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REVIEW ARTICLE

Advancements in the realm of calcium nanoparticles: An in-depth exploration of synthesis, characterization and multifaceted applications in agriculture

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Abstract

An extensive overview of nano calcium is given in this article, with particular attention paid to its synthesis methods, characterization techniques and agricultural applications. It highlights the unique properties of nano calcium and its potential as a promising nanomaterial in agriculture. The synthesis section discusses various methods to produce nano calcium, including sol-gel, precipitation, hydrothermal synthesis and green synthesis approaches and it highlights the nuances involved in tailoring nano calcium particles for agricultural purposes. The article also emphasizes the significance of characterization techniques in understanding the physicochemical attributes of nano calcium by using tools such as X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR) and atomic force microscopy (AFM). It explores the agricultural applications of nano calcium, particularly its role in enhancing nutrient uptake, soil fertility and crop yield. The impact of nano calcium on plant growth, stress tolerance and disease resistance is discussed, offering a comprehensive perspective on its potential benefits for sustainable agriculture. The article also highlights how nano calcium can be an eco-friendly alternative by reducing dependence on traditional fertilizers and minimizing environmental harm. In conclusion, it combines existing research on nano calcium synthesis, emphasizing its potential to transform modern agriculture and support global food security.

Keywords: agricultural applications; calcium nanoparticles; characterization; nutrient uptake; synthesis

Introduction

Nanotechnology, a dominant force in modern times, offers immense potential and diverse applications across various fields, from agriculture and pharmaceuticals to electronics and healthcare (1). It involves studying and manipulating materials at the nanoscale (1-100 nm), resulting in distinctive physical and chemical features due to their smaller size, reduced weight, enhanced durability and increased strength (2). Nanotechnology is significantly applied in chemistry to produce metal and metal oxide nanoparticles, focusing on green synthetic approaches to reduce hazardous chemicals, minimize waste, enhance efficiency and achieve cost-effectiveness (3). Due to their large surface area and unique properties, nanomaterials mimic atomic behaviour, enabling enhanced reactivity, quantum effects and novel mechanical, electrical and optical characteristics. Nanomaterials have a higher surface-to-volume ratio than bulk materials, which enhances their physical properties. Their size, shape and morphology undergo modifications at the nanoscale, resulting in improved characteristics and wider applicability (4).

Calcium, the fifth most profuse element on earth, is essential to plant growth and development, activating biochemical processes, facilitating membrane transport metabolisms, enhancing nitrate uptake and regulating photosynthetic rates (5). Research has shown that the presence of Ca^{2+} ions improves plant salinity tolerance and promotes overall plant growth (6). However, the slow uptake and translocation of calcium by the root system of plants pose challenges, necessitating the application of exogenous calcium, especially in soils with pH levels not optimal for calcium availability (7).

Nanotechnology offers a solution to these challenges by creating nanoparticles, typically 8-10 nm in size, to deliver nutrients more efficiently, thereby enhancing nutrient uptake efficiency, plant growth and overall productivity (8). Nano-technology fertilizers, leveraging the unique properties of nanoparticles, are cost-effective and eco-friendly, reducing toxicity. This approach is particularly relevant in traditional fertilizers, which often result in low efficiency of nutrient use and environmental contamination (9). Numerous studies have confirmed that nano fertilizers enhance plant growth and productivity in various crops, including peanuts, apples and cucumbers (10-12). Notably, in these crops, nano-calcium fertilizers have improved plant height, crop growth rate, seed yield and other agronomic traits. Nano-calcium fertilizers, in particular, have shown promise in improving various agronomic traits while extending fruits' shelf life post-harvest (10-12).

Various techniques, such as sol-gel, thermal decomposition, hydrothermal methods and others, are used to synthesize CaO nanoparticles. These techniques provide exact control over parameters, including shape and specific surface area and capture effectiveness (13). They also enable the manipulation of all physical and chemical properties of nano CaO. Advanced analytical tools such as X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR) and atomic force microscopy (AFM) are thoroughly examined to provide insights into the structural and morphological characteristics of nano calcium particles that are relevant to agricultural applications. This study encompasses many approaches for synthesizing and applying Ca nanoparticles, including the most recent characterization techniques for determining their physical and chemical structure.

Calcium nanoparticles synthesis

Precipitation method

$Ca(OH)_2$ synthesis involves reacting 1 M $CaCl_2.H_2O$ with 2 M NaOH at a 1:2 stoichiometric ratio. The resulting white precipitate is washed, air-dried and then calcinated to yield CaO powder from dry $Ca(OH)_2$ (14). The steps involved in synthesizing CaO Np through the precipitation method are depicted stepwise in Fig. 1.

