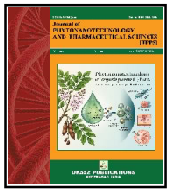
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Phytonanotechnology in sustainable agriculture and phytomedicine: Green synthesis, mechanisms and applications of plant-based nanoparticles

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Abstract

Phytonanotechnology integrates plant science with nanotechnology to develop sustainable and eco-friendly approaches for agriculture and phytomedicine. Phytochemicals present in plant materials, including flavonoids, phenolics, terpenoids, alkaloids and proteins, play an important role in the green synthesis and stabilization of nanoparticles, offering an alternative to conventional methods that rely on toxic chemicals and high energy inputs. Plant-mediated nanoparticles have shown promising applications in agriculture by supporting seed germination, improving nutrient-use efficiency and plant growth, enhancing tolerance to environmental stresses and assisting in pest and disease management. In phytomedicine, nano-based delivery systems can improve the stability, solubility, bioavailability and targeted delivery of plant-derived bioactive compounds. However, concerns regarding phytotoxicity, environmental safety, standardization and long-term effects need to be addressed before their wider adoption. Overall, Phytonanotechnology has considerable potential to provide safe, effective and environmentally sustainable solutions for agricultural production and plant-based healthcare.

1. Introduction

Phytonanotechnology combines plant science and nanotechnology to develop ecofriendly approaches for nanoparticle synthesis and the efficient delivery of bioactive phytochemicals using plant-derived materials. The field has developed in response to the limitations of conventional physicochemical methods of nanoparticle synthesis, which often involve toxic chemicals, high temperatures and the production of hazardous waste (Thatyana *et al*., 2023; El-Fitiany *et al*., 2024). Plant extracts are rich in phytochemicals such as flavonoids, terpenoids, alkaloids and polyphenols, which can naturally reduce metal ions and help stabilize and cap the newly formed nanoparticles. This plant-mediated process supports the formation of nanoparticles with desirable size, shape, stability and bio-compatibility (Bhat *et al*., 2025; Kaur *et al*., 2023). Compared with conventional chemical synthesis methods, this green approach is more economical, environmentally friendly and less toxic. These advantages make plant-derived nanoparticles promising for a wide range of biomedical, agricultural and environmental applications (Kaur *et al*., 2023). Phytonanotechnology also involves the application of nanomaterials to improve plant growth and functions in agriculture. These nanoscale systems can facilitate the targeted delivery of nutrients and support the monitoring of environmental conditions (Zaman *et al*., 2024).

Phyto-mediated nanoparticles possess a wide range of biological activities, making them promising candidates for applications in antibacterial, anticancer, antioxidant, anti-inflammatory and antidiabetic treatments (Mohanta *et al*., 2023). In research on neurodegenerative diseases, nanoparticle phytomedicine systems have emerged as promising tools for overcoming the blood-brain barrier and delivering therapeutic compounds directly to the brain while potentially minimizing unwanted side effects (Bhattacharya *et al*., 2022). In environmental remediation, combining nanotechnology with phytoremediation can improve the removal of pollutants while promoting plant growth. This approach works by increasing the availability of contaminants to plant roots and enabling the targeted delivery of essential nutrients (Zaman *et al*., 2024).

2. Plants as green nano factories

Plants can act as natural biological nano-factories, where their phytochemicals facilitate the reduction, capping and stabilization of metal ions, leading to nanoparticle formation under mild and environmentally friendly conditions (Alsaiari *et al*., 2023; Iravani, 2011). Plant-mediated synthesis offers a greener alternative to conventional physicochemical approaches by eliminating or minimizing the use of harmful chemicals and energy-intensive conditions. The process can be carried out under relatively mild conditions, thereby reducing the formation of toxic waste and making nanoparticle production safer and more environmentally sustainable (Khan *et al*., 2022; Soni *et al*., 2021). This approach is widely regarded as a cost-effective and environmentally friendly method for nanoparticle production. The use of naturally occurring plant

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compounds can improve the biocompatibility of the resulting nanoparticles while reducing the need for expensive and hazardous chemical reagents. Moreover, the simplicity of the synthesis process and the availability of plant materials make it a promising approach for scaling up nanoparticle production and meeting the requirements of large-scale manufacturing (Jeevanandam *et al*., 2022, Iravani, 2011). Different plant parts, including leaves, roots, seeds, flowers, fruitsand peels, provide abundant and renewable sources of bioactive compounds that can be utilized in nanoparticle synthesis. These materials are naturally rich in phytochemicals such as phenolic compounds, flavonoids, terpenoids, proteins, sugars and alkaloids, which play important roles in reducing metal ions and stabilizing the nanoparticles formed during the synthesis process. The easy availability, renewability and diverse chemical composition of plant materials make them promising resources for developing simple, sustainable, cost-effective and environmentally friendly methods of nanoparticle production (El Shafey, 2020; Villagrán *et al*., 2024).

