Research Article

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Review in green synthesis mechanisms, application, and future prospects *for Garcinia mangostana* L. (mangosteen)-derived nanoparticles

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Abstract: The growing global demand for sustainable and cost-effective methods of nanomaterial production has driven the development of green synthesis techniques, offering a safer alternative to traditional, hazardous approaches. Among the numerous plants utilized for this purpose, *Garcinia mangostana* L. (mangosteen) stands out due to its high content of bioactive phytochemicals, such as α-mangostin, xanthones, and other secondary metabolites. These compounds serve as natural reducing, capping, and stabilizing agents in the synthesis of metal and metal oxide nanoparticles (NPs) such as silver, gold, and zinc oxide. In contrast to traditional approaches reliant on toxic chemicals and harsh circumstances, mangosteen extracts facilitate the production of NPs in moderate and sustainable conditions, offering a viable strategy for sustainable nanotechnology. This review article offers a thorough examination of the green synthesis processes utilizing extracts from mangosteen, going over the physicochemical characteristics of the resultant NPs and their numerous uses, such as antimicrobial and anticancer properties, antioxidant therapy, and environmental remediation. It is highlighted that NPs synthesized from mangosteen have the potential to solve environmental and health issues. However, to enable wider industrial and commercial applications, important issues including scalability, repeatability of NP properties, and long-term stability need to be addressed. In addition to providing insights into the creation of sustainable NPs, this study critically evaluates existing research and lays the groundwork for future developments in green nanotechnology.

Keywords: green synthesis, nanomaterials, plant extracts, *Garcinia mangostana* L., phytochemicals

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1 Introduction

Nanotechnology has rapidly evolved as a transformative field with extensive applications across a broad spectrum of industries, including optics, electronics, energy storage, catalysis, biomedicine, and materials science [1–3]. Nanomaterials with at least one dimension smaller than 100 nm are at the core of nanotechnology advancements [4–8]. This nanoscale dimension imparts unique physicochemical properties that differ significantly from those of their bulk equivalents [9]. Their unique properties, including a high surface-area-to-volume ratio; quantum confinement effects; and remarkable mechanical, thermal, and electrical characteristics, have

positioned nanomaterials as key drivers in the development of technologies for drug delivery, antibacterial treatments, biosensing, and environmental remediation [10–16].

Nanomaterial synthesis typically occurs through three main approaches: chemical, physical, and green synthesis [17,18]. Chemical and physical methods are often preferred for their ability to yield nanoparticles (NPs) with precise sizes, shapes, and controlled properties. However, these methods pose significant challenges, including high costs, technical difficulties, low material conversion rates, and the production of toxic by-products due to the use of hazardous chemicals [19–23]. Additionally, these methods often involve harsh reaction conditions such as elevated temperatures, extreme pH values, and high-pressure environments, making them less suitable for generating biocompatible and eco-friendly nanomaterials [22–25].

In response to the limitations of traditional methods, green synthesis has gained prominence as a viable alternative, utilizing biological resources such as plant extracts, microorganisms, and enzymes to synthesize NPs under mild conditions [4–6,13,25]. This approach is not only cost-effective [12,22] but also promotes sustainability by minimizing or eliminating the use of hazardous chemicals [26]. Among the various biological entities used in green synthesis, plant extracts have garnered particular attention due to their rich content of phytochemicals, as flavonoids, alkaloids, polyphenols, and terpenoids, which function as natural reducing, capping, and stabilizing agents [9,19,20,24,27]. These biomolecules not only facilitate the formation of NPs but also improve their biocompatibility and enhance their potential therapeutic applications [28].

Mangosteen, or *Garcinia mangostana* L., is one plant species that has shown a great deal of promise in green nanotechnology. Native to Southeast Asia [29–33], mangosteen is renowned for its rich array of bioactive compounds, including xanthones, flavonoids, and α-mangostin, which possess various pharmacological properties [34–37]. These phytochemicals enable the plant to mediate the green synthesis of metal and metal oxide NPs under mild conditions, providing a sustainable and eco-friendly method for nanomaterial production [38–41]. Significantly, NPs synthesized using mangosteen extracts have shown notable antimicrobial, cytotoxic, anticancer, and antioxidant properties, highlighting their potential applications in biomedicine and environmental remediation [37,40,42].

Despite the increasing interest in green synthesis and the well-documented bioactivity of mangosteen, comprehensive studies on the plant's full potential in nanomaterial production remain limited. This review aims to address this gap by providing an in-depth analysis of the current state of research on the green synthesis of NPs using mangosteen extracts. The authors explore the diverse phytochemical profiles of various plant parts, including the seed, stem, leaf, bark, pericarp, and peel, and evaluate their role in mediating the formation of NPs. Additionally, the authors discuss the physicochemical properties of the synthesized NPs and their potential applications in antibacterial therapies, cancer treatment, and environmental pollution mitigation.

However, several challenges must be addressed to further advance the field of green nanotechnology. Key concerns include the scalability of green synthesis methods, the reproducibility of size and shape of NPs, and the long-term stability of the synthesized NPs. Additionally, a deeper understanding of the mechanisms by which phytochemicals mediate NP synthesis is needed to optimize the process and enhance the functional properties of the resulting nanomaterials. This study attempts to promote more inventive and sustainable methods of NP synthesis by critically analyzing these issues and suggesting future research avenues, which may lead to a wider use of NPs in commercial and industrial applications.

2 Plant extracts mediated green-synthesized nanomaterials

Green synthesis of nanomaterials using biological entities is an emerging field, with plant extracts receiving significant attention due to their simplicity, scalability, and eco-friendliness [4–6,13,25]. In contrast to other biological sources such as microorganisms or algae, plant extracts provide a simpler and more dependable way to synthesize nanomaterials without requiring complicated cell culture upkeep or sterile conditions [12,21,43]. Plant extracts are therefore particularly well suited for large-scale synthesis, where the bioactive phytochemicals they contain are essential for making the synthesis process more effectively [12,20,44,45].

Phytochemicals, including flavonoids, alkaloids, terpenoids, and phenolic compounds, act as natural reducing, stabilizing, and capping agents during the synthesis of nanomaterials. These compounds facilitate the reduction of metal ions into NPs and aid in stabilizing the particles to prevent agglomeration [9,19,20,24,27]. The variety of phytochemicals present in plants not only allows for the production of NPs with controlled size and morphology but also eliminates the need for toxic chemicals commonly used in conventional synthesis methods [25]. Thus, plant-mediated synthesis a highly attractive and straightforward

approach for creating nanomaterials with potential applications in agriculture, the food industry, and medicine [22,28].

Green synthesis utilizing plant materials is highly versatile, employing various plant parts such as flowers, leaves, stems, roots, and seeds [43,46,47], whether in their living or dried states [23,43]. Despite the broad range of phytochemicals available in plants [48,49], the full potential of these natural compounds in nanomaterial synthesis remains underexplored. The ability of these phytochemicals to produce NPs with specific properties tailored for targeted applications represents a promising avenue for future research. Numerous plant extracts have shown encouraging promise in the synthesis of green nanomaterials in recent research. For instance, extracts from Jamaican cherry leaves [50], papaya [44], soursop [19,51], pomegranate [52], and banana peels [53] have demonstrated significant effectiveness in synthesizing metallic NPs with varied applications. This review aims to provide a comprehensive overview of the green synthesis of silver (Ag), gold (Au), and zinc oxide (ZnO) NPs using aqueous extracts of *Garcinia mangostana* L. The underlying mechanisms involved in the synthesis process, the diverse applications of these NPs, and the future prospects for scaling up their production are explored in this review. This study also aims to demonstrate the potential of NPs produced from mangosteen in promoting sustainable nanotechnology and tackling urgent global issues by exploring the present status of research and highlighting important possibilities and difficulties.

3 *Garcinia mangostana* L. plant

G. mangostana L., commonly known as mangosteen, is a perennial evergreen species belonging to the Clusiaceae family. Native to Southeast Asia, particularly regions such as Malaysia, Indonesia, and Thailand [29–33], mangosteen is revered for its unique flavor and aromatic profile, earning it the moniker “Queen of Fruits” [29,33,34,54]. India is the world largest mangosteen producer, whereas Thailand is the second largest producer after Indonesia in Southeast Asia, with its export in 2020 being 292, 147 tons (409, 466 USD) [55]. Mangosteen is most widely and economically eaten in Southeast Asia countries [56]. Despite its high demand, the mangosteen tree exhibits slow growth due to its poorly developed, brownish-white taproot system, which hinders efficient nutrient and water uptake [33,35]. Additionally, the plant’s slow juvenile growth phase is characterized by low photosynthetic efficiency [33] and limited meristematic activity, resulting in a prolonged maturation period, with the first fruit typically appearing between 9 and 20 years [57].

A mature mangosteen tree can reach heights of 6–25 m. The leaves, with their oval shape and tapering tips, measure approximately 20–25 cm in length and 6–9 cm in width. The thick, cylindrical green petioles support the plant’s androgynous, solitary flowers, which are typically 1–2 cm long. The fruit has 83% pericarps, 15% pulp, and 2% seeds by weight. It is recognized for its distinct purplish-brown color, measures 6–8 cm in diameter, and contains a soft, white pulp with a slightly acidic taste [31,32,35,55,56].

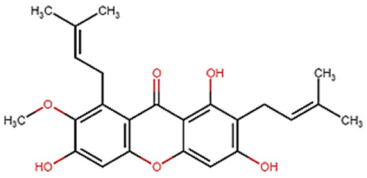
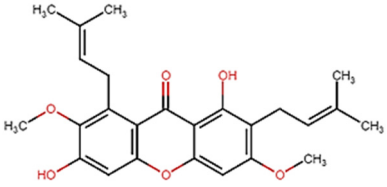
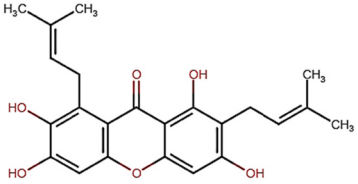
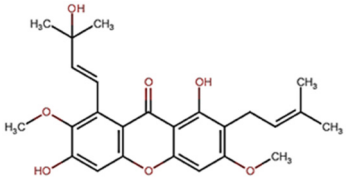
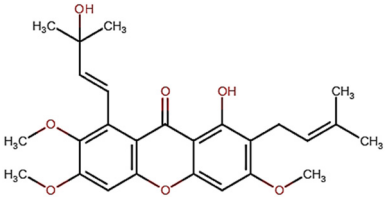
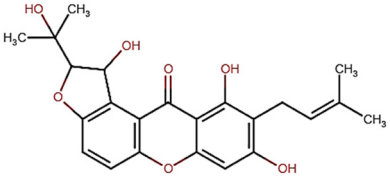
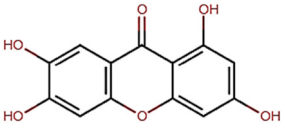
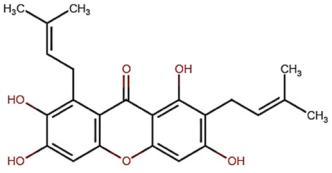
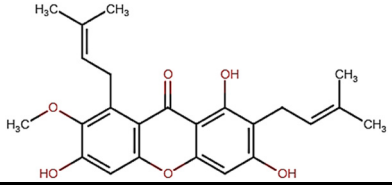
The mangosteen pericarps are particularly well known for its nutrient-rich byproducts, including 83% carbohydrate, 6% fat, 3% protein, 2% ash, and 2% free sugars [55]. Thus, mangosteen fruit has been extensively studied for its wide array of bioactive compounds, which confer several potential pharmacological properties. These include anti-allergic, anticonvulsant, anti-leukemic, antitumor, antidiabetic, antiplasmodial, hepatoprotective, and immunomodulatory effects [29–31,35–37,54,57]. Additionally, mangosteen has shown promise in enhancing lymphatic system function [57] and in the management of hypertension and arthritis [34]. In Aizat *et al.’s* study, mangosteen peel powder has been widely used in animal feed supplementation as it was reported that xanthones are able to increase the chickens’ weight and reduce heat stress. It is also served as food shelf-life indicator as the anthocyanin extract from the mangosteen could detect the chicken nuggets spoilage through color indication. Additionally, the tannin content in the mangosteen extract is used as natural dye (brown) in the textile industry as it is environmentally friendly compared to synthetic dyes (ruthenium complexes). The mangosteen dark purple dye is also widely utilized in dye-sensitized solar cells (third-generation solar cell) creation as it is more effective in harvesting solar energy due to the presence of active carbonyl and hydroxyl groups in the anthocyanin compounds [34].