Auto-combustion method

The auto-combustion method for synthesizing $CaFe_2O_4$ nanoparticles involves preparing a solution of calcium nitrate and ferric nitrate in distilled water (150 mL) at a 1:1 molar ratio, with citric acid (2 M) added as a chelating agent. This solution was stirred at 80 °C, after adding 6 mL of ethylene glycol, until it formed a gel-like substance. The gel undergoes self-propagation combustion to create a powdery residue. This residue is calcined at 550 °C for 2 hr, then lightly crushed to yield calcium ferrite nanoparticles in powder form (15).

Co-precipitation method

The co-precipitation method for synthesizing calcium ferrite nanoparticles involves dissolving calcium nitrate and ferric nitrate in distilled water (150 mL) at a 1:1 molar ratio. This solution is stirred at room temperature with ethylene glycol (6 mL) and a NaOH solution is added to adjust the pH to 8. After an hour of continuous stirring, the solution is centrifuged at 3000 rpm for 1 hr to separate the precipitate, which is then washed thrice with distilled water. The precipitate is dried in an oven at 80-90 °C for 6 hr, yielding calcium ferrite nanoparticles in powder form (15).

Self-combustion method

The synthesis of calcium phosphates was achieved using a self-combustion method. The raw materials used were calcium nitrate tetrahydrate and di-ammonium hydrogen phosphate. Glycine and nitric acid were used as fuel and catalyst. The process involved combining the raw materials in distilled water (20 mL) under continuous stirring, maintaining a Ca/P ratio 1.5. Nitric acid was added to dissolve the precipitate formed. The amount of glycine required was determined using the parameter φ, representing the stoichiometric ratio of oxidative fuel (16).

$$\Phi = \frac{\Sigma \text{ Coefficient .Reducingel ements x Valence}}{\Sigma \text{ Coefficient .Oxidantel ements x Valence}} \qquad \text{(Eqn. 1)}$$

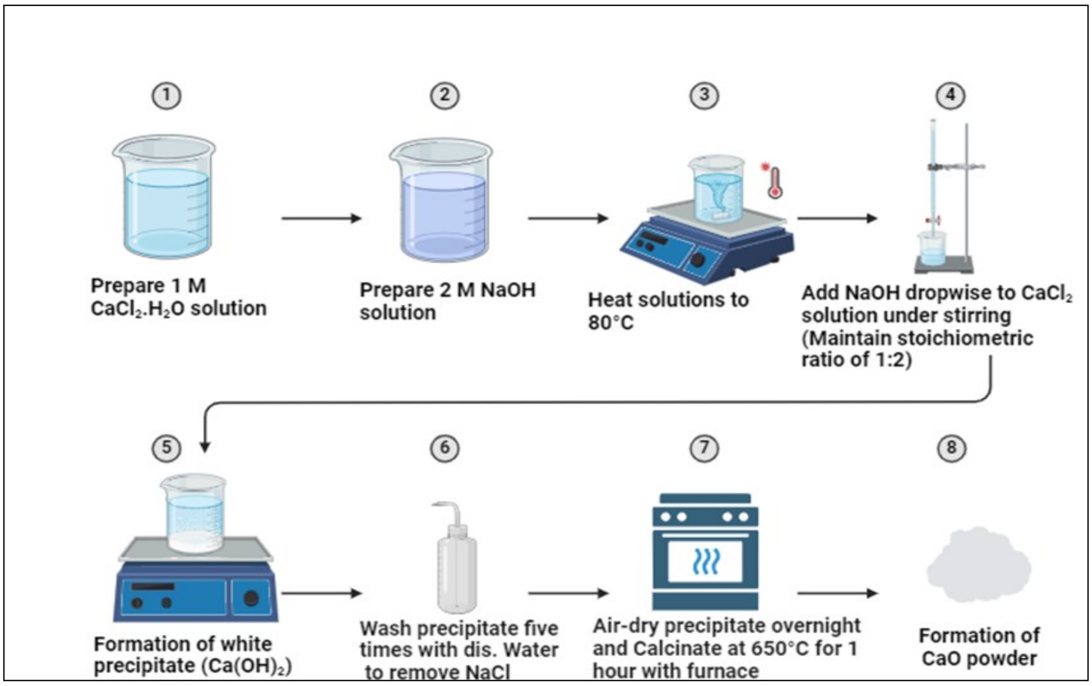

Fig. 1. Precipitation method for Ca NP synthesis.

The solution was heated (60 °C) evaporate the solvent, producing a resin after one hour of stirring. The temperature was subsequently raised to commence combustion. For two hours, the resultant ash was heated to 800 °C. The obtained powders were suspended in isopropyl alcohol and underwent ultrasonication. The powders were subsequently dried at 90 °C for 2 hr.

Sol-gel method (Chicken egg shell)

The synthesis of metal oxide nanoparticles involves four steps(17) and the detailed procedure is illustrated in Fig. 2.

