catalytic prodigy. The XRD data closely matches the

FTIR results by pinpointing the phytochemical-mediated reduction kinetics regulating the higher crystallinity of AgNPs.

Recent research studies exhibit a healthy rapport with our results that biogenic AgNPs in lower concentration is efficient for rapid degradation of dyes and confirms *Musa balbisiana* var *elavazhai* fruit peels are pluripotent waste material for biofabrication of biogenic metal nanoparticles, which can be employed in industrial wastewater treatment as a major breakthrough for waste valorization in the advanced era of phytotechnologies. By amalgamating these experimental inferences into industrial uses, the dependence over conventional chemical approaches for the breakdown of toxic organic dyes released from textile effluents can be wiped off and advanced into a sustainable means of wastewater treatment. Besides these, the coalescence of fruit peels often discarded as agro-waste into green nanoparticles *via* valorization can scale down the heap of organic waste generated from the agricultural sector by mitigating the ecocide. In a nutshell, it can be justified that valorization of agro-waste into a treasured product for waste water purification showcases the essence of environmental sustainability. This, in turn, throws light on the notion of sustainable development by acting as a life elixir for circular economy. The utilization of fruit waste (Musa peels) in multiple ways enhance ecological balance by diverting methane emissions or more precisely speaking green house gas emissions spiking up due to anaerobic decomposition of former ending up as landfills. The lowered green house gas emission mitigates global warming levels by altering resultant changes in global climate. This ironically pinpoints towards the lowering of emissions of fossil fuel vehicles (Sial et al., 2019; Phillip et al., 2025). By advocating biological approach for synthesis of biogenic AgNPs from fruit waste instead of endemic plants reduces our overdependence on classics of nature. This in turn lowers carbon foot print by inculcating the use of greener methods into nanoparticle fabrication over classical chemical or physical methods as former upholds nearly a one third drop in energy usage by escalating a two-fifth jump in cost effectiveness and yield. Hence, it can be substantiated that green synthesis of nanoparticle is a major step towards sustainable development that merges energy conservation and least waste production into the unified roof of sustainable green nanotechnology (Gupta et al., 2023; Osman et al., 2024; Saxena et al., 2025). Likewise, transformation of residual biomass into biocomposite films shrinks our reliance on petrochemical plastics which notably halts sudden hikes in scenario of global warming induce climatic adversities. These biological sources derive biocomposite films are believed to wipe out or soak up the biogenic carbon without releasing of carbon dioxide from fossilized produces into air (Erradhouani et al., 2026; Poveda-Giraldo et al., 2026).

The catalytic efficacy of spherical green AgNPs phytofabricated from these wild banana fruit peels was rigorously assessed through the reductive degradation of water soluble organic dyes. On using minimal metallic loading of 1.56μg to reduce 2mM dye substrate, the system achieved a maximal pseudo first order rate constant for MO (k = 0.149 min^{-1}) compared to MB (k = 0.022 min^{-1}). This corresponds to an impressive activity parameter (K) of 95.53 $min^{-1}mg^{-1}$(equivalent to 1592.09 $s^{-1}g^{-1}$) and a turnover frequency (TOF) of 1.44 min^{-1} for MO, which throws light over the high throughput nature of active sites on spherical surfaces. While for MB, the activity parameter (K) of 14.10 $min^{-1}mg^{-1}$(equivalent to 237.05 $s^{-1}g^{-1}$) and a turnover frequency (TOF) of 0.21 min^{-1} was relatively lower. The specific Surface Plasmon Resonance of these biogenic AgNPs assured the formation of stable monodisperse spheres which ensure high and uniform surface-to-volume ratio. The reaction kinetics is found to be in strict adherencewith the Langmuir-Hinshelwood model; where metallic silver surface facilitates the relay of electrons from the adsorbed borohydride ions to dye molecules. Higher catalytic efficiency at lower precursor concentration (0.723 mM) suggests that the fruit peel derived capping agents provide excellent colloidal stability without hindering the catalytic interface by ensuring high surface-to-volume ratio of the AgNPs remains accessible foe effective environmental remediation. Differing rate constants likely reflects the varying adsorption affinities of specific organic molecules onto biocapped silver surfaces, where rate determining step is governed by the surface reaction between co-adsorbed species. The enhanced rate of degradation for MO sparkles out the superior adsorption affinity for cationic species onto phytochemical-capped silver surface. In a nutshell, it can be justified that these green AgNPs are versatile catalysts with highly sensitive efficacy to molecular structure and charge of the target dye.

With further investigation, the exact mechanism of degradation of dye solutions can be decoded; hence it can be assumed that the phytometabolites in the peel extract of *Musa balbisiana* var *elavazhai* along with its bio-augmented silver nanoparticles are responsible for this catalytic degradation. Ironically, it can be stated that successful transformation of agricultural residue (underutilized Musa *balbisiana* peel) into dual functional products without addition of toxic ingredients protrudes over an integrated valorization loop as excellent life saving elixir of green engineering frameworks.

Table 1. Catalytic Reduction Rate of MB and MO

Synthetic dye (mM)	Degradation time (min)	Degradation efficiency %± SE(Uncatalysed)	Degradation efficiency %± SE (Catalysed-%)	Rate constant (k, min^{-1})	R^2	Activity parameter (K, $s^{-1}g^{-1}$)	Turnover Frequency (TOF, min^{-1})
MO (2 mM)	1	0	44 ± 0.27^b	0.149±0.0009	1	1592.09 ± 0.58	1.44
	5	10 ± 0.57^c	97 ± 0.33^a				
MB (2 mM)	1	0	8 ± 0.28^d	0.022±0.0006	0.99	235.07± 0.28	0.21
	5	9.2 ± 0.08^d	32 ± 0.17^b				
	10	16 ± 0.29^c	85 ± 0.22^a				

SE: Standard error, Means within a column followed by the same letters are not significantly different at $p < 0.05$ as determined by Duncan's multiple range test.