4 Phytochemical content in mangosteen

The mangosteen fruit is a rich source of various phytochemicals, including terpenes, xanthones, anthocyanins, flavonoids, polyphenols, and tannins, which collectively contribute to its medicinal properties [30,31,34–37]. Table 1 provides a detailed overview of the phytochemical composition of different parts of the mangosteen plant.

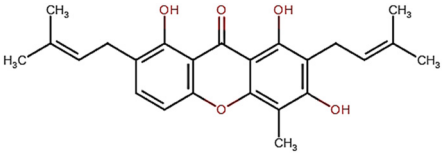
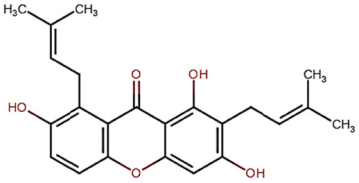
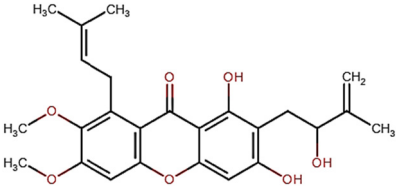
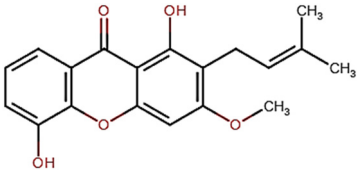
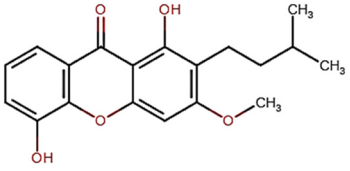
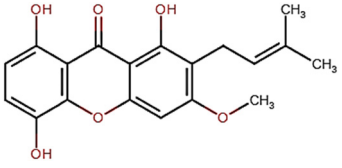
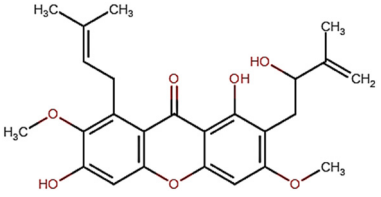
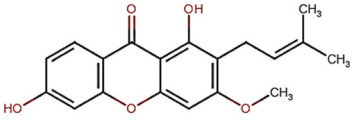
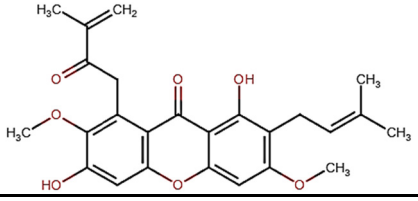
Different parts of the mangosteen, including its heartwood, bark, leaves, pericarp, and yellow gum (or yellow

Table 1: Phytochemical content in mangosteen in different parts of plant [58]

Phytochemicals	Compounds	Structures	Plant parts
Xanthones	α-Mangostin		Pericarp, whole fruit, stem, aril, and seed
	β-Mangostin		Pericarp, whole fruit, and stem
	γ-Mangostin		Pericarp and whole fruit
	(16E)-1,6-Dihydroxy-8-(3-hydroxy-3-methylbut-1-enyl)-3,7-dimethoxy-2-(3-methylbut-2-enyl)-xanthone		Heartwood
	(16E)-1,6-Dihydroxy-8-(3-hydroxy-3-methylbut-1-enyl)-3,6,7-trimethoxy-2-(3-methylbut-2-enyl)-xanthone		Heartwood
	1,2-Dihydro-1,8,10-trihydroxy-2-(2-hydroxypropan-2-yl)-9-(3-methylbut-2-enyl)furo[3, 2-a] xanthen-11-one		Whole fruit
	1 3,6,7-Tetrahydroxy xanthone		Heartwood
	1,3,6,7-Tetrahydroxy-2,8-(3-methyl-2-butenyl) xanthone P1		Pericarp
	1,3,6-Trihydroxy-7-methoxy-2,8-(3-methyl-2-butenyl)xanthone P2		Pericarp

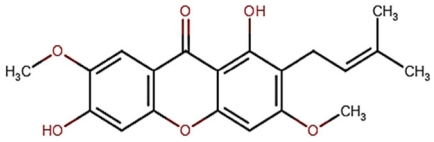
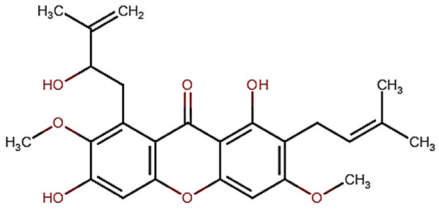
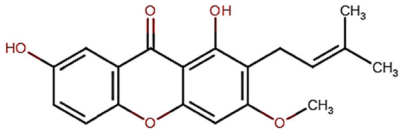
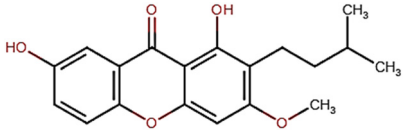
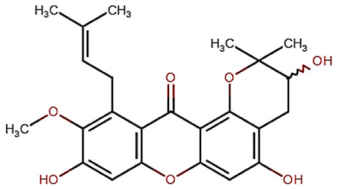
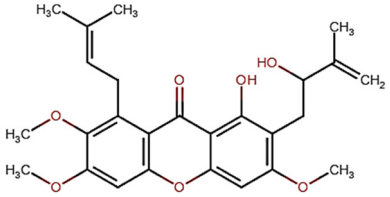
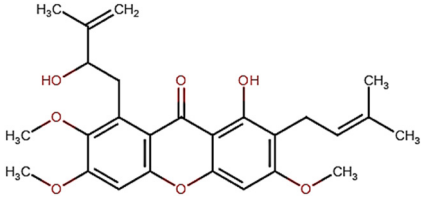
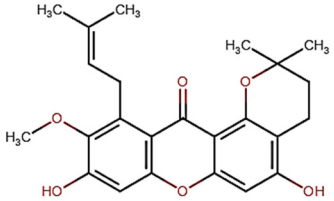
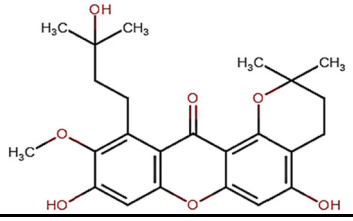
(*Continued*)

Table 1: *Continued*

Phytochemicals	Compounds	Structures	Plant parts
Xanthones	1,3,8-Trihydroxy-4-methyl-2,7-diisoprenylxanthone		—
	1,3,7-Trihydroxy-2,8-di-(3-methylbut-2-enyl)-xanthone		Whole fruit
	1,3-Dihydroxy-2-(2-hydroxy-3-methylbut-3-enyl)-6,7-dimethoxy-8-(3-methylbut-2-enyl)-xanthone		Heartwood
	1,5-Dihydroxy-2-(3-methylbut-2-enyl)-3-methoxy-xanthone		Pericarp
	1,5-Dihydroxy-2-isopentyl-3-methoxy xanthone		Pericarp
	1,5,8-Trihydroxy-3-methoxy-2-(3-methylbut-2-enyl) xanthone		Leaf
	1,6-Dihydroxy-2-(2-hydroxy-3-methylbut-3-enyl)-3,7-dimethoxy-8-(3-methylbut-2-enyl)-xanthone		Heartwood
	1,6-Dihydroxy-3-methoxy-2-(3-methyl-2-buthenyl)-xanthone		Leaf
	1,6-Dihydroxy-3,7-dimethoxy-2-(3-methylbut-2-enyl)-8-(2-oxo-3-methylbut-3-enyl)-xanthone		Heartwood

(*Continued*)

Table 1: *Continued*

Phytochemicals	Compounds	Structures	Plant parts
Xanthones	1,6-Dihydroxy-3, 7-dimethoxy-2-(3-methylbut-2-enyl)-xanthone		Heartwood and stem
	1,6-Dihydroxy-8-(2-hydroxy-3-methylbut-3-enyl)-3,7-dimethoxy-2-(3-methylbut-2-enyl)-xanthone		Heartwood
	1,7-Dihydroxy-2-(3-methylbut-2-enyl)-3-methoxy-xanthone		Pericarp
	1,7-Dihydroxy-2-isopentyl-3-methoxy xanthone		Pericarp
	11-Hydroxy-1-isomangostin		Whole fruit
	1-Hydroxy-2-(2-hydroxy-3-methylbut-3-enyl)-3,6,7-trimethoxy-8-(3-methylbut-2-enyl)-xanthone		Heartwood
	1-Hydroxy-8-(2-hydroxy-3-methylbut-3-enyl)-3 6,7-trimethoxy-2-(3-methylbut-2-enyl)-xanthone		Heartwood
	1-Isomangostin		Pericarp
	1-Isomangostin hydrate		Pericarp

(*Continued*)