The equations involved in this method is:

$CaCO_3(s) + 2HCl(aq) = CaCl_2(aq) + H_2O(l) + CO_2(g)$ (Eqn. 2)

$Ca\ (OH)_2(s) + Heat = CaO(s) + H_2O(l)$ (Eqn. 2)

Solution precipitation method

The solution precipitation method is a recognized technique for creating $CaCO_3$ nanoparticles (NPs), based on the reaction between Ca^{2+} and CO_3^{2-} in aqueous solutions (18). This method allows large-scale production of $CaCO_3$ NPs without surfactants, reducing costs. Due to its mild preparation conditions, it can incorporate bioactive agents like small molecule drugs, genes and proteins into $CaCO_3$ NPs during precipitation. The size, shape and phase of $CaCO_3$ NPs can be controlled by adjusting synthesis parameters such as pH, temperature, ion concentration, stirring speed, solvent species and additives (19).

Microemulsion method

Microemulsion techniques are used to synthesize $CaCO_3$ nanoparticles and gene encapsulation (20). These include the reversed microemulsion and double emulsion methods. Separate "calcium microemulsion" and "carbonate microemulsion" phases are prepared and combined to produce $CaCO_3$ nanoparticles. The double emulsion method involves an additional step of mixing a significant amount of an aqueous phase with the "calcium microemulsion" to form a W/O/W double emulsion (20). These methods allow control over the nanoparticles' structure, size and crystallinity.

Gas diffusion method

The gas diffusion technique fabricates amorphous calcium carbonate (ACC) loaded with small-molecule drugs (21). In this process, $CaCl_2$ is dissolved in ethanol and CO_2 and NH_3 are generated from ammonium bicarbonate (Fig. 3). These gases dissolve in the ethanol solution to yield CO_3^{2-} and NH_4^+ ions. These ions react under alkaline conditions to produce ACC. The properties of the ACC, such as size, shape and polymorph, can be controlled by adjusting additives, temperature and Ca^{2+} concentration (22).

Thermal decomposition method

The synthesis process involved using $CaCl_2{\cdot}2H_2O$, NaOH, distilled water and 99 % pure argon gas. To prepare the precursor $Ca(OH)_2$, 1 M and 2 M NaOH solutions were added to a 0.5 M calcium chloride solution at 80 °C under continuous stirring in an argon atmosphere (Fig. 4). A white precipitate of calcium hydroxide formed and the reaction was halted when the pH reached 11.2. The precipitate was then filtered, washed and dried. A portion of the dried powder was set aside for analysis, while the remaining was calcined at 650 °C for 1 hr in a nitrogen (N_2) atmosphere. The precursors and resulting CaO powders were labelled based on the molarity of NaOH used in the synthesis (23, 24).

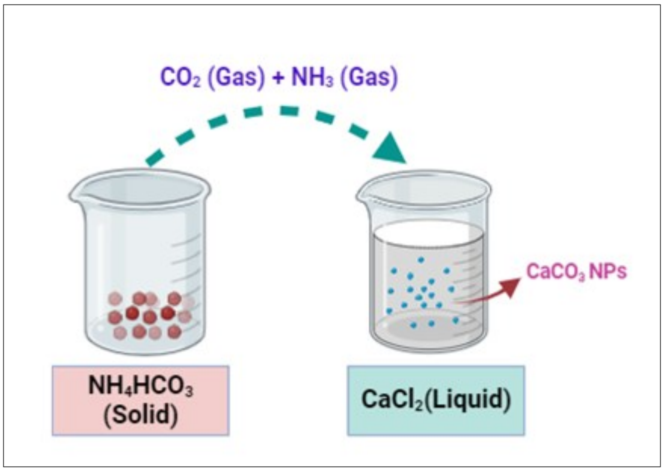

Fig. 3. Illustrates the gas diffusion technique (28).