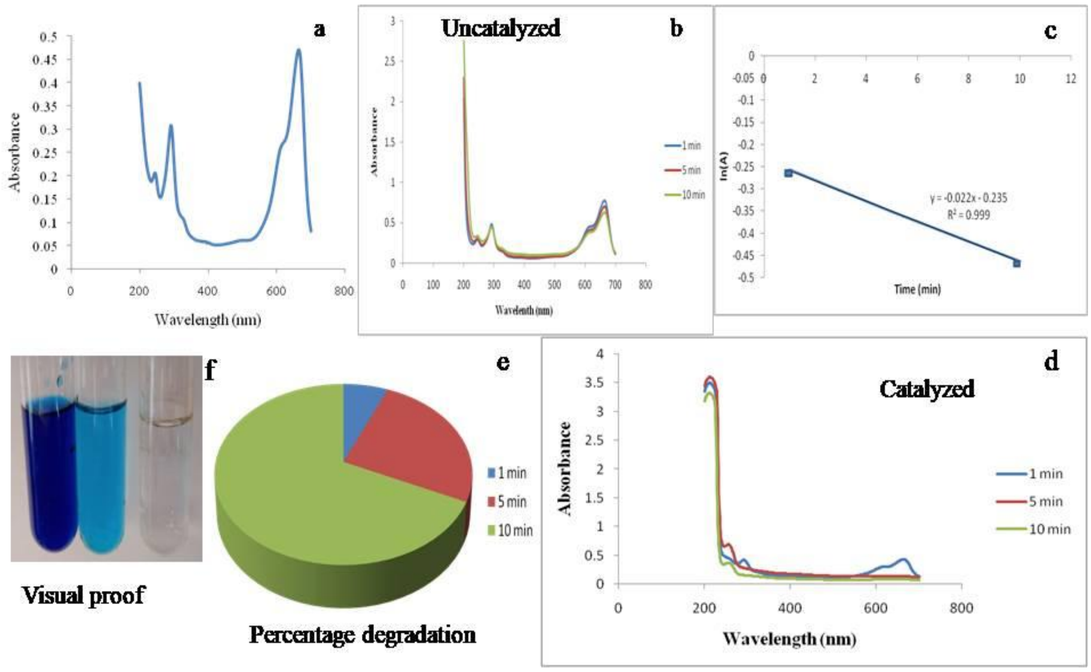

Figure 10. Dye degradation activity of silver nanopellets biosynthesized from the fruit peel extract of *Musa balbisiana* var *elavazhai*; a) UV-VIS absorption spectra of methylene blue; b) and d) UV-VIS spectra of catalytic reduction of MB with and without catalyst; c) plot of *ln* (A) vs. time for MB degradation; e) Degradation efficiency of MB; f) Visual color change of dye during degradation.