Plant-based bioactive compounds, including polyphenols, flavonoids, terpenoids, alkaloids and proteins, have an important role in the green production of nanoparticles. These compounds can act in two ways, first by reducing metal ions and then by helping to stabilize the nanoparticles that are formed. Various functional groups, such as hydroxyl, carbonyl and amino groups, present in these phytochemicals contribute to the conversion of metal ions into elemental or metal oxide nanoparticles. Once the nanoparticles are formed, the phytochemicals can attach to their surface and provide a protective layer, thereby limiting aggregation and improving their stability. In addition, differences in the composition and concentration of phytochemicals in plant extracts can influence the size, morphology, surface properties and stability of the synthesized nanoparticles. Thus, the natural chemical diversity of plants provides an effective basis for producing stable nanoparticles while minimizing the use of conventional synthetic chemicals (Jeevanandam *et al*., 2022; Soni *et al*., 2021). Plant-based phytochemicals such as rutin, quercetin, myricetin, kaempferol and gallic acid have been recognized for their important role in the green synthesis of nanoparticles. These compounds possess functional groups that can reduce metal ions and facilitate the formation of nanoparticles. In addition, they can bind to the surface of the newly formed nanoparticles, forming a protective layer that improves stability and reduces particle aggregation. The type and amount of these phytochemicals in the plant extract can also affect the physicochemical properties of the nanoparticles, particularly their size, shape, morphology, surface characteristics and stability (Nguyen *et al*., 2022). The biomolecules naturally associated with the surface of plant-mediated nanoparticles can form a protective coating that enhances their solubility, stability and compatibility under physiological conditions. This natural coating is especially beneficial for biomedical applications, where maintaining nanoparticle stability and biocompatibility is important for their safe and effective use. Plant-based synthesis also offers several practical advantages over microbial approaches, as plant extracts are relatively simple to prepare, readily available and capable of producing nanoparticles within a shorter time. These benefits make plants promising biological resources for the efficient and potentially large-scale production of stable nanoparticles (Alsaiari *et al*., 2023; Iravani, 2011).

3. Mechanisms of nanoparticle synthesis

Nanoparticle synthesis generally involves a series of steps that begin with the reduction of metal precursors into their corresponding atoms. The reduced metal species then come together to form small nuclei, which gradually grow into nanoparticles. Under certain reaction conditions, these particles may undergo aggregation during the growth process. Subsequently, biomolecules or other stabilizing compounds can attach to the nanoparticle surface and act as capping agents. This capping process helps regulate particle growth, limits excessive aggregation and improves the overall stability of the synthesized nanoparticles (Jun *et al*., 2022; Khan *et al*., 2022). Nucleation plays an important role in nanoparticle formation by determining the number and distribution of the initial nuclei. As synthesis proceeds, these nuclei grow through the gradual addition of atoms, which influences the size and shape of the resulting nanoparticles. The relative rates of nucleation and growth affect particle uniformity, crystallinity and the tendency of particles to aggregate (Amiri *et al*., 2024; Harish *et al*., 2022; Jun *et al*., 2022).