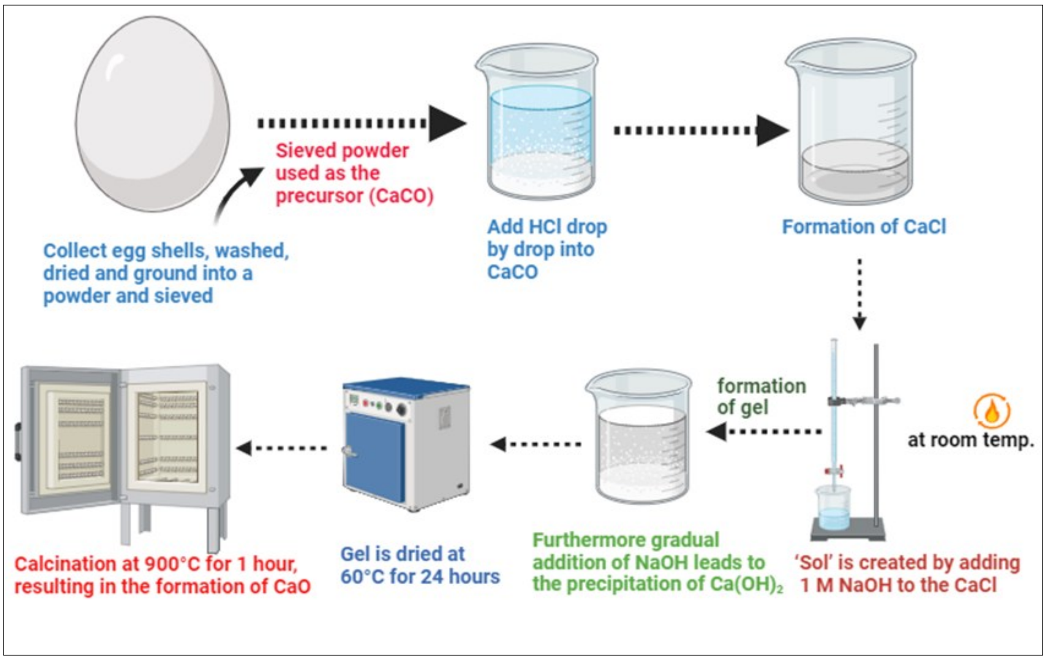

Fig. 2. Sol-gel method for Ca NP synthesis.

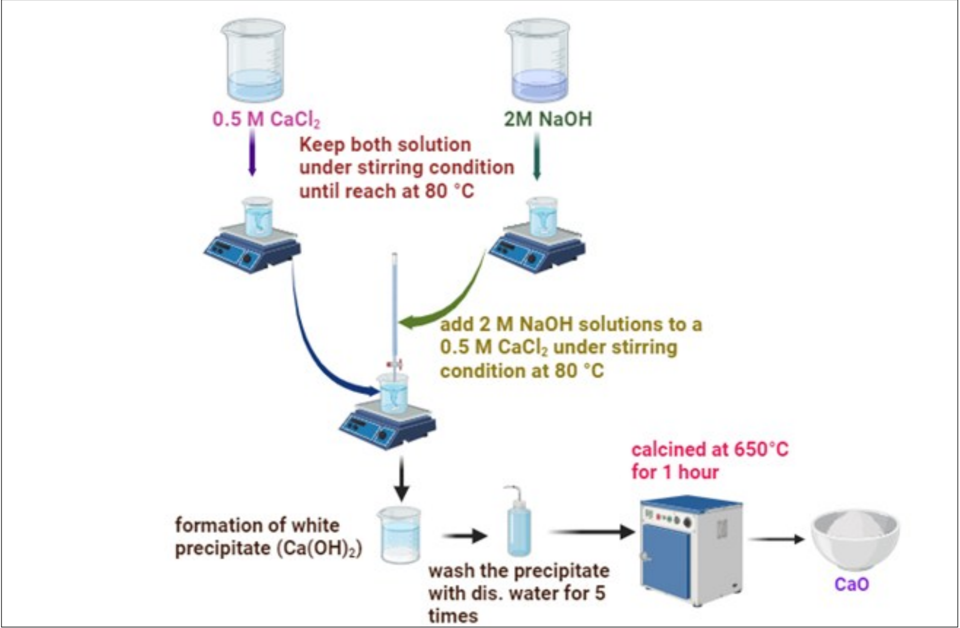

Fig. 4. Thermal decomposition for Ca NP synthesis.

Green synthesis of Ca NP

The biosynthesis of calcium nanoparticles follows a structured process with specific quantities at each stage. First, 10-100 g of plant material (leaves, fruit peels, or other parts) is washed, chopped, or powdered and then boiled in 100-250 mL of distilled or deionized water for 30-45 min to extract bioactive compounds. In microbial or enzyme-assisted synthesis, bacterial or fungal cultures are grown under optimal conditions to produce the required metabolites (Fig. 5). The extract or culture is then mixed with 10-50 mL of a calcium precursor solution, such as 0.1-0.5 M calcium nitrate ($Ca(NO_3)_2$ or calcium chloride ($CaCl_2$). To facilitate nanoparticle formation, the solution is stirred for 30-60 min using a magnetic stirrer and 0.1-2 M NaOH or NH_4OH is added dropwise to adjust the pH (typically above 10), inducing precipitation. A white precipitate forms, which is then centrifuged at 3000-10000 rpm for 10-30 min, washed multiple times with distilled water and dried in a hot air oven at 80-100 °C for 1-6 hr. Finally, the dried precipitate undergoes calcination at 400-700 °C for 1-3 hr. The resulting nano Ca is collected and stored for characterization and further applications. This standardized process ensures efficient and eco-friendly synthesis of calcium nanoparticles with controlled size and stability (25-32).