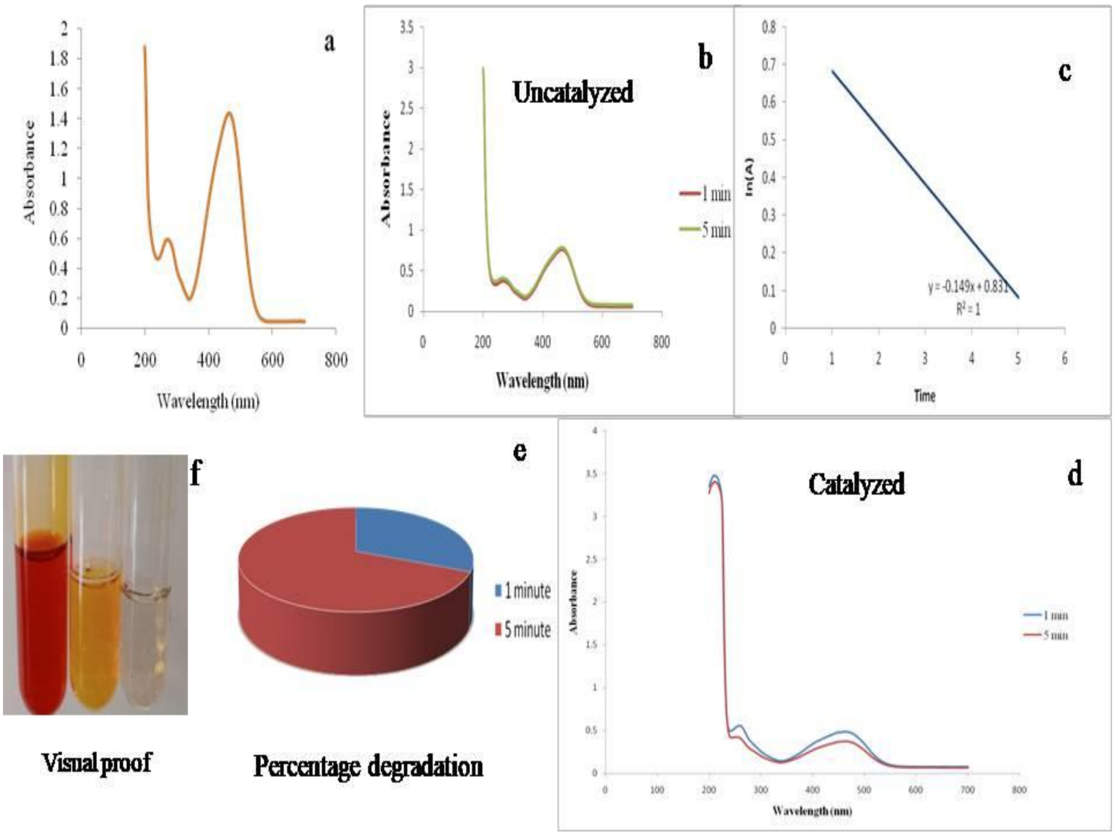

Figure 11. Dye degradation activity of silver nanopellets biosynthesized from the fruit peel extract of *Musa balbisiana* var *elavazhai*; a) UV-VIS absorption spectra of Methyl Orange; b) and d) UV-VIS spectra of catalytic reduction of MO with and without catalyst; c) plot of *ln* (A) vs. time for MB degradation; e) Degradation efficiency of MO; f) Visual color change of dye during degradation.

6. Conclusion

Ultimately, this research assures that green nanotechnology can surpass simple particle synthesis to become a restorative 'broom and mop' for industrial waste management. By harnessing the inherent phytochemical reserve of unrevealed wild Musa variety, we have effectively portrayed an integrated peel valorization approach for accomplishing total biomass valorization. High performance catalytic efficiency was established by synthesized biogenic AgNPs via a remarkable activity parameter (K) 1529.09 $s^{-1}g^{-1}$ and turnover frequency of 1.44 min^{-1}. The green synthesised AgNPs-MB was employed for the catalytic degradation of MB and MO in the presence of $NaBH_4$, resulting in the highest catalytic degradation efficiencies of 85% and 97% under favorable state of the reaction. The pseudo-first-order kinetics of this process displayed high correlation coefficients close to 1 for the degradation of both dyes.

Furthermore, by sculpturing of a cohesive biodegradable bioplastic or biocomposite film from its post extraction residue productively ends the loop by ensuring there is no secondary waste generation. This holistic approach depicts a scalable blueprint for evolution from linear consumption to a sustainable waste-to-wealth economy by unrevealing the cardinal essence of forsaken indigenous resource. In a nutshell, AgNPs derived from wild banana peel extract acts as cost effective, eco-friendly candidates for efficient wastewater treatment of toxic dye-contaminated water resources. More precisely, these pinpoints towards the amalgamation of zero-waste methods into fabrication of functional nanomaterials and sustainable packaging via deploying regional biodiversity as a cornerstone of future environmental remediation. Further studies could unravel the durability of these wild banana derived films under diverse environmental conditions to further validate its commercial viability. By inculcating the attitude of valorising similar fruit and vegetable waste into eco-friendly nanofactories, a prosperous and clutter free earth can be carved out.

Acknowledgement
The authors are grateful to the University of Calicut for the financial support during the entire study. The authors feel indebted to CSIF (University of Calicut) for providing various analysis facilities.

Funding
This work was supported by the PhD fellowship offered by University of Calicut.

Author's contributions
H. H performed the analysis, processed the experimental data, interpreted the results, drafted the manuscript and designed the figures. J. E T provided critical feedback and helped shape the Manuscript.

Ethics approval: Not applicable.
Ethical approval declaration:- The peels were procured from local residential areas and processed in accordance with local biological material handling protocols and institutional waste management guidelines.

Consent to participate
Not applicable

Consent for publication
Not applicable

Declaration of interest
The authors declare that they have no conflict of interest.

Availability of data and materials
Data sharing is not applicable to this article as all new created data is already contained within this article.

Competing Interests
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.

Data availability statement
The data that has been used is confidential. Data sharing is not applicable to this article as all new created data is already contained within this article.

References

Abdelhalim, M., Mady, M., &Ghannam, M. (2012). Physical properties of different gold nanoparticles: ultraviolet-visible and fluorescence measurements. *Journal of Nanomedicine& Nanotechnology, 3*(3), 178-194.http://dx.doi.org/10.4172/2157-7439.1000133

Adilah, A., Jamilah, B., Noranizan, M., &Hanani, Z. (2018). Utilization of mango peel extracts on the biodegradable films for active packaging. *Food packaging and shelf life*, *16*, 1-7.https://doi.org/10.1016/j.fpsl.2018.01.006

Adilah, Z., Jamilah, B., &Hanani, Z. (2018). Functional and antioxidant properties of protein-based films incorporated with mango kernel extract for active packaging. *Food Hydrocolloids*, *74*, 207-218.https://doi.org/10.1016/j.foodhyd.2017.08.017

Adiraju, P.C., Babu, K. S., &Devivasigamani, G. (2025). Analysis of *Althaea officinalis*'s Biological characterization by means of Gold nanoparticle (AuNPs). *Prestieesci Research Review*, *2*(3), 451-465.

Ajila, C., Brar, S., Verma, M., &Prasada Rao, U. (2012). Sustainable solutions for agro processing waste management: An overview. *Environmental protection strategies for sustainable development*, 65-109.https://doi.org/10.1007/978-94-007-1591-2_3

Al hamzaHasoon, B., Mahmood, B., Mohamed, E., Jabir, M., Jawad, K., Hussein, N., &Mendler-Drienyovszki, N. (2024). Tangerine fruit peel extract mediated biogenic synthesized silver nanoparticles and their potential antimicrobial, antioxidant, and cytotoxic assessments. *Green Processing and Synthesis*, *13*(1), 20240126.https://doi.org/10.1515/gps-2024-0126