Table 1: *Continued*

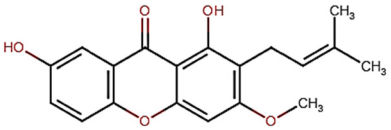
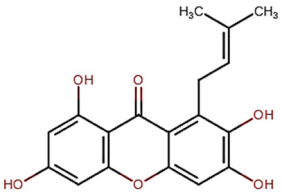
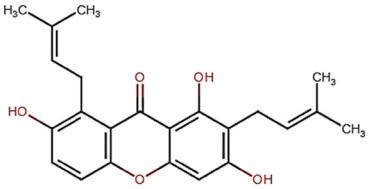
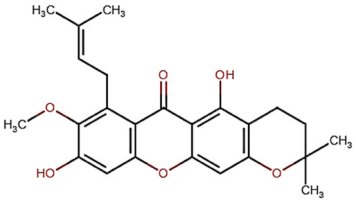
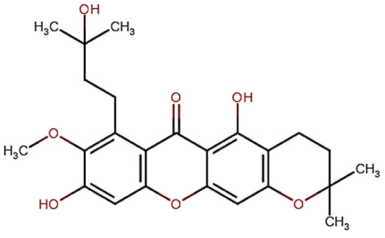
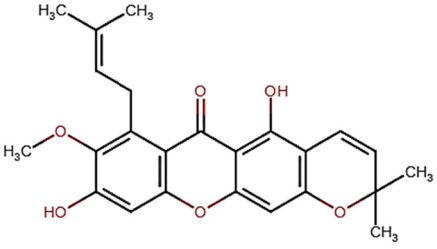
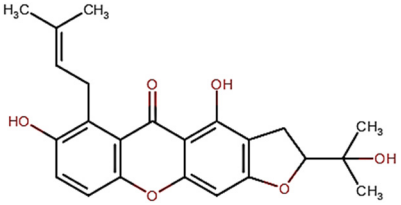
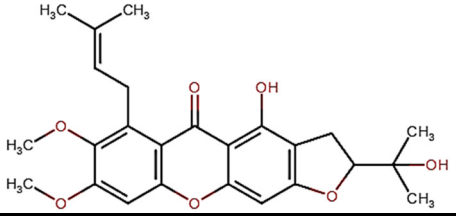
Phytochemicals	Compounds	Structures	Plant parts
Xanthones	2-(γ, γ-Dimethylallyl)-1,7-dihydroxy-3-methoxyxanthone		Pericarp and aril
	2,3,6,8-Tetrahydroxy-1-isoprenylxanthone		—
	2,8-bis-(γ, γ-Dimethyallyl)-1,3,7-trihydroxyxanthone		Aril
	3-Isomangostin		Pericarp
	3-Isomangostin hydrate		Pericarp
	5,9-Dihydroxy-8-methoxy-2,2-dimethyl-7-(3-methylbut-2-enyl)-2H, 6H-pyrano-[3,2,6]-xanthone-6-one		Fruit hull
	6-Deoxy-7-demethylmangostin		Whole fruit
	6-O-Methylmangostanin		—

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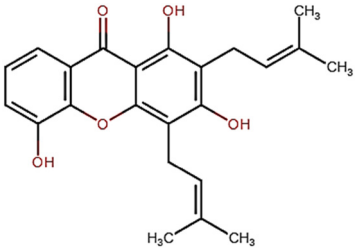
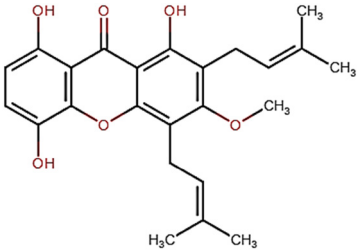
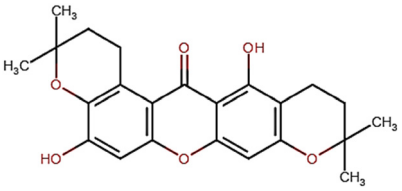
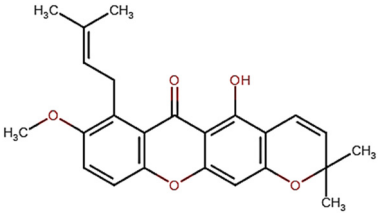
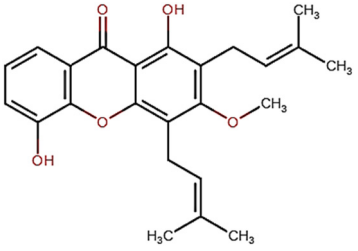
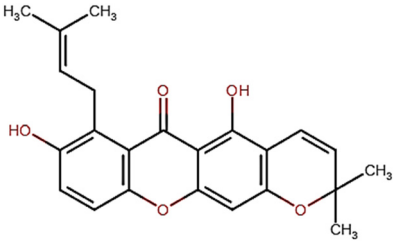
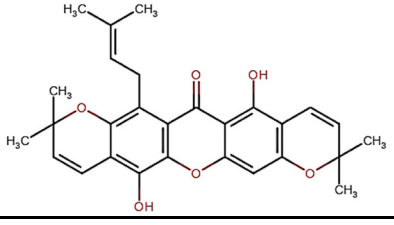
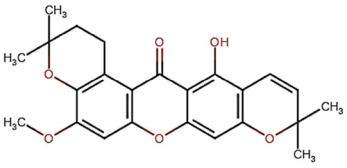
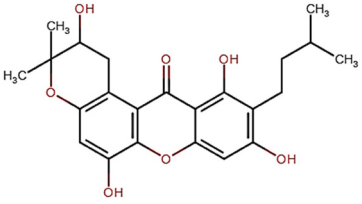
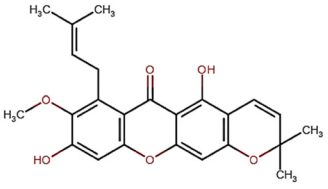
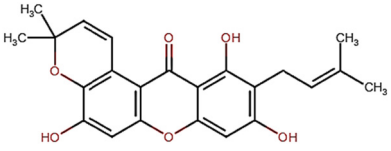
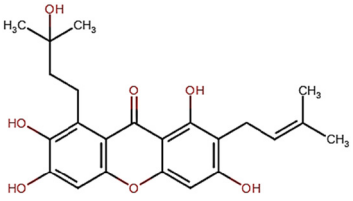
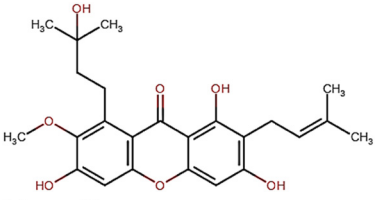
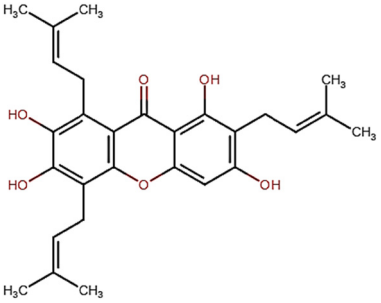
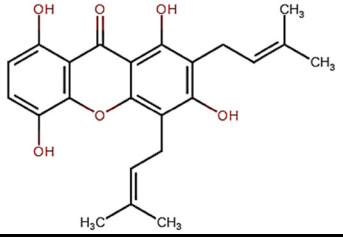
Table 1: *Continued*

Phytochemicals	Compounds	Structures	Plant parts
Xanthones	8-Deoxygartanin		Pericarp and whole fruit
	8-Hydroxycudraxanthone		Pericarp
	BR-xanthone		Pericarp
	Calabaxanthone		Aril
	Cudraxanthone G		Pericarp
	Demethylcalabaxanthone		Whole fruit, aril, and seed
	Garcimangosone A		Fruit hull

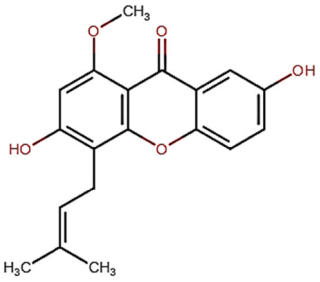
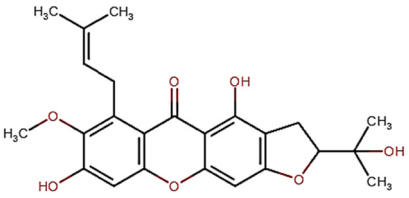
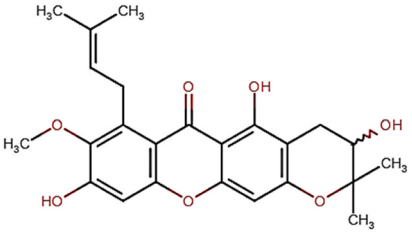
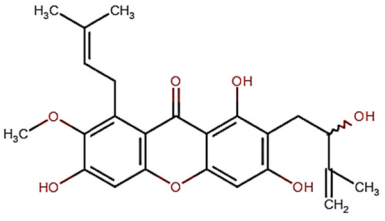
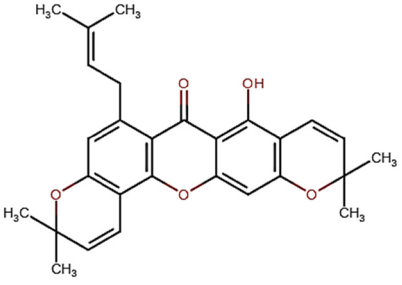
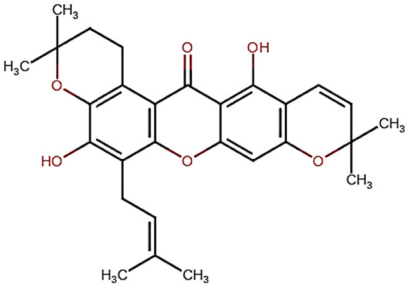
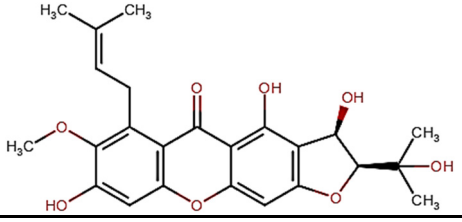
(*Continued*)

Table 1: *Continued*

Phytochemicals	Compounds	Structures	Plant parts
Xanthones	Garcimangosone B		Pericarp
	Garcimangosone C		Pericarp
	Garciniafuran		Heartwood
	Garcinone B		Pericarp and whole fruit
	Garcinone C		Whole fruit
	Garcinone D		Pericarp, whole fruit, and stem
	Garcinone E		Pericarp and whole fruit
	Gartanin		Pericarp and whole fruit

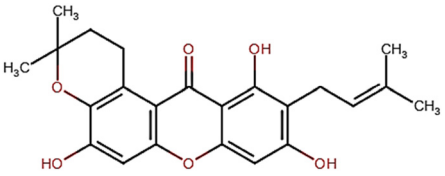
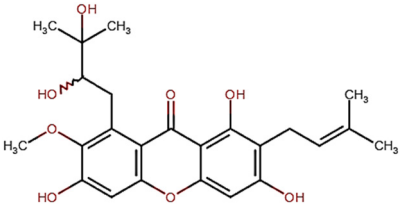
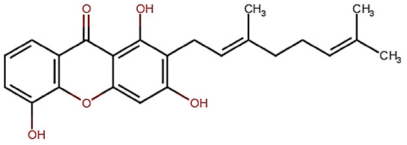
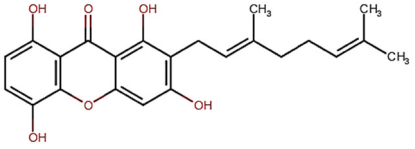
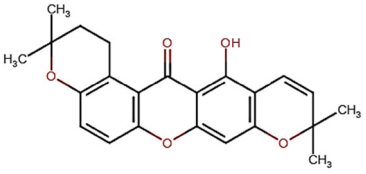
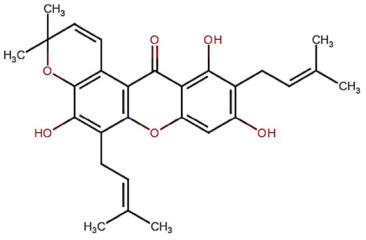
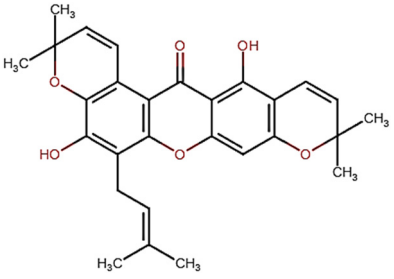
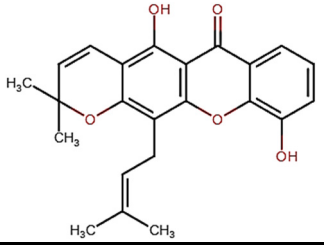
(*Continued*)