Characterization techniques for Ca nanoparticles

Nanoparticles (NPs) are primarily identified by their physical attributes, spatial distribution, dimensions, uniformity and surface characteristics (1). Various analytical methods are employed to assess these properties (Fig. 6).

UV-Visible spectroscopy

UV-visible spectroscopy serves as a fundamental yet vital instrument that elucidates the formation of calcium nanoparticles at the initial stage of synthesis. Its properties are highly influenced by the size, form and distribution of Ca nanoparticles because of the surface plasmon resonance phenomena. Calcium nanoparticles have absorbance in the range of 260 nm to 410 nm (2). Broad peaks were observed at

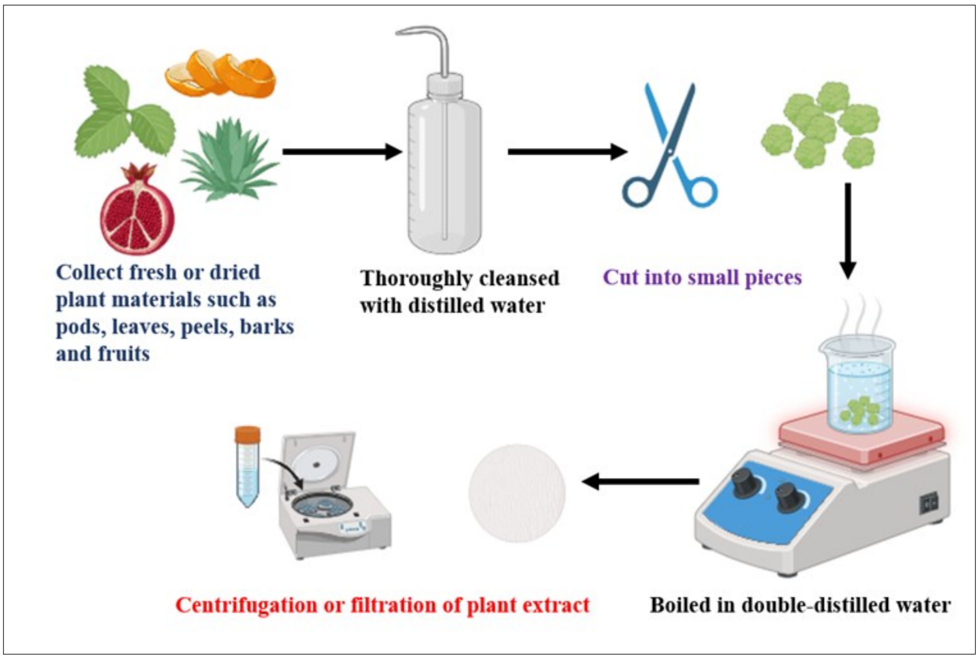

Fig. 5. Overview of aqueous extract preparation steps.

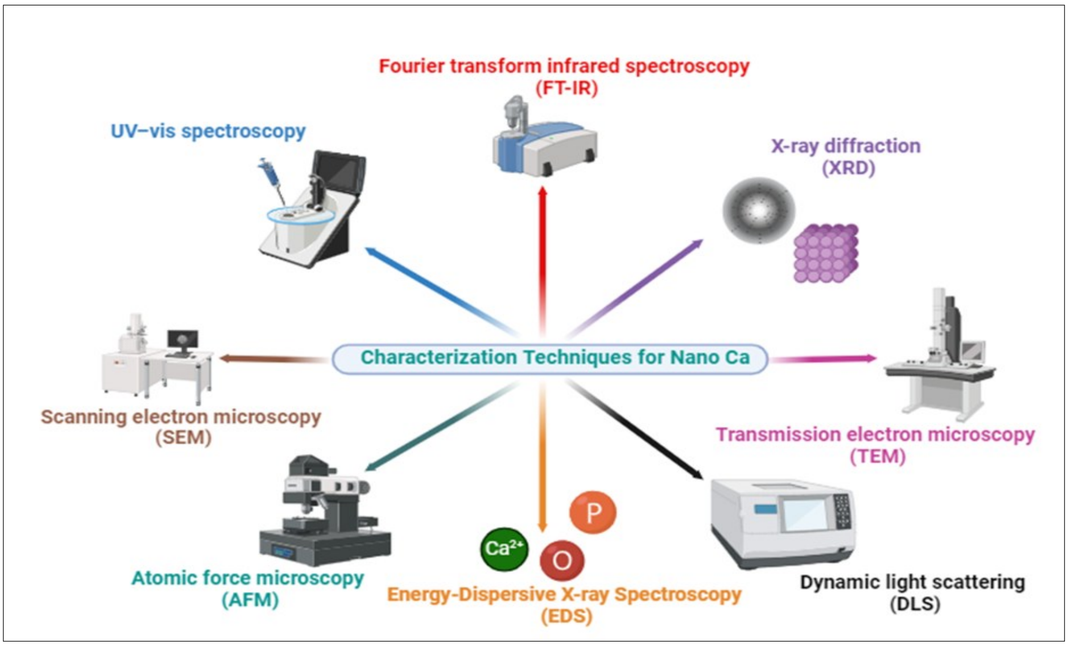

Fig. 6. Characterization techniques for nanoparticles.