Recent studies suggest that these processes do not always occur in a fixed sequence but may take place simultaneously during nanoparticle synthesis. The formation of monomers, nucleation and subsequent particle growth are closely connected and can influence one another throughout the reaction. Changes in the rate of one process can affect the progression and characteristics of the other stages. This close interaction between the processes is commonly observed under both hot-injection and heat-up synthesis conditions (Wen *et al*., 2021). Green and plant-mediated synthesis generally follow the basic principles involved in nanoparticle formation. In this approach, naturally occurring phytochemicals and other biomolecules present in plants play an important role in the reaction. These compounds help convert metal ions into nanoparticles and also act as capping and stabilizing agents (Joudeh and Linke, 2022; Salem and Fouda, 2021). The formation of nanoparticles is greatly influenced by factors such as reduction rate, precursor characteristics, pH and temperature. Ligands and other additives can affect how the reacting molecules interact with the surface of developing nanoparticles. These conditions play an important role in controlling nucleation, surface stabilization and the subsequent growth of particles. They may also cause structural changes or phase transformations, ultimately influencing the properties and characteristics of the resulting nanoparticles (Amiri *et al*., 2024; Halford *et al*., 2024).

4. Types of plant-mediated nano-particles

Plant-based green synthesis offers a simple approach for producing different types of metallic, metal oxide and bimetallic nanoparticles. Silver, gold, zinc oxide and palladium nanoparticles are among the most widely studied materials in this area. The growing interest in these nanoparticles reflects the promising potential of plant-derived methods for sustainable nanoparticle production (Jadoun *et al*., 2021; Bilal *et al*., 2021). Noble metal nanoparticles have received considerable attention because of their wide range of applications, especially in biomedical research. Silver and gold nanoparticles are frequently produced using different parts of plants, particularly leaf and bark extracts. The use of plant extracts can help regulate the size, shape and surface properties of the nanoparticles during synthesis. Depending on the synthesis conditions, the particles may develop various forms, such as spherical, triangular, or hexagonal

structures (Berta *et al*., 2021; Sultana *et al*., 2024; Ankamwar *et al*., 2021). Plant extracts are also widely employed for the green synthesis of metal oxide nanoparticles, especially zinc oxide and copper oxide nanoparticles. These nanoparticles have gained significant attention due to their strong antibacterial and photocatalytic properties. Their distinctive characteristics make them useful for a variety of biomedical, environmental and industrial applications (Paiva-Santos *et al*., 2021; Mutukwa *et al*., 2024).

Bimetallic nanoparticles have gained increasing attention as an important area of green nanotechnology. In plant-mediated synthesis, phytochemicals can reduce two different metal ions simultaneously, resulting in the formation of bimetallic nanoparticles. Examples include gold-silver (Au-Ag), silver-palladium (Ag-Pd) and platinum-palladium (Pt-Pd) nano-particles. The combination of two metals can provide improved properties, including enhanced antioxidant and anticancer activities (Berta *et al*., 2021). Plant-based synthesis provides a greener and more sustainable method for producing palladium nanoparticles with valuable catalytic properties. Phytochemicals naturally present in plant extracts can act as reducing and stabilizing agents during nanoparticle formation. Their use reduces the dependence on harsh chemical reagents and helps limit the formation of harmful by-products. Therefore, plant-derived palladium nanoparticles have considerable potential as selective and environmentally friendly nano-catalysts (Nasrollahzadeh *et al*., 2020). Plant-based methods can be used to synthesize a variety of elemental and metal oxide nanoparticles. These include copper, titanium dioxide, iron, cerium oxide and selenium nanoparticles. The use of plant extracts therefore broadens the range of nanomaterials that can be produced through greener synthesis approaches. Such nanoparticles have gained attention for their potential applications in agriculture, healthcare and biomedical research (Barathi *et al*., 2024; Humbal and Pathak, 2023).

5. Applications in plant growth and development

Phytonanotechnology can enhance plant growth by enabling the targeted and efficient delivery of agrochemicals and useful biomolecules. Nanomaterials can improve the uptake and utilization of essential nutrients and bioactive compounds within plants. They may also support faster seed germination, better photosynthetic activity and improved overall plant growth. Nanoparticles can help plants cope with environmental stresses and contribute to better crop productivity (Agrawal *et al*., 2022; Muzammil *et al*., 2023: Raba and Kerfeld, 2022). Nanoparticles can serve as efficient carriers for delivering nutrients, plant growth regulators and genetic materials to different parts of the plant. They can help transport these substances more precisely to targeted tissues, improving their absorption and effectiveness. Such targeted delivery can minimize losses to the surrounding environment and make the applied materials more efficient. Therefore, nanoparticles have considerable potential for improving plant nutrition, growth and genetic processes (Fincheira *et al*., 2020). Nano-priming is a promising method that uses nanoparticles to promote seed germination and healthy early seedling development. Nanoparticles can facilitate water absorption by improving the movement of water through the seed surface. They may also enhance amylase activity, which helps break down stored starch into sugars required for early seedling growth. Furthermore, nanoparticles can influence ROS-mediated signalling, helping to overcome seed dormancy and achieve faster and more uniform germination (Nile *et al*., 2022).