Alam, M. (2022). Analyses of biosynthesized silver nanoparticles produced from strawberry fruit pomace extracts in terms of biocompatibility, cytotoxicity, antioxidant ability, photodegradation, and in-silico studies. *Journal of King Saud University-Science*, *34*(8), 102327.doi:
10.1016/j.jksus.2022.102327

Albahri, G., Badran, A., Hellany, H., Kafrouny, N., El Kurdi, R., Alame, M., Hijazi, A., Maresca, M., Patra, D., &Baydoun, E.. (2025). Green synthesis of gold nanoparticles using *Mandragoraautumnalis*: characterization and evaluation of its antioxidant and anticancer bioactivities. *Pharmaceuticals, 18*(9), 1294.https://doi.org/10.3390/ph18091294

Albuquerque, B., Pereira, C., Calhelha, R., Alves, M., Abreu, R., Barros, L., & Ferreira, I. (2020). Jabuticaba residues (*Myrciariajaboticaba* (Vell.) Berg) are rich sources of valuable compounds with bioactive properties. Food chemistry, 309, 125735. DOI: 10.1016/j.foodchem.2019.125735

Alharbi, F. N., Abaker, Z. M., &Makawi, S. Z. A. (2023). Phytochemical substances—mediated synthesis of zinc oxide nanoparticles (ZnO NPS). *Inorganics, 11*(8), 328. https://doi.org/10.3390/inorganics11080328

Ali, A., Chen, Y., Liu, H., Yu, L., Baloch, Z., Khalid, S., & Chen, L. (2019). Starch-based antimicrobial films functionalized by pomegranate peel. *International journal of biological macromolecules*, *129*, 1120-1126.D OI: 10.1016/j.ijbiomac.2018.09.068

Anand, K., Kaviyarasu, K., Muniyasamy, S., Roopan, S., Gengan, R., &Chuturgoon, A. (2017). Bio-synthesis of silver nanoparticles using agroforestry residue and their catalytic degradation for sustainable waste management. *Journal of Cluster Science*, *28*, 2279-2291.https://doi.org/10.1007/s10876-017-1212-2

Arora, N., Manchanda, H., & Gupta, M. (2026). Recent advances in green synthesis, characterization and emerging applications of nanoparticle and derived nanofluids. *Renewable and Sustainable Energy Reviews*, *226*, 116354. https://doi.org/10.1016/j.rser.2025.116354

Ashour, A., Raafat, D., El-Gowelli, H., & El-Kamel, A. (2015). Green synthesis of silver nanoparticles using cranberry powder aqueous extract: characterization and antimicrobial properties. *International Journal of Nanomedicine*, 7207-7221.https://doi.org/10.2147/IJN.S87268

Azad, M., Khan, G., Ismail, F., & Ahmed, W. (2022). Facile and efficient dye degradation using silver nanoparticles immobilized cotton substrates. *Inorganic Chemistry Communications*, *145*, 109987.https://doi.org/10.1016/j.inoche.2022.109987

Banker, A., Joshi, B., Kumar, A. R., &Zinjarde, S. (2010). Banana peel extract mediated novel route for synthesis of silver nanoparticle. *Colloids and Surfaces A: Physicochemical and EngineeringAspects*, *368*(1-3), 58-63. DOI: 10.1016/j.colsurfa.2010.07.024

Bharadwaj, K. K., Rabha, B., Pati, S., Sarkar, T., Choudhary, B. K., Barman, A., Bhattachariya, D., Srivastava, A., Barishya, D., Edinur, H. A., & Abdul Kari, Z. (2021). Green synthesis of gold nanoparticle using plant extracts as beneficial prospect for cancer theranostics. *Molecules*, *26*(1), 6389. https://doi.org/10.3390/molecules26216389

Bogireddy, N., Anand, K., & Mandal, B. (2015). Gold nanoparticles—synthesis by *Sterculiaacuminata* extract and its catalytic efficiency in alleviating different organic dyes. *Journal of Molecular Liquids*, *211*, 868-875.DOI: 10.1016/j.molliq.2015.07.027

Bogireddy, N., Kumar, H., & Mandal, B. (2016). Biofabricated silver nanoparticles as green catalyst in the degradation of different textile dyes. *Journal of environmental chemical engineering*, *4*(1), 56-64.https://doi.org/10.1016/j.jece.2015.11.004

Chand, K., Jiao, C., Lakhan, M., Shah, A., Kumar, V., Fouad, D., & Cao, D. (2021). Green synthesis, characterization and photocatalytic activity of silver nanoparticles synthesized with *Nigella sativa* seed extract. *Chemical Physics Letters*, *763*, 138218.DOI: 10.1016/j.cplett.2020.138218

Chang, W. (2025). Synthesis and applications of gold nanoparticles. https://doi.org/10.3390/books978-3-7258-4378-7

Covilakam, P. K. K., Habee, H., &Thoppil, J. E. (2025). Evaluation of cytotoxic potential of biogenic silver nanoparticle phytofabricated using *Nerium oleander*. *Environmental Science and Pollution Research, 1-14. https://doi.org/10.1007/s11356-025-37088-7*

Cyril, N., George, J., Nair, P., Joseph, L., Sunila, C., Smitha, V., & Sylas, V. (2020). Catalytic activity of *Derris trifoliata* stabilized gold and silver nanoparticles in the reduction of isomers of nitrophenol and azo violet. *Nano-Structures & Nano-Objects*, *22*, 100430.https://doi.org/10.1016/j.nanoso.2020.100430

De FariaArquelau, P., Silva, V., Garcia, M., de Araújo, R., &Fante, C. (2019). Characterization of edible coatings based on ripe "Prata" banana peel flour. *Food Hydrocolloids*, *89*, 570-578.https://doi.org/10.1016/j.foodhyd.2018.11.029