265 nm and 350 nm, indicating the formation of calcium oxide nanoparticles at these wavelengths. The distinct spectral band for calcium oxide nanoparticles at 332 nm. The broad-spectrum peak at 264 nm and the shoulder peak at 331 nm are the measurements of calcium oxide nanoparticles. The prominent peaks for calcium phosphate nanoparticles correspond to characteristic wavelengths in the visible range, specifically 430 nm and 542 nm (33). This technique indicates the stability of Ca NPs as the peaks decrease in intensity and expand, with secondary peaks appearing at higher wavelengths, signalling particle aggregation. The widening of peaks provides information about the dispersion of Ca nanoparticles. Broad peaks generally signify the development of a wider size distribution (wide dispersity) of calcium nanoparticles in solution (34). The colour of the solution can also determine size and shape during synthesis. As a result of the solutions' unique colour, it is possible to perceive and monitor the synthesis reactions' advancement (35).

Dynamic light scattering (DLS)

Furthermore, Dynamic Light Scattering (DLS) is a straightforward, non-invasive method employed to ascertain the size of particles in both the micrometre and nanometer scales. This technique involves using a monochromatic light source, typically a laser, which is directed through a nanoparticle suspension (29). The nanoparticles, undergoing Brownian motion, scatter the light at varying intensities. After that, the Stokes-Einstein equation is used to determine the particle size. DLS primarily quantifies the hydrodynamic diameter of the nanoparticles, which is affected by elements including surfactants, stabilizers, capping agents and an adsorbed electrical double layer on the nanoparticle surface. This approach is most effective when applied to monodisperse nanoparticles (36). As a result, the nanoparticle size obtained using DLS is generally more significant than the actual size measured by X-ray diffraction (XRD) and Transmission Electron Microscopy (TEM) (34, 37). In addition to size measurement, DLS is also utilized to measure the zeta potential of Calcium Nanoparticles (Ca NPs). A high magnitude value of zeta potential indicates electrostatically stabilized nanoparticles, implying the absence of aggregation (38).

Zeta potential has been analyzed to know the samples' negative or positive polarity, which is contingent upon the chemical properties of particles. This phenomenon arises from the presence of charged entities on the surfaces of particles, manifesting as an electrical potential. Zeta potential facilitates assessing the rate at which similarly charged particles repel each other within a compound. Zeta potential measurement of particles is frequently referenced as a metric for determining the stability of sample dispersion. In this context, the values at high magnitude indicate that the suspension maintains good electrostatic stability (29).

X-ray diffraction (XRD)

X-ray diffraction (XRD) is essential for clarifying nanomaterials' atomic and crystalline structure. It is a device employed to verify the formation of nanoparticles (NPs) and analyze their crystal structure, crystal planes and crystalline size, which functions as a fingerprint (39). Its' a non-destructive method. It provides essential data on crystal planes and structures using the Joint Committee on Powder Diffraction Standards (JCPDS) reference cards. XRD characterization of various nanoparticles is given in Table 1.

The Scherrer equation is primarily used to quantify line broadening, precisely the full width at half maximum (FWHM), to determine the crystallite size of Ca nanoparticles from diffraction peaks (42). The widening of diffraction peaks suggests the synthesis of smaller-size Ca NPs as line broadening (β) is inversely related to crystallite size (t). While determining the size of the equation, the phrase "crystallite size" should be used rather than "particle size":

$$D = \frac{K\lambda}{\beta \cos\theta} \qquad \text{(Eqn. 4)}$$

Here, D represents the average crystallite size, while K stands for Scherers' constant, which is typically assigned a value of 0.89. The variable λ signifies the wavelength of X-rays,

Table 1. X-ray Diffraction (XRD) analysis of calcium nanoparticles

Nanoparticle type	Crystal structure	JCPDS card No.	Key findings	Reference
Calcium ferrite	Orthorhombic	72-1199	Higher crystallinity in co-precipitation, broader peaks in auto-combustion	(24, 43)
Calcium oxide	Face-centered cubic	00-033-0664, 00-004-0784	Crystalline nature confirmed crystallinity increases with heat treatment	(27, 40)
Calcium hydroxide	Hexagonal	00-004-0733	Well-defined peaks indicate high crystallinity	(23)
Calcium carbonate	Rhombohedral	00-081-2027	Crystallinity enhanced after calcination	(41)
Hydroxyapatite	Hexagonal	01-074-0566	Indexed structure and phase stability confirmed	(33)
Tricalcium phosphate	Monoclinic	01-070-2065	Heat treatment eliminates the pyrophosphate phase	(33)

β defines the peak width at half maximum and θ pertains to Braggs' diffraction angle (15).