Table 1: *Continued*

Phytochemicals	Compounds	Structures	Plant parts
Xanthones	Mangosharin		Stem
	Mangostanin		Pericarp
	Mangostanol		Whole fruit and stem
	Mangostenol		Pericarp
	Mangostenone A		Pericarp
	Mangostenone B		Pericarp
	Mangostenone C		Whole fruit

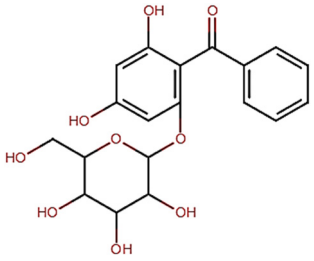
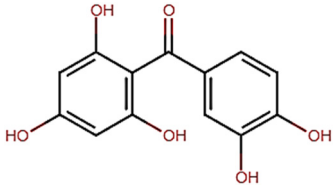
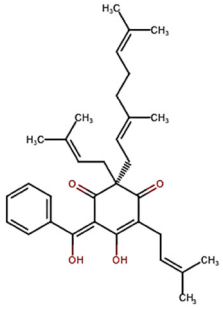
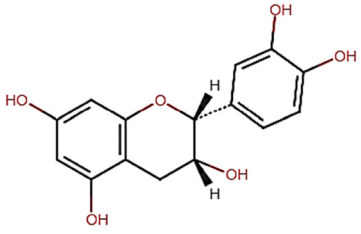
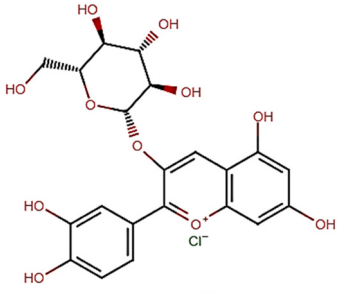
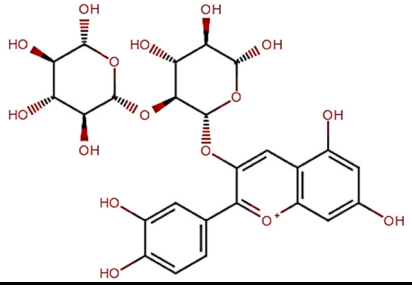
(*Continued*)

Table 1: *Continued*

Phytochemicals	Compounds	Structures	Plant parts
Xanthones	Mangostenone D		Whole fruit
	Mangostenone E		Whole fruit
	Mangostinone		Pericarp and whole fruit
	Smeathxanthone A		Pericarp
	Thwaites xanthone		Whole fruit
	Tovophyllin A		Pericarp
	Tovophyllin B		Pericarp
	Trapezifolixanthone		Pericarp

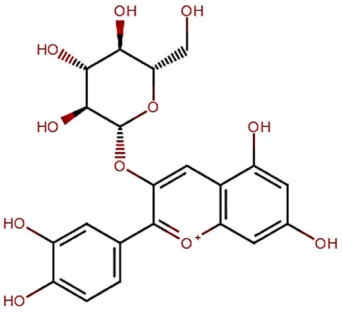
(*Continued*)

Table 1: *Continued*

Phytochemicals	Compounds	Structures	Plant parts
Benzophenones	Garcimangosone D		Pericarp
	Maclurin		Pericarp and heartwood
	Kolanone		Pericarp
Flavonoid	Epicatechin		Pericarp
Anthocyanins	Chrysanthemin		Pericarp
	Cyanidin-3-O-sophoroside		Pericarp

(*Continued*)

Table 1: *Continued*

Phytochemicals	Compounds	Structures	Plant parts
Anthocyanins	Cyanidin-3-O-glucoside		—

latex), contain xanthones ($CH_3H_8O_2$). Both α- and γ-mangostin concentrations in yellow gum extracted from the exterior of the mangosteen pericarp were 382.2 and 144.9 mg/g wet basis, respectively. An estimated 200 distinct xanthone species may be found in nature, most of which are members of the Bonnetiaceae, Clusiaceae, and Podostemaceae families [55]. The biosynthesis of xanthones in mangosteen occurs through the shikimate pathway. The intermediates such as 2,4,6-trihydroxybenzophenone undergo cyclization to form the xanthone structure. This biosynthetic process can be influenced by environmental factors and optimized through biotechnological methods, such as using elicitors or applying stress conditions to enhance xanthone production in cultured cells [59]. The chemical xanthone is a potent bioactive substance with outstanding health advantages. It has a high level of viral resistance and functions as an antioxidant, antibacterial, anti-cancer, and anti-tumor chemical. These xanthones predominantly concentrated in the pericarp contributed in plant's defense mechanisms and therapeutic potential [29,30,36,55,59]. According to studies, one kilogram of fresh mangosteen may yield two grams of pure xanthones. This is 15 times higher value than the price of fresh pericarp alone [55].

The majority of studies concentrate on the structure and extraction of xanthones from the heartwood, stem, seed, and hull of mangosteen [58]. The role of these phytochemicals in green synthesis has attracted significant attention, especially in the production of nanomaterials. It is hypothesized that the donor–acceptor mechanism will most likely be used to successfully biofabricate green NPs due to the interaction between the metal ions of the salt precursor and the oxygen atoms of the biofunctional groups (like hydroxyl) present in mangosteen extract. As a biomolecule model, the O–H groups in xanthones would give an electron to electrophile metal species, oxidizing the hydroxyl group and reducing electron-deficient metal ions to metal atoms [40]. Thus, phytochemicals are able to act as a sustainable and eco-friendly reducing agent alternative to conventional nanotechnology methods [43,60].

5 Green synthesis pathway

The green synthesis of nanomaterials using plant extracts, including those from mangosteen, can be effectively carried out at ambient temperatures by using either powdered plant material or aqueous extracts [43]. The process typically involves mixing the plant extract with a metal salt solution [2,5,43,61] or using less harmful, non-toxic reagents. This results in the formation of nanomaterials within a time frame ranging from minutes to hours [62].

The exact mechanisms through which phytochemicals facilitate nanomaterial synthesis are not completely understood, but a plausible model can be proposed as illustrated in Figure 1. In this model, hydroxyl groups from the phytochemicals act as electron donors, reducing metal ions to their metallic states. Following this reduction, metal atoms are oxidized to form electron-deficient metal ions. The green synthesis process generally comprises three main stages: nucleation, growth, and stabilization. During the nucleation phase, metal ions dissociate from their precursors when dissolved in the mangosteen extract. The phytochemical functional groups reduce these ions from their higher oxidation states to metallic forms. If metal oxide NPs are desired, a calcination step is introduced, where the increased surface reactivity of the nascent NPs facilitates their oxidation to metal oxides. In the growth phase, these metallic or metal oxide NPs aggregate, driven by interactions with the phytochemicals in the extract. Finally, in the stabilization phase, the phytochemicals cap and stabilize the NPs, preventing further aggregation

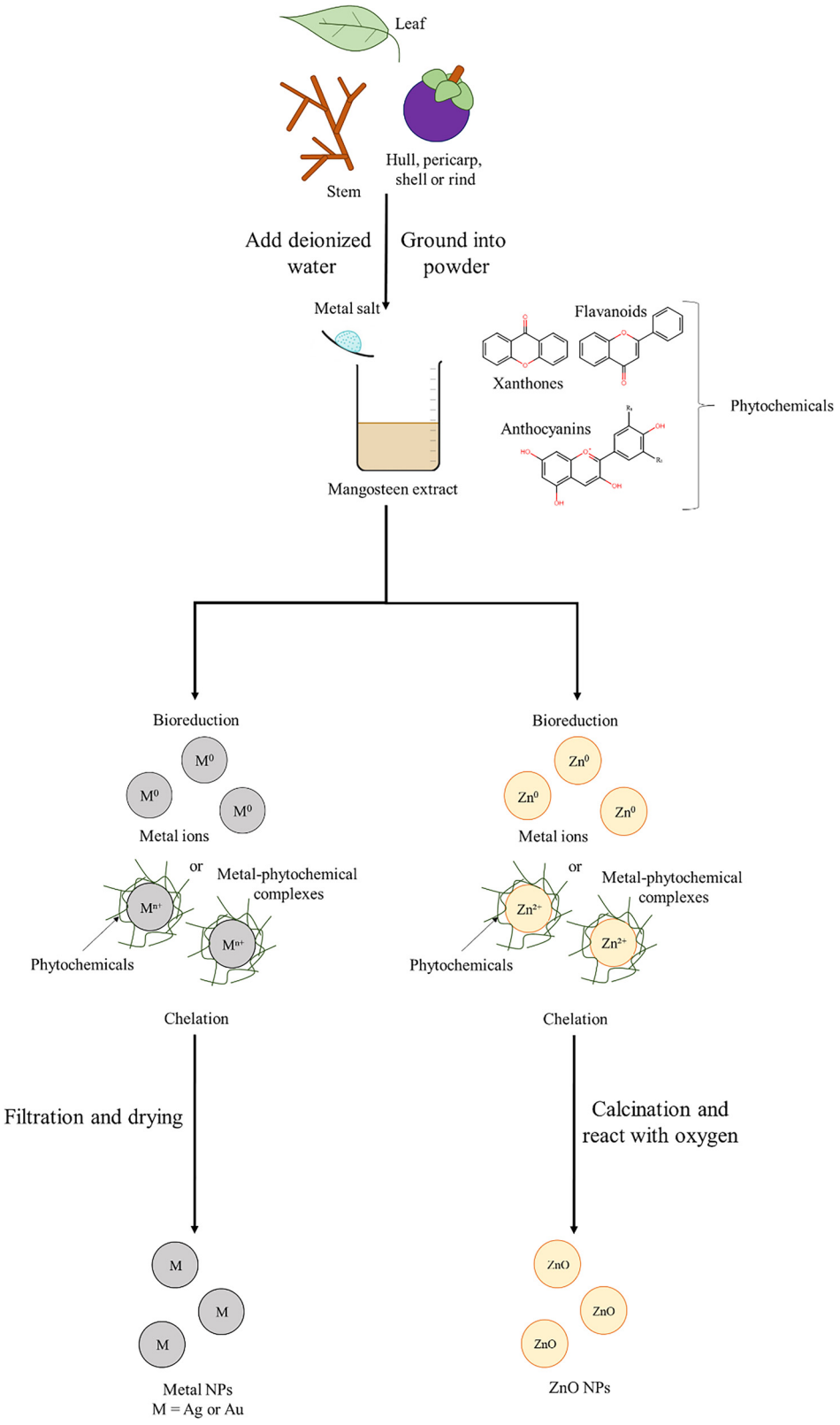


Figure 1: Mechanisms for the formation of Ag, Au, and ZnO NPs involving bio-reduction and chelation processes utilizing mangosteen extract.

and ensuring the desired size and shape. Additionally, Ostwald ripening – a process where smaller particles dissolve and redeposit onto larger ones – may contribute to the stabilization and uniformity of the NPs [39,40]. However, the aforementioned procedure is precisely the same when synthesizing metal oxide NPs in a green way by replacing calcination process with filtration and drying (room temperature or in oven) to obtain metal NPs [37,63,64].