Foliar application of chitosan-based NPK nanofertilizers can improve the uptake of essential nutrients through the leaves of wheat plants. The small particle size may facilitate better nutrient movement and utilization within plant tissues. Improved nutrient availability can encourage vigorous growth and help the crop reach maturity earlier. Overall, these nanofertilizers can enhance plant performance and contribute to higher crop yield and productivity (Wohlmuth *et al*., 2022). Iron oxide and zinc nanoparticles have shown promising effects in supporting plant growth and development. Their application can enhance chlorophyll content and improve the photosynthetic performance of treated plants. They may also encourage greater biomass production and promote faster overall plant growth (Ali *et al*., 2021; Wohlmuth *et al*., 2022). In addition to providing nutrients, nanoparticles can affect various physiological activities that are important for healthy plant growth. They can enhance photo-synthetic efficiency, thereby supporting better energy production and plant development. Nanoparticles may also influence the regulation of phytohormones that control plant growth and developmental processes. Furthermore, they can stimulate antioxidant defence systems, helping plants better withstand environmental stresses (Sakthivel *et al*., 2025; Sodhi *et al*., 2025). Silver nanoparticles can improve photosynthetic performance by enhancing the efficiency with which plants utilize light energy. They can also function as nano-pesticides, helping to protect plants against a range of harmful microbial pathogens.

Therefore, their application may support plant growth while also contributing to better protection against plant diseases (Khan *et al*., 2023). Under abiotic stress conditions, phyto-synthesized nanoparticles can help plants minimize oxidative damage by enhancing the removal of harmful reactive oxygen species (ROS). They also contribute to improved water-use efficiency, allowing plants to maintain better water balance during stressful conditions. In addition, these nanoparticles can promote the accumulation of compatible solutes and secondary metabolites, which strengthen the plants natural defense mechanisms and improve its ability to tolerate stress (Riyazuddin *et al*., 2025; Sodhi *et al*., 2025). Iron oxide nanoparticles have been reported to improve water-use efficiency and maintain higher chlorophyll levels in crops exposed to drought stress. Similarly, titanium dioxide nanoparticles can enhance water retention and support photosynthetic activity when water availability is limited. These effects indicate that nanoparticles may help plants maintain better growth and physiological performance under drought conditions (Shoukat *et al*., 2024; Wahab *et al*., 2023).

6. Nanoparticles as nanofertilizers

Nanofertilizers can enhance nutrient-use efficiency by delivering nutrients more effectively to the plant tissues where they are needed. Their controlled-release nature provides nutrients gradually, helping to match nutrient availability with plant requirements. This can minimize nutrient losses caused by leaching and volatilization, which are often associated with conventional fertilizers. Nanofertilizers provide a promising and more sustainable approach to improving nutrient management in crops (Khan *et al*., 2023; Hanif *et al*., 2024; Semenova *et al*., 2024). The small size and high surface-area-to-volume ratio of nanoparticles enable them to move more easily through biological barriers and reach plant tissues effectively. This property helps improve the delivery and utilization of nutrients by plants. Nanofertilizers can potentially maintain or enhance crop productivity even when applied at much lower rates than conventional

mineral fertilizers. In some cases, fertilizer doses up to 100 times lower have been reported to achieve comparable or improved crop performance (Zhang *et al*., 2024; Jakhar *et al*., 2022).

Nano-fertilizers are generally grouped into macronutrient, micronutrient and nanocomposite formulations, with zinc oxide, iron oxide, hydroxyapatite and chitosan being commonly used as nanomaterials or carriers. These formulations improve nutrient delivery by making nutrients more available and allowing their controlled release according to plant requirements. For example, hydroxyapatite nanoparticles combined with humic substances can enhance phosphorus availability while also supporting plant resistance to stress. Such formulations have shown better performance in promoting early corn growth compared with conventional superphosphate fertilizer (Yoon *et al*., 2020). Urea-hydroxyapatite and urea-silica nanohybrids can enhance nitrogen-use efficiency by releasing nitrogen gradually into the soil. Their controlled-release nature helps maintain a steady supply of nitrogen for plant uptake over time. This approach can minimize the rapid loss of nitrogen commonly associated with the application of conventional urea. These nanohybrids have been reported to sustain nitrogen release for up to one week, thereby improving nitrogen availability and utilization by plants (Zhang *et al*., 2024).