Method of synthesis and calcination temperatures also played a major role in particle crystallinity. For example, calcium ferrite nanoparticles calcined at higher temperatures (500 °C, 700 °C and 900 °C) revealed their crystalline nature, whereas the uncalcined particles displayed an amorphous nature, evidenced by the absence of diffraction peaks (42, 44).

Fourier transform infrared spectroscopy (FT-IR)

FT-IR spectroscopy is a molecular analysis technique that examines diverse chemical functional groups within the 400 to 4000 cm^{-1} spectral range. This method is employed to ascertain potential biomolecules responsible for calcium nanoparticle reduction, capping and effective stabilization (37, 45). This approach is characterized by its speed, cost-effectiveness and non-destructive nature when utilized with the attenuated total reflectance accessory. It boasts a high degree of reproducibility. FT-IR characterization of various calcium nanoparticles is given in Table 2.

Scanning electron microscopy (SEM)

SEM is an essential technique for nanoparticle characterization, providing detailed insights into shape, size, morphology and distribution. It generates high-resolution micro-images, revealing polydispersity, purity and encapsulation processes in calcium nanoparticles (46). SEM characterization of various calcium nanoparticles is given in Table 3 and Fig. 7. While SEM offers valuable structural insights, it requires dry, conductive samples and size measurements may be less precise than TEM due to nanoparticle clustering (48).

Transmission electron microscopy (TEM)

TEM serves as an indispensable tool for the characterization of materials, enabling the examination of particle sizes at the nanoscale and providing a detailed analysis of crystal structures with high resolution. This technique leverages a beam of electrons to interact with an ultrathin sample (45). Transmission Electron Microscopy (TEM) is a key technique for analyzing calcium nanoparticles (CaNPs), as shown in Table 4 and Fig. 8.

Atomic force microscopy (AFM)

Atomic Force Microscopy (AFM) is an advanced three-dimensional technology that examines the nanoscale structure of nanoparticles using a mechanical probe affixed to a cantilever. It holds a distinct edge over other methods such as XRD, DLS, SEM and TEM due to its ability to provide information on the height and volume of nanoparticles, analyze their 3D topology and visualize hydrated nanoparticles, their dispersity and the variability in their shapes and sizes (38, 45). Nonetheless, it is a laborious technique that solely provides information regarding the external structure of the nanoparticles. AFM images (Fig. 9) indicated that nanosized particles are absorbed on flat surfaces and reveal the smooth and uniform surfaces of the particles (29).

Energy-dispersive X-ray spectroscopy (EDX)

Energy-dispersive X-ray Spectroscopy (EDX) is utilized to determine the elemental composition, relative abundance and contaminants of nanoparticles. This technique entails the interaction of X-rays with the specimen being examined. Identifying emission peaks at 3 keV indicates the presence of silver crystallites. The lack of supplementary peaks corroborates the purity of the Calcium Nanoparticles. The presence of peaks associated with components like carbon and oxygen may indicate the interaction of metabolites with Ca NPs on the surface or result from the oxidation of Ca NPs. For example, CaO NPs prepared through the thermal decomposition of waste eggshells at 900 °C were characterized using EDX. The results revealed identical peaks with weight percentages of 71.4 % for calcium and 28.6 % for oxygen (24). This finding was consistent with previous research (2, 28, 30). Similarly, the EDS of calcium ferrite nanocapsules affirms the presence of calcium (Ca) and, oxygen (O_2), Iron (Fe) with a minor amount of carbon (C) attributed to the sample holder (44). The presence of calcium (Ca) and phosphorus (P) peak at a level of 1.04 confirms the Calcium phosphate nanoparticle (29).