Dias, P., Sajiwanie, J., Rathnayaka, R., &Awolu, O. (2021). Optimization of composite fruit peel powder as a texture modifier for fat free set yoghurt: A mixture design approach. *Journal of Agricultural Sciences–Sri Lanka*, *16*(2).DOI: 10.4038/jas.v16i2.9328

Doan, V. D., Huynh, B. A., Nguyen, T. D., Cao, X. T., Ngyugen, V. C., Nguyen, T. L. H., & Le, V. T. (2020). Biosynthesis of silver and gold nanoparticle using aqueous extracts of *Codonopsispilosula* roots for antibacterial and catalytic applications. *Journal of Nanomaterials*, *2020*(1), 8492016.https://doi.org/10.1155/2020/8492016

Drago, L. (2019). Probiotics and colon cancer. *Microorganisms*, *7*(3), 66.https://doi.org/10.3390/microorganisms7030066

Erradhouani, B., Coma, V., Sonnemann, G., &Loubet, P. (2026). Transition to bio-based plastic packaging reveals complex climate–biodiversity trade-offs. *Nature Communications*, 17, 3630. https://doi.org/10.1038/s41467-026-69016-9

Fahim, M., Shahzaib, A., Nishat, N., Jahan, A., Bhat, T. A., &Inam, A. (2024). Green synthesis of silver nanoparticles: A comprehensive review of methods, influencing factors, and applications. JCIS Open, 16, 100125.https://doi.org/10.1016/j.jciso.2024.100125

Fissan, H., Ristig, S., Kaminski, H., Asbach, C., &Epple, M. (2014). Comparison of different characterization methods for nanoparticle dispersions before and after aerosolization. *Analytical Methods*, *6*(18), 7324-7334.DOI: 10.1039/C4AY01203H

Garibo, D., Borbón-Nuñez, H., de León, J., García Mendoza, E., Estrada, I., Toledano-Magaña, Y., &Susarrey-Arce, A. (2020). Green synthesis of silver nanoparticles using *Lysilomaacapulcensis* exhibit high-antimicrobial activity. *Scientific reports*, *10*(1), 12805.https://doi.org/10.1038/s41598-020-69606-7

George, J. B., Cyril, N., Radhamany, R., Sylas, V. P., Kumar, N. P., Sreejith, M. S., & John, S. (2025). Biogenic Silver and Gold nanoparticles capped by *Thespesiapopulnea* metabolites: Catalytic Reduction and Antibacterial Potency. *ChemistrySelect*, *10*(41), e03536. https://doi.org/10.1002/slct.202503536

Githala, C. K., Raj, S., Dhaka, A., Mali, S. C., & Trivedi, R. (2022). Phyto-fabrication of silver nanoparticles and their catalytic dye degradation and antifungal efficacy. *Frontiers in Chemistry*, *10*, 994721.https://doi.org/10.3389/fchem.2022.994721

Gonçalves, S. M., Dos Santos, D. C., Motta, J. F. G., Dos Santos, R. R., Chávez, D. W. H., & de Melo, N. R. (2019). Structure and functional properties of cellulose acetate films incorporated with glycerol. *Carbohydrate polymers*, *209*, 190-197. https://doi.org/10.1016/j.carbpol.2019.01.031

Goula, A. M., Ververi, M., Adamopoulou, A., &Kaderides, K. (2017). Green ultrasound-assisted extraction of carotenoids from pomegranate wastes using vegetable oils. *Ultrasonics sonochemistry*, *34*, 821-830. DOI: 10.1016/j.ultsonch.2016.07.022

Gupta, D., Boora, A., Thakur, A., & Gupta, T. K. (2023). Green and sustainable synthesis of nanomaterials: recent advancements and limitations. *Environmental Research*, 231, 116316.https://doi.org/10.1016/j.envres.2023.116316

Gupta, N., Singh, H., & Sharma, R. (2011). Metal nanoparticles with high catalytic activity in degradation of methyl orange: an electron relay effect. *Journal of Molecular Catalysis A: Chemical*, *335*(1-2), 248-252.https://doi.org/10.1016/j.molcata.2010.12.001

Habeeb, H., &Thoppil, J. E. (2023). Green synthesis of silver nanoparticle from *Wrightiaarborea*: physicochemical profiling and genotoxic potency. *Inorganic Chemistry Communications, 156,*111179. https://doi.org/10.1016/j.inoche.2023.111179

Halász, K., &Csóka, L. (2018). Black chokeberry (*Aroniamelanocarpa*) pomace extract immobilized in chitosan for colorimetric pH indicator film application. *Food Packaging and Shelf Life*, *16*, 185–193. https://doi.org/10.1016/j.fpsl.2018.03.002

Hiba, H., &Thoppil, J. E. (2022). Medicinal herbs as a panacea for biogenic silver nanoparticle. *Bulletin of the National Research Centre, 46*(1), 9.https://doi.org/10.1186/s42269-021-00692-x

Hijazi, B., Faraj, M., Mhanna, R., & El-Dakdouki, M. (2024). Biosynthesis of silver nanoparticles as a reliable alternative for the catalytic degradation of organic dyes and antibacterial applications. *Current Research in Green and Sustainable Chemistry*, *8*, 100408.https://doi.org/10.1016/j.crgsc.2024.100408

Ibrahim, H. M. (2015). Green synthesis and characterization of silver nanoparticle using banana peel extract and their antimicrobial activity against representative microorganisms. *Journal of radiation research and applied sciences*, *8*(3), 265-275.https://doi.org/10.1016/j.jrras.2015.01.007