7. Nanoparticles for pest and disease management

Nanoparticles have gained attention as promising tools for the effective management of agricultural pests and diseases. They can directly exhibit antimicrobial or insecticidal activity, helping to control harmful pathogens and insect pests. Nanoparticles can also be used as carriers for pesticides, fungicide sand RNA-based agents, improving their stability, delivery and effectiveness. Their controlled release properties may further enhance crop protection while reducing the excessive use of conventional agrochemicals (Worrall *et al*., 2018; Dutta *et al*., 2023). Different types of nanoparticles, including metal, metal-oxide, polymeric, carbon-based and biogenic nanoparticles, have demonstrated potential in controlling various agricultural pests and pathogens. They can act against fungi, bacteria, viruses, nematodes and insect pests through different modes of action. These include damaging cell membranes, generating reactive oxygen species (ROS) and interfering with DNA and enzyme functions. In addition, nanoparticles can stimulate the plant's own Défense mechanisms, thereby enhancing its resistance to pests and diseases (Manisha, *et al*., 2025; Sharma *et al*., 2025). Silver nanoparticles have received considerable attention in crop protection due to their broad antibacterial, antifungal, antiviral and insecticidal properties. Other nanomaterials, such as copper, zinc oxide, magnesium oxide, chitosan and nano-based biopesticides, have also shown promising effects in managing crop and stored-product pests. However, their wider adoption is still constrained by limited field-based studies and insufficient information on their long-term environmental effects (Yin *et al*., 2023; Kadir *et al*., 2025).

8. Environmental safety and phytotoxicity

Nanoparticles entering agricultural ecosystems can interact with plants and their uptake, movement and toxic effects may vary depending on different environmental and plant-related factors. Once absorbed through the roots or leaves, they can move to other plant parts through the vascular tissues. Excessive accumulation may trigger oxidative stress, interfere with antioxidant enzymes and cause genetic damage, including chromosomal abnormalities. Such effects can negatively influence seed germination, root growth and overall plant development (Gao *et al*., 2023; Gowtham *et al*., 2024). When nanoparticles accumulate in excess, they can adversely affect plant cells by damaging cell membranes and organelles and promoting the release of toxic ions. This can increase the formation of reactive oxygen species (ROS), resulting in oxidative stress and disturbances in normal cellular metabolism and division. Such cellular damage may further lead to DNA damage and other genotoxic effects (Yang *et al*., 2023).

Metal-based nanoparticles, particularly silver, zinc oxide and titanium dioxide, may cause phytotoxicity in a concentration-dependent manner, with their effects also varying according to particle size, shape, surface charge, plant species and growth stage (Banerjee *et al*., 2025; Yang *et al*., 2023). The presence of multiple nanoparticles in the environment can increase safety concerns because their combined effects may differ from those of individual nanoparticles. Plants exposed to nanoparticle mixtures may show synergistic, additive, or antagonistic responses depending on the type and concentration of the nanoparticles. These interactions can also vary with environmental conditions and other abiotic factors. For instance, simultaneous exposure to zinc oxide nanoparticles and multi-walled carbon nanotubes can modify antioxidant enzyme activity in *Arabidopsis thaliana*. Such combined exposure may increase oxidative stress and consequently cause greater inhibition of plant growth (Yang *et al*., 2023).

9. Phytomedicine nanotechnology

Phytomedicine nanotechnology combines plant-derived bioactive compounds with nanoscale delivery systems to overcome common limitations of conventional phytomedicines, such as poor solubility, instability, rapid metabolism, low bioavailability and limited target specificity. Various nanocarriers, including lipid-based, polymeric, inorganic, hybrid and plant-derived systems, have been explored to improve the therapeutic performance of phytochemicals (Table 1). These include liposomes, phytosomes, polymeric nanoparticles, nano-emulsions, solid lipid nanoparticles, self-nanoemulsifying systems, extracellular vesiclesand bioinspired plant-based nanoparticles. Such nano-formulations can protect bioactive compounds from degradation, enhance their absorption and cellular uptake, provide controlled release and improve pharmacokinetic behavior and delivery to specific tissues (Parvin *et al*., 2025; Kumar *et al*., 2025).