6 *G. mangostana* L. extract-assisted green synthesis of nanomaterials

The synthesis of Ag, Au, and ZnO NPs has predominantly been achieved thorough green methods using various parts of mangosteen extracts, with a literature review revealing that 60.71% of studies focused on Ag NPs, followed by Au NPs at 25.00% and ZnO NPs at 14.29%. Table 2 provides a summary of various nanomaterials synthesized using mangosteen extracts, including their morphologies and applications.

6.1 Silver NPs

Ag NPs are predominantly synthesized using different parts of mangosteen extract. Ag NPs were initially utilized in Mesopotamia in the ninth century according to Michael Faraday's first scientific document [83]. Ag has long been recognized for its antimicrobial properties, proving effective in both industrial and medicinal applications [48]. In many reports, Ag NPs are commonly utilized in drug delivery, fungicides, tumor suppressor, photocatalyst, semiconductor materials, and electronic devices [63,75]. Green synthesis of Ag NPs has been reported to be simpler and faster compared to microbial synthesis methods [43,48]. The process typically involves the clustering of colloidal Ag NPs followed by the reduction of Ag^{+} to metallic Ag [84]. Plant-synthesized Ag NPs are frequently prepared using silver nitrate. A brownish-yellow solution is formed, indicating the successful synthesis of Ag NPs after the addition of silver nitrate to the plant extract [43].

6.2 Gold NPs

Au NPs have attracted significant interest due to their unique size, shape, optical properties, biocompatibility, and surface characteristics [61,84]. Although Au NPs were used in Mesopotamia as early as the ninth century, Michael Faraday provided the first scientific description of their properties [83]. Reports suggest that Au NPs have potential applications in drug delivery systems, biosensors, tumor detection, and hyperthermia treatments [61,84]. In response to environmental concerns about traditional chemical synthesis methods, researchers are increasingly focusing on environmentally friendly approaches to synthesize Au NPs [48]. In green synthesis, chloroauric acid is commonly reduced to form Au NPs [43].

6.3 Zinc oxide NPs

The use of mangosteen plant extracts for the green synthesis of ZnO NPs is relatively uncommon. ZnO NPs can form various nanostructures, including nanowires, nanorods, nanotubes, nanobelts, and other intricate shapes [56,85]. Initially, ZnO NPs were employed in the rubber industry to enhance the performance of rubber composites by improving properties such as anti-aging, toughness, and strength [16]. Due to their unique physical and chemical properties, ZnO NPs are essential metal oxide NPs with applications in diverse fields, including drug delivery [13], solar cells, photocatalysis, photoluminescence, and sensor technologies [8,28,86]. The ability of ZnO NPs to remain highly active in intracellular environments is its primary advantage over other metal particles such as Ag and Au. Thus, by enzymatic oxidative stress, it can modify insulin resistance and further control lipid, protein, carbohydrate, and chronic inflammatory metabolisms [16].

7 Applications

This section explores the applications of nanomaterials synthesized through green methods using mangosteen extracts, highlighting their antimicrobial, cytotoxic, antioxidant, and environmental remediation properties, among other relevant activities.

7.1 Antimicrobial activity

The advent of antibiotics marked a groundbreaking shift in medicine during the twentieth century [87,88]. However, the overuse and abuse of these drugs have led to the rise of

Table 2: Summary of the different nanomaterials synthesized with mangosteen extract, highlighting their morphologies and applications

Nanomaterials	Mangosteen extracts	Salt precursors	Shapes	Average sizes (nm)	Applications	Ref.
Ag	0.15 g/mL stem extract	1 mM [1]$AgNO_s$	Spherical	30	Antibacterial activity	[42]
	0.01 g/mL seed extract	10 mM $AgNO_s$	Spherical	47–291	Photocatalytic and fluorescence quenching activities	[65]
	0.01 g/mL peel extract	1 mM $AgNO_s$	Spherical	62–94	Photocatalytic and fluorescence quenching activities	[65]
	0.026 g/mL leaf extract	4.71 mM $AgNO_s$	Spherical	25	Antibacterial activity	[66]
	0.025 g/mL leaf extract	0.25–5.00 mM $AgNO_s$	Spherical	35	Antibacterial activity	[67]
	Bark extract	1 mM $AgNO_s$	Spherical	65	Antibacterial and anti-larvicidal activities	[68]
	0.25 g/mL bark extract	1 mM $AgNO_s$	Spherical	12–15	Lung cancer treatment activity	[69]
	0.025–0.075 g/mL rind extract	1 mM $AgNO_s$	Spherical	20–40	Antibacterial and antifungal activities	[70]
	0.025 g/mL rind extract	1 mM $AgNO_s$	Spherical	30–50	Antibacterial and antioxidant activities	[71]
	0.03 g/mL rind extract	1 mM $AgNO_s$	Spherical	23	Antibacterial activity	[72]
	0.001 g/mL rind extract	50–1,000 mM $AgNO_s$	—	—	Antibacterial activity	[73]
	0.1 g/mL pericarp extract	$AgNO_s$	Spherical	69–90	Mercuric ion sensing, catalytic, antioxidant, antibacterial, antifungal, and anticancer activities	[63]
	Methanolic pericarp extract	10 mM $AgNO_s$	Dumbbell	13–31	Cytotoxicity activity	[74]
	0.005 g/mL pericarp extract	1 mM $AgNO_s$	Spherical	15	Antifungal activity	[75]
	Peel extract	10 mM $AgNO_s$	Spherical	32	Drug delivery for anticancer activity	[76]
	Peel extract	0.1 mM $AgNO_s$	Spherical or polygonal	93	Anti-listerial activity	[77]
	0.03–0.11 g/mL peel extract	Ag rod	Spherical	23–55	Detection of Fe(III) ions in aqueous solution	[64]
Au	0.025 g/mL peel extract	0.1–10.0 mM [2]$HAuCl_4$	Spherical	15–100	Antioxidant, antibacterial, anti-inflammatory, and wound healing activities	[37]
	0.015 g/mL rind extract	1 mM $HAuCl_4$	Spherical	20–40	Antibacterial activity	[72]
	Methanolic pericarp extract	10 mM $HAuCl_4$	Spherical	15–44	Cytotoxicity activity	[74]
	0.03 g/mL rind extract	1 mM $HAuCl_4$	Spherical	25–60	Antibacterial activity	[78]
	0.0025–0.05 g/mL peel extract	10 mM $HAuCl_4$	Spherical	47	—	[79]
	1 g/mL peel extract	1 mM $HAuCl_4$	Mostly spherical	75–130	Cotton dyeing activity	[80]
	0.025 g/mL peel extract	10 mM $HAuCl_4$	Mostly spherical	32	—	[81]
ZnO	0.08 g/mL pericarp extract	4 g [3]$Zn(NO_3)_2{\cdot}6H_2O$	Mostly spherical	21	Photocatalytic activity	[56]
	0.01 g/mL seed extract	0.01 M [4]$Zn(CH_3COOH)_2$	Flower	233–334	Photocatalytic, fluorescence quenching, and photoluminescence activities	[82]
	0.01 g/mL rind extract	0.01 M $Zn(CH_3COOH)_2$	Rod	92–247	Photocatalytic, fluorescence quenching, and photoluminescence activities	[82]
	0.02–0.04 g/mL leaf extract	4 g $Zn(NO_3)_2{\cdot}6H_2O$	Spherical	14	Antibacterial activity	[40]

[1]$AgNO_3$ = Silver nitrate, [2]$HAuCl_4$ = Tetrachloroauric(III) acid, [3]$Zn(NO_3)_2{\cdot}6H_2O$ = Zinc nitrate hexahydrate, [4]$Zn(CH_3COOH)_2$ = Zinc acetate.

antibiotic-resistant bacteria [87–90], which poses a significant global health crisis in the twenty-first century [91]. According to the World Health Organization, millions of deaths each year are attributed to bacterial infections resistant to multiple antibiotics [88,92,93]. Even while attempts to create new antibiotics are still underway, the rate at which bacteria become resistant frequently outpaces the rate at which new therapies are discovered, underscoring the pressing need to investigate other antimicrobial strategies [87]. A possible remedy for this problem is provided by nanomaterials, especially those made utilizing environmentally friendly processes and plant extracts. Unlike traditional antibiotics, nanomaterials can inhibit bacterial growth through multiple mechanisms, including direct interaction with bacterial cell walls [94], the generation of reactive oxygen species (ROS), disruption of cellular components, and interference with essential biochemical processes [88]. These multifaceted modes of action reduce the likelihood of bacteria developing resistance, making nanomaterials a potent alternative to conventional antibiotics [90]. In general, the antimicrobial properties of the synthesized NPs are tested using disk diffusion method by measuring their zone of inhibition (ZOI) after overnight incubation in oven at 37°C [73]. In some studies, minimum inhibitory concentration (MIC) assay is also applied in determining the minimum concentration of synthesized NPs required to inhibit the growth of microbial after overnight incubation at 37°C. The 96-well plate microplate reader is used in reading the bacterial culture growth absorbance [63].

7.1.1 Antibacterial activity

Research has uncovered various mechanisms through which nanomaterials exert antibacterial effects. These mechanisms include disrupting bacterial cell walls and peptidoglycan layers, releasing toxic ions, altering membrane potential, generating ROS that cause oxidative damage, degrading DNA and proteins, and inhibiting ATP synthesis [95], as illustrated in Figure 2.