Jasuja, N., Gupta, D., Reza, M., & Joshi, S. (2014). Green Synthesis of AgNPs Stabilized with biowaste and their antimicrobial activities. *Brazilian Journal of Microbiology*, *45*, 1325–1332.https://doi.org/10.1590/S1517-83822014000400024

Kalishwaralal, K., BarathManiKanth, S., Pandian, S., Deepak, V., &Gurunathan, S. (2010). Silver nanoparticles impede the biofilm formation by *Pseudomonas aeruginosa* and *Staphylococcus epidermidis*. *Colloids and Surfaces B: Biointerfaces*, *79*(2), 340-344. DOI: 10.1016/j.colsurfb.2010.04.014

Khaled, F., Ramadan, A., &Ashoush, I. (2014). Nanoencapsulation and nanoemulsion of bioactive compounds to enhance their antioxidant activity in food. *International Journal of food science and technology*, *4*(3), 1-22.

Khanal, L., Sharma, K., Paudyal, H., Parajuli, K., Dahal, B., Ganga, G., &Kalauni, S. (2022). Green synthesis of silver nanoparticles from root extracts of *Rubusellipticus* Sm. and comparison of antioxidant and antibacterial activity. *Journal of Nanomaterials*, *2022*(1), 1832587. https://doi.org/10.1155/2022/1832587

Kharb, J.,& Saharan, R. (2022).Sustainable Biodegradable Plastics and their Applications: A Mini Review. In *IOP conference series: materials science and engineering* (Vol. 1248, No. 1, p. 012008. IOP Publishing.DOI: 10.1088/1757-899X/1248/1/012008

Kharb, J.,& Saharan, R. (2023). Design and synthesis of eco-friendlycucumber peel-based bioplastic materials. *Materials Today: Proceedings*, *82*,123–128. DOI: 10.1016/j.matpr.2022.12.109

Kharb, J.,& Saharan, R. (2025). Development of biodegradable and eco-friendly fruit peel-derived bioplastic film with antibacterial potential for food packagingapplication. *Biomass Conversion and Biorefinery*, *15*(7), 10839-10854.https://doi.org/10.1007/s13399-024-05834-5

Khatun, R., Mamun, M. S. A., Islam, S., Khatun, N., Hakim, M., Hossain, M. S., ... &Barai, H. R. (2022). Phytochemical-assisted synthesis of Fe3O4 nanoparticles and evaluation of their catalytic activity. *Micromachines, 13*(12), 2077.https://doi.org/10.3390/mi13122077

Kifle, D., Bacha, K., &Gonfa, G. (2025). Antimicrobial activities of biosynthesized nanosilver using *Musa paradisiaca* and *Citrus sinensis* peel extracts against major human and plant pathogens. *Scientific Reports*, *15*(1), 6600. https://doi.org/10.1038/s41598-025-91020-0

KoKo, M. K. H., Sum, J. Y., Yeap, S. P., &Cheok, C. Y. (2025, June). The effect of pH on the green synthesis of silver nanoparticles using Garcinia mangostana L.(mangosteen) rind extract. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1516, No. 1, p. 012030). IOP Publishing. DOI: 10.1088/1755-1315/1516/1/012030

Kumar, A., Shah, S. R., Jayeoye, t. J., Kumar, A., Parjapati, B., Singh, S., & Kapoor, D. U. (2023). Biogenic metallic nanoparticle: Biomedical, analytical, food preservation and applications in other consumable products. *Frontiers in Nanotechnology*, *5*, 1175149. https://doi.org/10.3389/fnano.2023.1175149

Kumar, K., Yadav, A., Kumar, V., Vyas, P., & Dhaliwal, H. (2017). Food waste: A potential bioresource for extraction of nutraceuticals and bioactive compounds. *Bioresources and Bioprocessing*, *4*, 1-14.https://doi.org/10.1186/s40643-017-0148-6

Laysandra, L., Santosa, F., Austen, V., Soetaredjo, F., Foe, K., Putro, J., &Ismadji, S. (2018). Rarasaponin-bentonite-activated biochar from durian shells composite for removal of crystal violet and Cr (VI) from aqueous solution. *Environmental Science and Pollution Research*, *25*, 30680-30695.https://doi.org/10.1007/s11356-018-3104-x

Lin, P., Lin, S., Wang, P., & Sridhar, R. (2014). Techniques for physicochemical characterization of nanomaterials. *Biotechnology advances*, *32*(4), 711-726.DOI:10.1016/j.biotechadv.2013.11.006

Luchese, C., Garrido, T., Spada, J., Tessaro, I., & de la Caba, K. (2018). Development and characterization of cassava starch films incorporated with blueberry pomace. *International Journal of Biological Macromolecules*, *106*, 834-839.DOI: 10.1016/j.ijbiomac.2017.08.083

Murador, D., Braga, A., Martins, P., Mercadante, A., & de Rosso, V. (2019). Ionic liquid associated with ultrasonic-assisted extraction: A new approach to obtain carotenoids from orange peel. *Food research international*, *126*, 108653. DOI: 10.1016/j.foodres.2019.108653

Muthu, K., &Priya, S. (2017). Green synthesis, characterization and catalytic activity of silver nanoparticles using *Cassia auriculata* flower extract separated fraction. *SpectrochimicaActa Part A: Molecular and Biomolecular Spectroscopy*, *179*, 66-72.https://doi.org/10.1016/j.saa.2017.02.024

Nayak, D., Ashe, S., Rauta, P., Kumari, M. &Nayak, B. (2016). Bark extract mediated green synthesis of silver nanoparticles: evaluation of antimicrobial activity and antiproliferative response against osteosarcoma, *Materials Science and Engineering*: C, *58*, 44–52. https://doi.org/10.1016/j.msec.2015.08.022