Phytosomes have emerged as an important nanotechnology-based platform because their phospholipid complexes can improve the solubility, stability, permeability and overall therapeutic effectiveness of herbal bioactive compounds. By enhancing the delivery and absorption of these constituents, phytosomes have shown potential in a wide range of applications, including cancer, neurodegenerative and cardiovascular diseases, diabetes, inflammation and wound healing. They are also being explored for topical formulations and targeted delivery through ocular and nasal routes (Chauhan *et al*., 2024). The therapeutic applications of nanophytomedicine have expanded to a wide range of health conditions, including cancer, neurodegenerative, cardiovascular, metabolic, infectious, pulmonary and gastrointestinal disorders. Nanotechnology has also supported the development of localized and targeted delivery systems for

improved therapeutic outcomes. Early clinical findings have shown potential for some phytosomal and plant-derived nanoformulations; however, most of the available evidence is still based on preclinical studies (Parvin *et al*., 2025).

Table 1: Therapeutic bioactivities of phytonanoparticles

Bioactivity	Therapeutic effect	Nanoparticle/Plant source	References
Antibacterial and Antifungal	Membrane disruption, intracellular damage, antibacterial activity	AgNPs/*Fumaria indica*, *Phragmanthera austroarabica*	Rahman *et al*., 2026
	Potent antibacterial activity	ZnO NPs/*Syzygium aromaticum*	Hussien *et al*., 2025
Antioxidant	Strong antioxidant activity High ABTS and SOD activity	AgNPs/Plant extracts CuO nanocomposites/*A. occidentale*	Karunakaran *et al*., 2023 Rajkumar *et al*., 2025
Antidiabetic	Antihyperglycemic, insulin resistance, pancreatic regeneration	AgNPs/ *A. indica*, *P. austroarabica*	Khodeer *et al*., 2023
	α-amylase and α-glucosidase inhibition	CuO nanocomposites/*A. occidentale*	Rajkumar *et al*., 2025
Anti-inflammatory	COX-1 and COX-2 inhibition	CuO nanocomposites/*A. occidentale*	Rajkumar *et al*., 2025
	Cytokine suppression, NF-κB/MAPK downregulation	Various nanocarriers/*Myristica fragrans*	Parvin *et al*., 2025
Anticancer	Tumor accumulation, cellular uptake, apoptosis, ROS induction	Various nanocarriers/*Curcuma longa*	Parvin *et al*., 2025
	Cytotoxicity against MCF-7 cells	CuO nanocomposites/*A. occidentale*	Rajkumar *et al*., 2025

10. Conclusion

Phyto nanotechnology provides a sustainable connection between plant-derived resources and nanotechnology. Plant-mediated nanoparticles have shown potential in agriculture by supporting plant growth, improving nutrient use, protecting crops and enhancing stress tolerance. Similarly, nanophytomedicine can improve the delivery and therapeutic activity of plant-based bioactive compounds. However, challenges related to phytotoxicity, environmental safety, standardization and long-term effects still need attention. Overall, phytonanotechnology offers promising opportunities for developing safe, effective and environmentally friendly approaches in sustainable agriculture and phytomedicine.

11. Future perspectives

Future efforts should aim to develop safe, effective and scalable plant-mediated nanoparticles for use in agriculture and phytomedicine. Research should emphasize optimizing synthesis methods, improving nanoparticle stability and assessing phytotoxicity and long-term environmental impacts. Advanced nano formulations may also improve the targeted delivery and bioavailability of plant derived bioactive compounds. Field evaluation, standardized production, appropriate regulations and collaborative research will be essential for converting laboratory findings into practical and sustainable applications.

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Availability of data and material

All data are provided within the manuscript.

Authorship contribution statement

K. Sundharaiya: Supervision, academic oversight and overall monitoring of the research work; **M. Kabilan and R. V. Sundarrajan:** Conceptualization, supervision, critical review and overall guidance of the manuscript; **Adnan A. Khan:** Critical review, validation of scientific content and final approval of the manuscript.

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