The antibacterial efficacy of green-synthesized nanomaterials varies depending on the bacterial strain and the type of nanomaterial used. For instance, Jamila *et al.* demonstrated that Ag NPs synthesized from mangosteen pericarp extract were more effective against Gram-positive bacteria such as *Staphylococcus aureus* and *Bacillus subtilis*, showing inhibition zones of 12.0–18.0 mm. In contrast, Gram-negative bacteria such as *Pseudomonas aeruginosa* and *Escherichia coli* exhibited smaller inhibition zones of 6.0–11.0 mm. The MIC assays further supported these findings, with Ag NPs being more sensitive to Gram-positive bacteria (MIC: 62.50–125.00 µg/mL) compared to Gram-negative bacteria (MIC: 500.00–1000.00 µg/mL) [63]. Similarly, Chan *et al.* reported that ZnO NPs synthesized from mangosteen leaf extract were more effective against Gram-positive bacteria, with MIC values as low as 15.63 µg/mL for *S. aureus* and *B. subtilis*. Gram-negative bacteria such as *E. coli* and *Klebsiella pneumoniae* were less sensitive, with MIC values of 62.50 and 125.00 µg/mL, respectively [40].

However, contrasting results have been observed in other studies where green-synthesized Ag NPs and Au

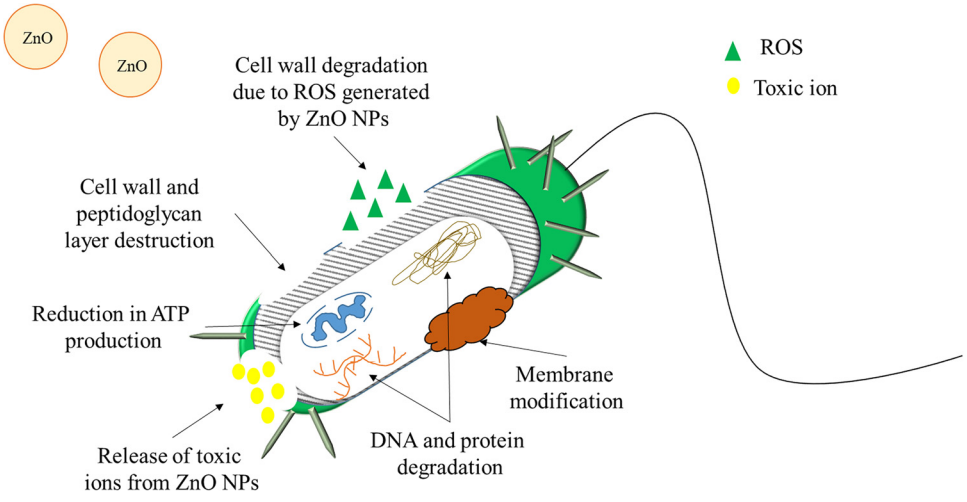


Figure 2: Formation of ROS, direct interaction between bacteria and their cell membrane, and the degradation of bacteria cell contents, such as DNA and protein, are some of the suggested antibacterial mechanisms.

NPs showed greater efficacy against Gram-negative bacteria. Karthiga found that Ag NPs synthesized from mangosteen stem extract were more effective against *E. coli* compared to Gram-positive bacteria such as *B. subtilis* and *Klebsiella planticola* [42]. Similarly, Gupta *et al.* reported that Ag NPs synthesized from mangosteen leaf extract had a lower MIC for *E. coli* (0.38 μg/mL) than for *S. aureus* (0.92 μg/mL), despite a larger ZOI for *S. aureus* (28.0 mm) compared to *E. coli* (25.0 mm) [66]. Additionally, Karthiga *et al.*'s study observed that Ag NPs synthesized from mangosteen bark extract had better inhibition on *E. coli* compared to that on *B. subtilis*, *S. aureus*, *Bacillus cereus*, and *K. pneumoniae* [68]. Furthermore, Nishanthi *et al.* observed that Ag NPs synthesized from mangosteen rind extract had better inhibition against Gram-negative bacteria such as *Klebsiella* sp. (18.0 mm) and *Pseudomonas* sp. (15.0 mm) compared to Gram-positive bacteria such as *Staphylococcus* sp. (12.0 mm) and *Bacillus* sp. (14.0 mm) [72]. Madhavan *et al.* also reported similar findings, with Ag NPs showing more effective inhibition of *Pseudomonas* (15.0 mm) than that of *Staphylococcus* (13.0 mm) [73].

Interestingly, some studies have demonstrated that green-synthesized nanomaterials can surpass traditional antibiotics in efficacy. For example, Gupta *et al.* found that Ag NPs synthesized from mangosteen leaf extract exhibited lower MIC values and larger ZOI compared to standard antibiotics such as ciprofloxacin, amikacin, and penicillin [66]. Similarly, Veerasamy *et al.* reported that Ag NPs synthesized from mangosteen leaf extract were highly effective against multidrug-resistant pathogens such as *E. coli* and *S. aureus*, showing inhibition zones of 15.0 and 20.0 mm, respectively, compared to 20.0–36.0 mm and 25.0–40.0 mm for standard drugs [67].

These findings indicate that green-synthesized nanomaterials from mangosteen extracts demonstrate significant antibacterial potential, effective against both Gram-positive and Gram-negative bacteria. However, the level of effectiveness can vary based on the bacterial strain, the specific type of nanomaterial, and the synthesis method used. This variability underscores the importance of further research to refine these factors and enhance the clinical and environmental applications of these nanomaterials.

7.1.2 Antifungal activity

The widespread and excessive use of fungicides has led to significant environmental and health issues [96]. For instance, *Candida* species have developed high levels of resistance to several antifungals, including amphotericin B, clotrimazole, fluconazole, and itraconazole [97]. The rise of multi-drug-resistant *Candida* strains has driven researchers to seek alternative treatments to conventional antifungal agents [98]. Plant-derived antifungal agents have emerged as potential substitutes [97] due to their ability to biologically inhibit pathogenic fungi [96]. The NPs, with their nanoscale dimensions, can penetrate fungal cell membranes and disrupt fungal growth [70,75]. They can also target key cellular components such as ergosterol, triglycerides, and phospholipids, leading to membrane instability and cell damage [70]. Figure 3 illustrates the antifungal mechanisms of nanomaterials.

In a study conducted by Karthiga and Soranam, Ag NPs synthesized *via* a green method using mangosteen rind extract demonstrated a significant antifungal activity against *Aspergillus niger*, with a ZOI measuring 12.0 mm [70]. However, Jamila *et al.* found that Ag NPs synthesized from mangosteen pericarp extract were less effective compared to conventional antifungal agents such as fluconazole and amphotericin. Their study reported ZOI values of 8.0 to 9.0 mm for Ag NPs against fungi such as *Aspergillus flavus*, *Trichophyton mentagrophytes*, *Candida albicans*, and *Candida krusei*, with MIC of 500 μg/mL. In contrast, traditional fungicides showed ZOI values ranging from 19.0 to 25.0 mm [63]. Conversely, Le *et al.* reported that Ag NPs synthesized from mangosteen pericarp extract exhibited effective antifungal activity, successfully inhibiting the growth of *Aspergillus niger*, *Aspergillus flavus*, and *Fusarium oxysporum* [75].

7.2 Cytotoxicity activity

Cancer, characterized by the uncontrolled proliferation of malignant cells, remains one of the leading causes of death worldwide. Traditional treatments, including surgery, chemotherapy, and radiation, are effective but often come with high costs and significant side effects. As a result, there is a growing need for therapies that are non-toxic, cost-effective, and have minimal adverse effects. Nanomaterials, with their high biocompatibility, ease of surface functionalization, and unique interactions with biomolecules, offer promising alternatives for drug delivery, diagnosis, and treatment of cancer. Various nanomaterials, such as Ag NPs and Au NPs, have demonstrated anticancer properties. These properties are attributed to mechanisms such as chromosome aberration, DNA breakage, cell apoptosis, and disruption of membrane function, which lead to cellular leakage and death [45,86]. Figure 4 illustrates the anticancer mechanisms

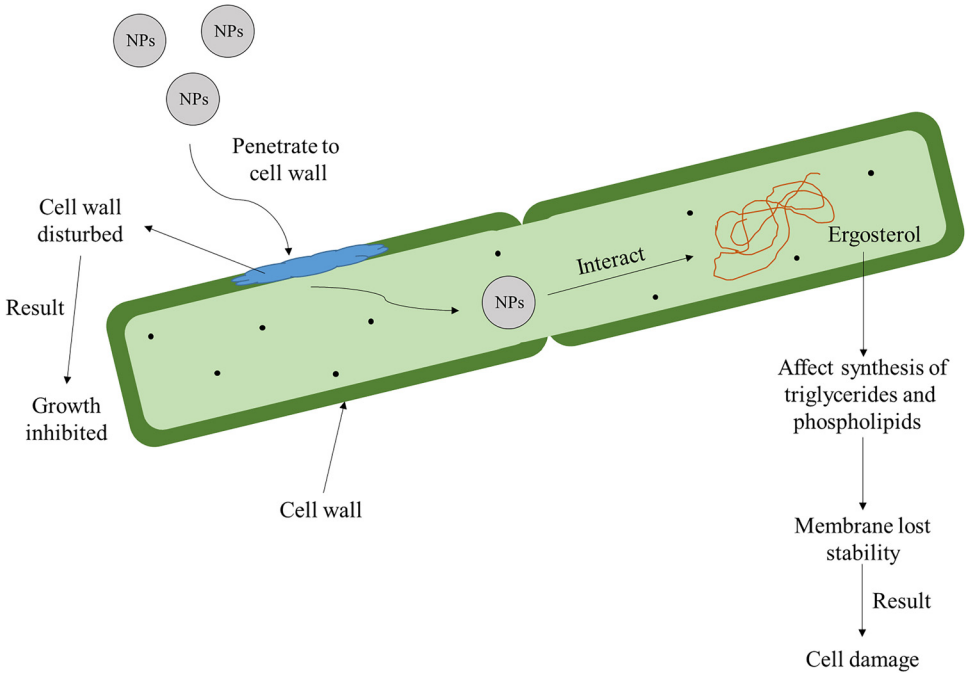


Figure 3: Proposed antifungal mechanism using nanomaterials, including the penetration of NPs into fungal resulting in ergosterol destruction and rupture of cell wall. The fungal growth is inhibited or resulted in even death after losing their membrane stability.

associated with nanomaterials. The cell viability is commonly tested using 3-(4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophemyl)-2*H*-tetrazolium (MTS) assay in the determination of synthesized NPs' cytotoxicity effect by measuring the cell optical density using multimode microplate reader at 490 nm after incubation at 37°C [76].

The A549 cancerous lung cells exhibited a lower survival rate when treated with Ag NPs synthesized from mangosteen bark extract compared to untreated cells (78.50% *vs* 81.85% survival) as reported in the study by Zhang and Xiao. Notably, applying low-intensity ultrasound further enhanced the effectiveness of the Ag NPs, reducing the survival rate of A549 cells to 28.70% [69].