NushibaNaser, P. T., &Thoppil, J. E. (2023). synthesis, characterization and antimicrobial efficacy of gold and silver nanoparticle from fruit extracts of *Ficusdrupacea*Thund. var. *pubescens* . *BioNanoScience, 13* (2), 405-412.https://doi.org/10.1007/s12668-023-01078-1

Osman, A. I., Zhang, Y., Farghali, M., Rashwan, A. K., Eltaweil, A. S., Abd El-Monaem, E. M., … & Yap, P. S. (2024). Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. Environmental Chemistry Letters, 22(2), 841-887.https://doi.org/10.1007/s10311-023-01682-3

Ovais, M., Khalil, A. T., Islam, N. U., Ahmad, I., Ayaz, M., Saravanan, M., … & Mukherjee, S. (2018). Role of plant phytochemicals and microbial enzymes in biosynthesis of metallic nanoparticles. Applied microbiology and biotechnology, 102(16), 6799-6814.https://doi.org/10.1007/s00253-018-9146-7

Pal, T., Sau, T., & Jana, N. (1997). Reversible formation and dissolution of silver nanoparticles in aqueous surfactant media. *Langmuir*, *13*(6), 1481-1485.https://doi.org/10.1021/la960834o

Parfitt, J., Barthel, M., &Macnaughton, S. (2010). Food waste within food supply chains: quantification and potential for change to 2050. *Philosophical transactions of the royal society B: biological sciences*, *365*(1554), 3065-3081.DOI:10.1098/rstb.2010.0126

Pavia, D., Lampman, G., Kriz, G., (2001). *Introduction to spectroscopy, a guide for students of organic chemistry*. 3rd Edition, Thomas Learning, Boston.

Phillip, A., Kumar, S., & Shah, S. A. (2025). Valorization of Fruit Processing Wastes for Sustainable Biofuel Production: Composition, Co-Digestion Approaches for Enhanced Biogas Production, and Associated Challenges. European Journal of Scientific Research and Reviews, 3(3), 191-203. DOI:10.5455/EJSRR.20250626080851

Photinam, R., Moongngarm, A., Detchewa, P., & Wang, Y. J. (2024). Improvement of amylose–lipid complex and starch digestibility profiles of corn starch added with rice bran oil or linoleic acid using ultrasonic and microwave treatment. *Journal of Food Science and Technology*, *61*(12), 2287-2298.https://doi.org/10.1007/s13197-024-05993-3

Podgorbunskikh, E., Kuskov, T., Matveeva, A., Ulihin, A., Bychkov, A., Lomovskiy, I., &Polienko, Y. (2023). Disordering of Starch Films as a Factor Influencing the Release Rate of Biologically Active Substances. *Polymers*, *15*(10), 2303.https://doi.org/10.3390/polym15102303

Poveda-Giraldo, J. A., Jo, H. M., Ahn, M. R., Choi, J. H., Kim, H., & Park, S. (2026). Environmental Life Cycle Assessment of Hemp Hurd-Based Biocomposites for Packaging and Mulch Film Applications. Journal of Bioresources and Bioproducts, 100264.https://doi.org/10.1016/j.jobab.2026.100264

Pradhan, N., Pal, A., & Pal, T. (2002). Silver nanoparticle catalyzed reduction of aromatic nitro compounds. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *196*(2-3), 247-257.DOI:10.1016/S0927-7757(01)01040-8

Raj, S., Singh, H., Trivedi, R., &Soni, V. (2020). Biogenic synthesis of AgNPs employing *Terminalia arjuna* leaf extract and its efficacy towards catalytic degradation of organic dyes. *Scientifiic reports, 10*(1), 9616.https://doi.org/10.1038/s41598-020-66851-8

Rajasekar, R., Thanasamy, R., Samuel, M., Edison, T., & Raman, N. (2022). Ecofriendly synthesis of silver nanoparticles using *Heterothecasubaxillaris* flower and its catalytic performance on reduction of methyl orange. *Biochemical Engineering Journal*, *187*, 108447.DOI: 10.1016/j.bej.2022.108447

Robert, P., Gorena, T., Romero, N., Sepulveda, E., Chavez, J., & Saenz, C. (2010). Encapsulation of polyphenols and anthocyanins from pomegranate (*Punicagranatum*) by spray drying. *International Journal of Food Science & Technology*, *45*(7), 1386-1394.https://doi.org/10.1111/j.1365-2621.2010.02270.x

Rodriguez, E., Vidallon, M., Mendoza, D., & Reyes, C. (2016). Health-promoting bioactivities of betalains from red dragon fruit (*Hylocereuspolyrhizus* (Weber) Britton and Rose) peels as affected by carbohydrate encapsulation. *Journal of the Science of Food and Agriculture*, *96*(14), 4679-4689.https://doi.org/10.1002/jsfa.7681

Ruiz-Rodriguez, A., Marín, F., Ocaña, A., &Soler-Rivas, C. (2008). Effect of domestic processing on bioactive compounds. *Phytochemistry Reviews*, *7*, 345-384.https://doi.org/10.1007/s11101-007-9073-1

Sah, B., Vasiljevic, T., McKechnie, S., &Donkor, O. (2015). Effect of refrigerated storage on probiotic viability and the production and stability of antimutagenic and antioxidant peptides in yogurt supplemented with pineapple peel. *Journal of Dairy Science*, *98*(9), 5905-5916.https://doi.org/10.3168/jds.2015-9450