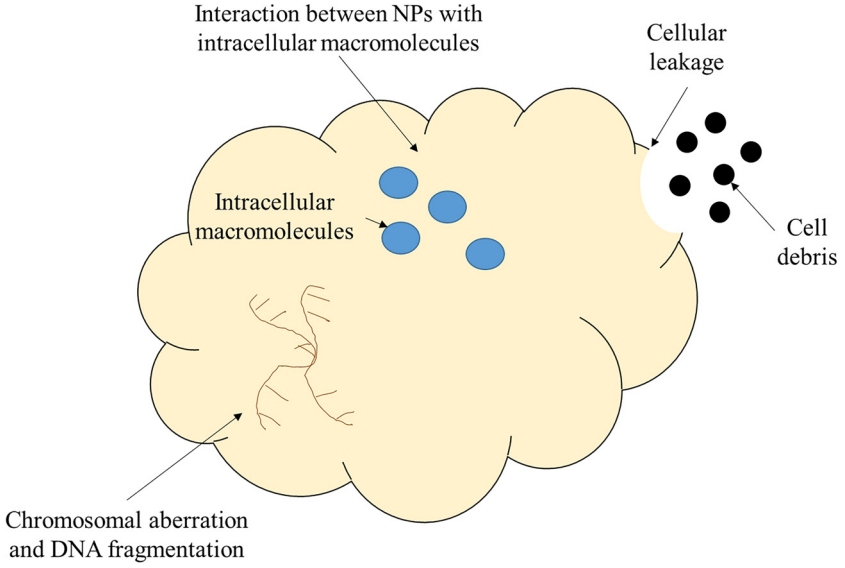


Figure 4: Proposed mechanism in cytotoxicity activity using nanomaterials by breaking the cell DNA, resulted in cellular leakage and cell death.

Conversely, Jamila *et al.* found that Ag NPs synthesized from mangosteen pericarp extract showed less cytotoxicity, with an half maximal inhibitory concentration (IC_{50}) value of 22.40 µg/mL against DU-145 cell lines, and a minimal impact on normal L-929 cells (1.00–2.00% cytotoxicity) [63]. In contrast, Park *et al.* reported differing results; Ag NPs from the same extract demonstrated 12.70% cytotoxicity in A549 cells at 37.50 µg/mL, while Au NPs exhibited only 23.50% cytotoxicity at 75.00 µg/mL. Ag NPs showed 63.00% cytotoxicity against NIH3T3 cells, whereas Au NPs resulted in 98.00% cell viability. This suggests that Au NPs might be a promising candidate for drug delivery and bioactive compound administration [74]. Additionally, Lee *et al.* observed that Ag NPs from mangosteen peel extract inhibited both HCT116 malignant and CCD112 normal colon cell lines in a dose-dependent manner, with IC_{50} values of 40.20 and 47.00 µg/mL, respectively. However, there was no significant difference in cytotoxicity between the two cell lines across most tested concentrations [76].

7.3 Antioxidant activity

Mangosteen extracts, rich in phenolic compounds, demonstrate a notable antioxidant activity due to their redox properties. These extracts act as reducing agents, hydrogen donors, and singlet oxygen quenchers [71]. The antioxidant activity of mangosteen extracts, particularly from the pericarp, is largely attributed to a variety of primary and secondary metabolites, including alkaloids, carbohydrates, flavonoids, glycosides, anthraquinone glycosides, saponins, phenolic compounds, phytosterols, and diterpenes. Additionally, the flavonoid and phenolic components in mangosteen extracts not only contribute to antioxidant properties but also play a crucial role in the successful green synthesis of nanomaterials [37,74], enhancing the antioxidant activity of the resulting materials [71].

Both 2,2-diphenyl-1-picrylhydrazyl radical ($DPPH^{\cdot}$) and 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid radical ($ABTS^{\cdot}$) scavenging activity assays are the popular antioxidant activity assays [99,100]. The $DPPH^{\cdot}$ is a stable organic free radical [101,102] with the presence of delocalized spare electron on the whole molecule, which is able to keep the molecule from dimerization [103], accept an electron or hydrogen radical to produce a stable diamagnetic molecule [104], and give rise to deep purple color [101,103]. On the other hand, the $ABTS^{\cdot}$ scavenging activity assay is based on the inhibition of the $ABTS^{\cdot+}$ [105] without using any substrate. It has been used to measure the total antioxidant activity in pure samples, including body fluids and plant materials [106]. Figure 5 shows the reaction mechanism of DPPH and ABTS assays, respectively.

In the study by Jamila *et al.*, mangosteen pericarp extract and its green-synthesized Ag NPs demonstrated greater activity in $DPPH^{\cdot}$ scavenging compared to $ABTS^{\cdot}$ scavenging. This finding suggests that the $ABTS^{\cdot}$ scavenging activity assay's effectiveness is highly dependent on the number of hydroxyl groups in phenolic compounds, regardless of their positions [63]. Rajakannu *et al.* observed that Ag NPs synthesized using mangosteen rind extract exhibited higher $DPPH^{\cdot}$ scavenging activity (46.00–88.00%) compared to the extract alone (22.00–71.00%), with both showing dose-dependent behavior [71]. Similarly, Jassim *et al.* found that increasing the content of mangosteen peel extract-mediated synthesized Au NPs was associated with enhanced antioxidant activity, ranging from 47.20 to 71.30% [37].

7.4 Environment remediation

Anthropogenic pollutants, including dyes, heavy metals, surfactants, solvents, and pesticides, persistently contaminate aquatic environments globally. Many of these pollutants are not biodegradable and can become mutagenic and carcinogenic through natural reductive anaerobic degradation processes. Consequently, researchers are exploring the use of nanomaterials as alternative solutions for environmental remediation. Nanomaterials offer advantages such as availability, non-toxicity, and both biological and chemical stabilities, making them a promising approach for addressing environmental contamination [19,24]. In experiment, dye or heavy metal is added to solution with synthesized NPs and allowed for light penetration to undergo photocatalytic degradation. The efficiency of the synthesized NPs in photodegrading pollutants is measured using ultraviolet–visible spectrophotometer [63–65].

7.4.1 Photocatalytic, fluorescence quenching, and photoluminescence activities

The continuous release of dye into the environment without proper treatment or conversion into less hazardous substances can severely impact ecosystems and living organisms [12]. To address this issue, the development of semiconductor-based photocatalytic processes offers an alternative method for reducing environmental pollution by breaking down organic contaminants into non-toxic compounds [2,24]. Photocatalytic activity primarily occurs on the surface of the catalyst. Thus, nanomaterials, with their high

surface area, can exhibit enhanced photocatalytic performance compared to their bulk counterparts [24]. During photocatalytic reactions, electron-hole pairs are generated in the valence and conduction bands of nanomaterials. These pairs migrate to the surface of the semiconductor photocatalyst, where they facilitate the formation of ROS, including hydroxyl radicals, superoxide ion radicals, hydroperoxyl radicals, hydroxide ions, and oxygen radicals. These ROS then degrade the dye into less toxic substances, such as water, carbon dioxide, nitrogen dioxide, and nitrogen oxide [2,17,19]. The photocatalytic mechanism is illustrated in Figure 6.

In the study by Jamila *et al.*, it was observed that the green-synthesized Ag NPs using mangosteen pericarp extract significantly reduced the absorption maxima and decolorized the tested dyes within 5 min when sodium borohydride was added. In contrast, a lesser effect was noted with the mangosteen pericarp extract alone. The percentage reductions in dye concentrations using green-synthesized Ag NPs from mangosteen pericarp extract were as follows: 86.00–92.00% for Congo red, 79.00–85.00% for methylene blue (MB), 89.00–95.00% for malachite green (MG), 89.00–96.00% for methylene orange, 85.00–91.00% for *p*-nitrophenol, 88.00–93.00% for rhodamine B (RB), 80.00–87.00% for Bismarck brown Y, and 88.00–92.00% for sulfo-cyanine. [63]. The green-synthesized Ag NPs from mangosteen seed and peel extracts achieved a

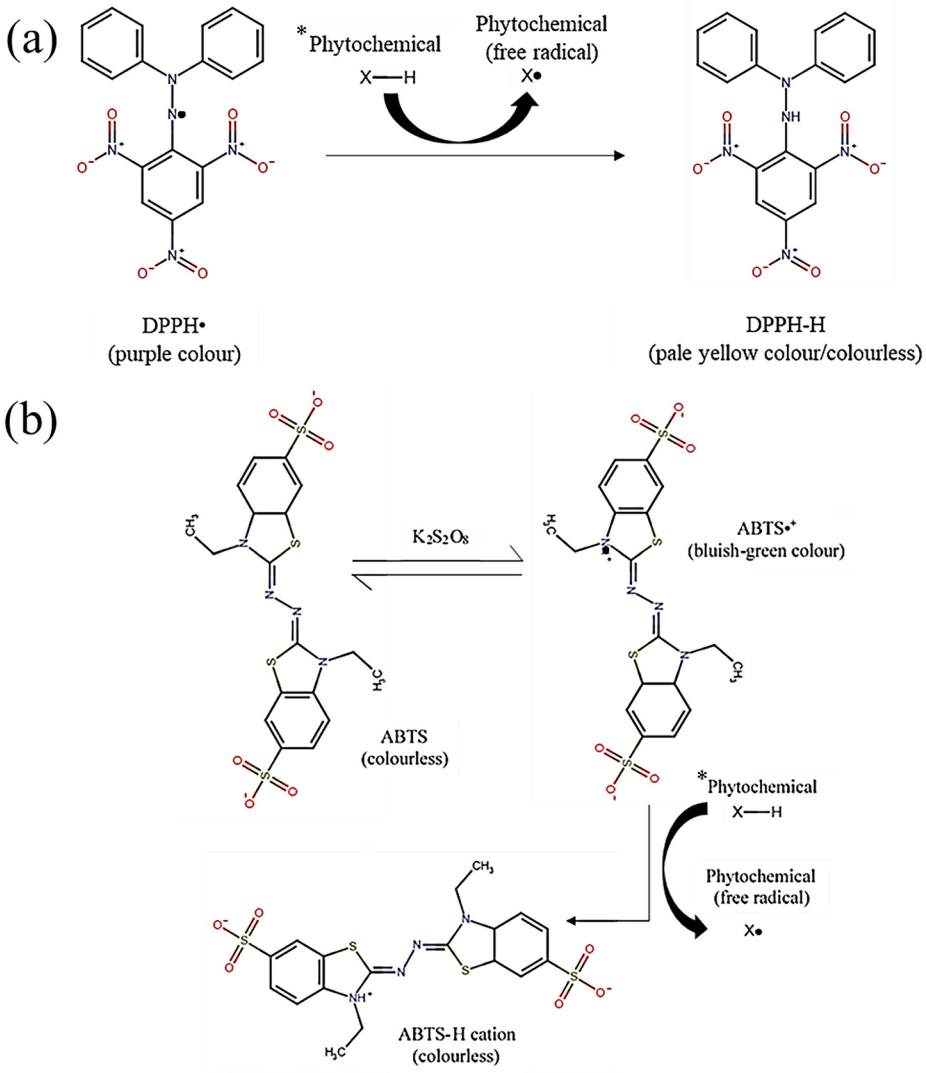


Figure 5: Reaction mechanism of (a) DPPH and (b) ABTS assays. "*" represents the phytochemicals on the nanomaterial surface. In (a), the purple solution DPPH$^{\cdot}$ turned pale yellow or colorless after receiving proton from phytochemicals and oxidizing into DPPH-H. On the other hand, the colorless ABTS turned bluish-green in the presence of potassium persulfate ($K_2S_2O_8$), which indicated the formation of ABTS$^{\cdot+}$. In the presence of phytochemicals, ABTS$^{\cdot+}$ oxidized into colorless ABTS-H cation.

95.00% degradation efficiency of MB at pH 2, with a half-life of 22 min under sunlight as reported in Perera *et al.*'s study [65]. Similarly, Kuruppu *et al.* demonstrated that ZnO NPs synthesized from mangosteen seed and rind extracts achieved 92.00 and 85.00% degradation efficiencies, respectively, with half-lives of 102 and 108 min for MB degradation at pH 4 [82]. Additionally, Aminuzzaman *et al.* reported that ZnO NPs derived from mangosteen pericarp extracts achieved a 99.00% removal efficiency of MG after 180 min of sunlight radiation, whereas only 13.70% degradation efficiency was observed in the dark over the same duration [56]. The polarity of the solvent, the nature of the fluorophore, the concentration, and the quencher molecule all affect the ability to quench fluorescence. In the Perera *et al.'s* research, the fluorescence intensity of RB gradually reduced with an increasing amount of sunlight-irradiated Ag NPs green-synthesized from mangosteen seed and mangosteen peel extracts [65]. Furthermore, in the Kuruppu *et al.'s* research, a reduction in RB fluorescence emission was observed when the concentration of green-synthesized ZnO NPs from mangosteen seed and mangosteen rind extracts increased [82]. The findings by both researchers demonstrated that the prepared nanomaterials' fluorescence quenching was in both dynamic and static quenching because both processes were present simultaneously and were caused by the creation of chemical complexes or excited-state collisions [65,82].

Photoluminescence spectroscopy, a non-destructive technique valuable for assessing material quality by revealing intrinsic and extrinsic defects, was used by Kuruppu *et al.* to evaluate green-synthesized ZnO NPs from mangosteen seed and rind extracts. The spectra revealed a broad, intense peak in the visible range and a distinct peak in the UV region, indicating intrinsic defects within the ZnO material. The UV emission peak is attributed to near-band emission and free exciton recombination, while the broad visible peak is due to the recombination of photo-generated holes with single ionized charge states of specific defects. Therefore, the photoluminescence activity of green-synthesized ZnO NPs was both higher and more asymmetric than that of chemically synthesized ZnO NPs [82].

7.4.2 Heavy metal ion detection

Heavy metal pollution, caused primarily by anthropogenic activities, remains a significant environmental concern

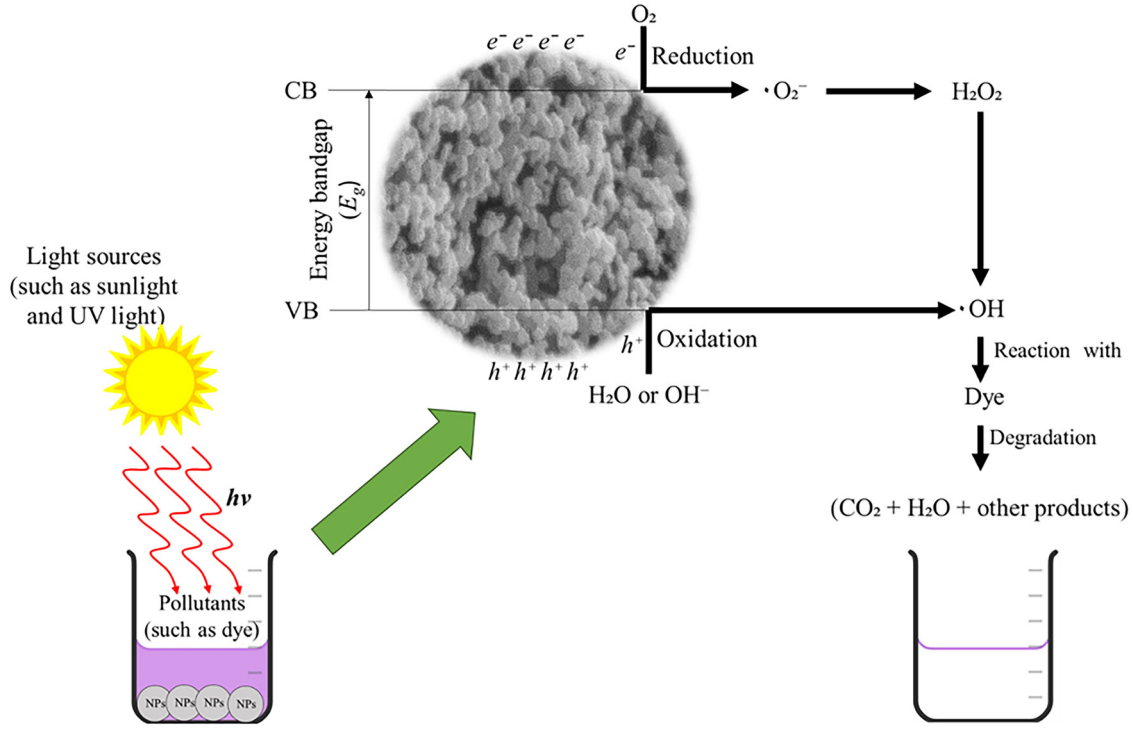


Figure 6: Formation of electron-hole pair in nanomaterials after irradiated by light as modified from Chan *et al.*'s study [41]. Electron in valance band (VB) is transferred to conduction band (CB) and left behind the formation of hole. Subsequently, oxidation and reduction that occurred at VB and CB happened simultaneously with hydroxide ions and oxygen to produce reactive radicals. Consequently, the reactive radicals react with organic pollutants (such as dye) degraded into less harmful products, such as carbon dioxide, water, and intermediate.

due to the toxicity of metals such as nickel, copper, iron, chromium, and mercury, even at low concentrations. Traditional methods for detecting heavy metals, although highly sensitive, are often costly, labor-intensive, skill-dependent, and not portable. In contrast, nanomaterials offer a more straightforward, cost-effective, and sensitive approach for detecting trace amounts of heavy metal ions through colorimetric sensing [60]. In the study by Jamila *et al.*, green-synthesized Ag NPs derived from mangosteen pericarp extract were successfully used to detect mercuric ions through colorimetric sensing. The surface plasmon resonance band of these Ag NPs showed a significant decrease and a blue shift in absorbance when exposed to mercuric ion concentrations ranging from 1.00 to 50.00 μM in spiked water samples within 10–15 min, demonstrating their sensitivity and effectiveness in identifying heavy metal contaminants [63]. Similar observation was reported in Trang *et al.*'s study as slight blue shifting and decreasing of absorbance in UV-Vis absorption peak when mangosteen peel extract-derived Ag NPs were exposed to ferric ion concentrations ranging from 1.00 to 25.00 μM. In their study, the limit of detection and limit of quantitation of the synthesized Ag NPs were 0.532 and 1.77 μM, respectively [64].

7.5 Other applications

Au NPs synthesized from mangosteen peel extract were investigated for their potential in repairing hepatocellular damage in mice in Jassim *et al.*'s study. In their study, clinical observation from 24 h up to 14 days is conducted using adult albino mice by feeding them synthesized Au NPs. The study found that these green-synthesized Au NPs improved blood pharmacokinetics and vascular transport by creating congestion in blood vessels and inhibiting liver absorption. Additionally, a cream containing these Au NPs accelerated wound healing by enhancing the interaction between the nanomaterials and the cream ingredients, which penetrated the skin and improved tensile strength, collagen formation, and epithelial-layer repair after the mice dorsal fur is shaved and let the wound opened to cause acute inflammation [37]. In a separate study by Alkhuriji *et al.*, Ag NPs synthesized from mangosteen peel extract demonstrated significant anti-inflammatory effects caused by oral injection of *Listeria monocytogenes* to the mice. These NPs reduced the expression levels of inflammatory genes (TNF-α mRNA and IL-1β mRNA) in female mice infected with *L. monocytogenes*. The treated mice exhibited expanded villi and a healthy intestine, in contrast to the untreated group. Furthermore, the Ag NP-treated group showed less lamina propria degeneration, indicating protective effects against intestinal damage [77].

Ag NPs synthesized from mangosteen bark extract demonstrated a lethal concentration for 50% of larvae (LC_{50}) of 5.93 μM and were effective in inhibiting the growth of the fourth-instar *Aedes aegypti* larvae after 24 h by placing them in 100 mL of distilled water with synthesized Ag NPs reported in the Karthiga *et al.*'s study. The observed larvicidal effect is attributed to the Ag NPs' ability to penetrate individual cells, disrupting molting and other physiological processes [68].

Sivakavinesan *et al.* investigated the use of mangosteen peel extract-mediated synthesized Au NPs for dyeing cotton wicks. They varied the Au ion concentration ranging from 10^{-2} to 10^{-6} M and observed that the Au NPs adsorbed onto the cotton wicks with high aggregation. At a concentration of 1 mM Au ion solution, the Au NPs were well dispersed and deposited on the cotton wick surfaces. In contrast, Au NPs synthesized from lower concentration Au ion solutions did not adhere to the cotton wick surfaces and did not affect the binding of nanomaterials to the surfaces [80].

8 Conclusion and future outlook

Plant extracts offer a straightforward, rapid, cost-effective, sustainable, and environmentally friendly approach to nanomaterial production. Among these, the mangosteen plant stands out due to its rich array of bioactive phytochemicals such as flavonoids, phenolics, and xanthones, which can act as effective stabilizers and reducing agents in nanomaterial synthesis. These green-synthesized NPs exhibit enhanced biocompatibility, reduced toxicity, and superior functionality compared to their chemically synthesized counterparts. The review study indicates that mangosteen-derived nanomaterials exhibit promising potential across various fields, although most applications are still confined to laboratory settings. The successful transition from laboratory-scale to broader applications could significantly enhance human life quality in areas such as medicine, agriculture, and environmental remediation. However, thorough research on the large-scale synthesis of nanomaterials from mangosteen extracts is lacking in the present literature study. Optimizing nanomaterial morphology, consistency, and yield during synthesis are the key challenges in green synthesis. Despite advancements in plant extract-mediated synthesis, mangosteen's potential remains relatively unexplored compared to other plants. Addressing this gap through targeted research is essential to fully leverage mangosteen's capabilities in green

nanomaterial synthesis. Emphasizing large-scale production and exploring broader applications will be crucial.

By overcoming these challenges, future research should emphasize refining these synthesis processes for scalability and exploring more extensive applications for mangosteen-derived nanomaterials. By prioritizing studies on industrial-level production and assessing potential commercial applications, researchers can contribute to reducing reliance on traditional, resource-intensive synthesis methods. This advancement would mark a critical step toward sustainable and eco-friendly nanotechnology solutions, leveraging mangosteen's unique properties to support greener innovations across various industries.

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