Sah, B., Vasiljevic, T., McKechnie, S., &Donkor, O. (2016). Effect of pineapple waste powder on probiotic growth, antioxidant and antimutagenic activities of yogurt. *Journal of Food science and Technology*, *53*, 1698-1708.https://doi.org/10.1007/s13197-015-2100-0

Saha, P., Mahiuddin, M., Islam, A., &Ochiai, B. (2021). Biogenic synthesis and catalytic efficacy of silver nanoparticles based on peel extracts of *Citrus macroptera* fruit. *ACS omega*, *6*(28), 18260-18268.https://doi.org/10.1021/acsomega.1c02149

Saini, A., Panesar, P., &Bera, M. (2019). Valorization of fruits and vegetables waste through green extraction of bioactive compounds and their nanoemulsions-based delivery system. *Bioresources and Bioprocessing*, *6*(1), 1-12.https://doi.org/10.1186/s40643-019-0261-9

Salvia-Trujillo, L., Rojas-Graü, A., Soliva-Fortuny, R., & Martín-Belloso, O. (2015). Physicochemical characterization and antimicrobial activity of food-grade emulsions and nanoemulsions incorporating essential oils. *Food hydrocolloids*, *43*, 547-556.https://doi.org/10.1016/j.foodhyd.2014.07.012

Salvia-Trujillo, L., Rojas-Graü, M., Soliva-Fortuny, R., & Martín-Belloso, O. (2015). Use of antimicrobial nanoemulsions as edible coatings: Impact on safety and quality attributes of fresh-cut

Fuji apples. *Postharvest Biology and Technology*, *105*, 8-16. DOI: 10.1016/j.postharvbio.2015.03.009

Saxena, R., Kotnala, S., Bhatt, S. C., Uniyal, M., Rawat, B. S., Negi, P., & Riyal, M. K. (2025). A review on green synthesis of nanoparticles toward sustainable environment. Sustainable Chemistry for Climate Action, 6, 100071.https://doi.org/10.1016/j.scca.2025.100071

Shaikh, A., & Das, S. (2025). Biogenic Gold Nanoparticle: Methods, Characterization, and Diverse Applications. In using *Computational intelligence for Sustainable Manufacturingof Advanced Materials* (pp. 83-100). IGI Global Scientific Publishing.DOI: 10.4018/979-8-3693-7974-5.ch005

Shamsuddin, I. M., Jafar, J. A., Shawai, A. S. A., Yusuf, S., Lateefah, M., &Aminu, I. (2017). Bioplastics as better alternative to petroplastics and their role in national sustainability: a review. *Advances in Bioscience and. Bioeng*ineering, *5*(4), 63-70.doi: 10.11648/j.abb.20170504.13

Shukor, U., Nordin, N., Tawakkal, I., Talib, R., & Othman, S. H. (2021). Utilization of jackfruit peel waste for the production of biodegradable and active antimicrobial packaging films. In Biopolymers and Biocomposites from Agro-Waste for Packaging Applications (pp. 171-192). WoodheadPublishing.https://doi.org/10.1016/B978-0-12-819953-4.00004-5

Sial, T. A., Khan, M. N., Lan, Z., Kumbhar, F., Ying, Z., Zhang, J., … & Li, X. (2019). Contrasting effects of banana peels waste and its biochar on greenhouse gas emissions and soil biochemical properties. Process Safety and Environmental Protection, 122, 366-377.DOI: 10.1016/j.psep.2018.10.030

Sidhu, A. K., Verma, N., &Kaushal, P. (2022). Role of biogenic capping agents in the synthesis of metallic nanoparticles and evaluation of their therapeutic potential. Frontiers *in Nanotechnology, 3*, 801620.https://doi.org/10.3389/fnano.2021.801620

Socas-Rodríguez, B., Álvarez-Rivera, G., Valdés, A., Ibáñez, E., &Cifuentes, A. (2021). Food by-products and food wastes: are they safe enough for their valorization?. *Trends in Food Science & Technology*, *114*, 133-147.https://doi.org/10.1016/j.tifs.2021.05.002

Sohany, M., Tawakkal, I., Ariffin, S. H., Shah, N., &Yusof, Y. (2021). Characterization of anthocyanin associated purple sweet potato starch and peel-based pH indicator films. *Foods*, *10*(9), 2005.https://doi.org/10.3390/foods10092005

Suart, B. (2004). *Infrared Spectroscopy: Fundamental and Applications*. JohnWiley& Sons, Inc. UK.

Swargiary, A., Boro, H., & Roy, M. K. (2021). Phytochemistry and Pharmacological Property of*Musabalbisiana*Colla: A mini review. *Pharmacognosy Reviews,15*(29), 91-95. DOI : 10.5530/phrev.2021.15.11

TaraziRiess, H., Shani Levi, C., &Lesmes, U. (2022). Inclusion of phenolic bioactives in high amylose corn starch for gastro-intestinal delivery. *Frontiers in Nutrition*, 9, 981408.https://doi.org/10.3389/fnut.2022.981408

Varadavenkatesan, T., Selvaraj, R., &Vinayagam, R. (2016). Phyto-synthesis of silver nanoparticles from *Mussaendaerythrophylla* leaf extract and their application in catalytic degradation of methyl orange dye. *Journal of Molecular Liquids*, *221*, 1063-1070.DOI: 10.1016/j.molliq.2016.06.064

Wang, W., Bostic, T., &Gu, L. (2010). Antioxidant capacities, procyanidins and pigments in avocados of different strains and cultivars. *Food chemistry*, *122*(4), 1193-1198. DOI: 10.1016/j.foodchem.2010.03.114