Table 2. FT-IR spectroscopy analysis of calcium nanoparticles

Nanoparticle type	Key functional groups identified	Peak position (cm^{-1})	Key findings	Reference
Calcium ferrite	O-H bending, N-H stretching	1411.11, 3391.28	The sharp peak for O-H, the smaller peak for N-H	(15)
Calcium oxide	C–O bonds (carbonate presence)	1400–1500	Broad and weak bands indicate carbonation	(23)
Calcium phosphate	CO_3 groups, phosphate minority phase	1400–1500	IR spectrum confirms phosphate phase presence	(33)
Calcium carbonate	Transformation into CaO	1418.04 (absent)	Lack of peak confirms $CaCO_3$ conversion to CaO	(23)
General Ca–O bond	Strong metal-oxygen bond	455.38	Characteristic Ca-O stretching band	(23)

Table 3. Scanning electron microscopy (SEM) in calcium nanoparticle characterization

Nanoparticle type	Morphology & size	Synthesis method	Reference
$CaFe_2O_4$	Spherical, prone to agglomeration	Co-precipitation	(43)
$CaFe_2O_4$	5–18 nm, spherical	Auto-combustion (550 °C)	(15)
$Ca(OH)_2$	Hexagonal platelet, 135-143 nm	Not specified	(23)
CaO	Spherical, 20-70 nm	Thermal degradation (900 °C, eggshell)	(40)
MO-CaO	Spherical, aggregated, 30-40 nm	*Moringa oleifera* leaf extract	(28)
$CaCO_3$	Rhombohedral, 80-120 nm	Not specified	(25)
$CaCO_3$ carbonation mud	Semi-hexagonal, agglomerated	Carbonation method	(41)
Limex-treated $CaCO_3$	Nonporous, irregular crystal structure	Carbonation method	(41)

Table 4. Transmission electron microscopy (TEM) in calcium nanoparticle characterization

Technique	Function	Key features	Reference
TEM	Examines nanoscale particle sizes and crystal structures.	Uses an electron beam on an ultrathin sample, crucial for studying capping agents, precursors and metabolite encapsulation in CaNPs.	(45)
HRTEM (High resolution- TEM)	Provides high-resolution imaging of atomic lattice structures.	Reveals crystal flaws and atomic packing (Fig. 8).	(50)
SAED (Selected area electron diffraction)	Determines crystallinity and lattice parameters.	Uses electron diffraction; confirms XRD results by computing d-spacing.	(37, 47)
TEM evaluations	Estimates particle size and distribution.	Time-intensive, requires a vacuum and specialized skills; best for homogeneous samples.	(37, 45, 49)

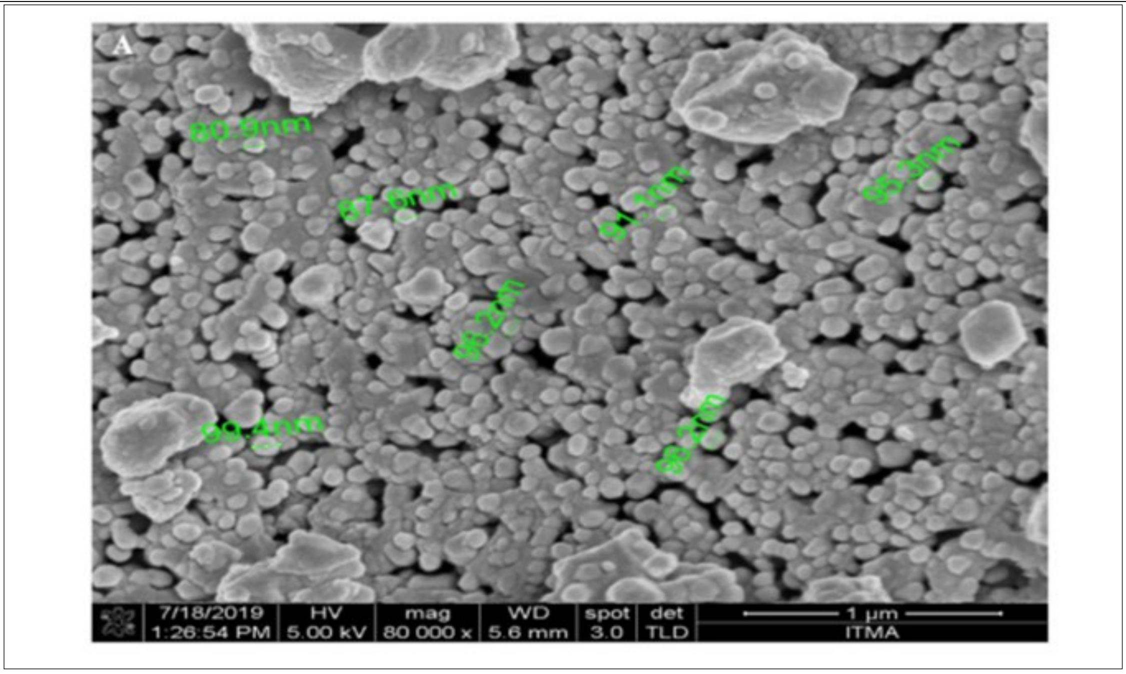

Fig. 7. SEM micrographs of CaO NPs synthesized from *Trigona sp.* Honey by thermal decomposition method (60).

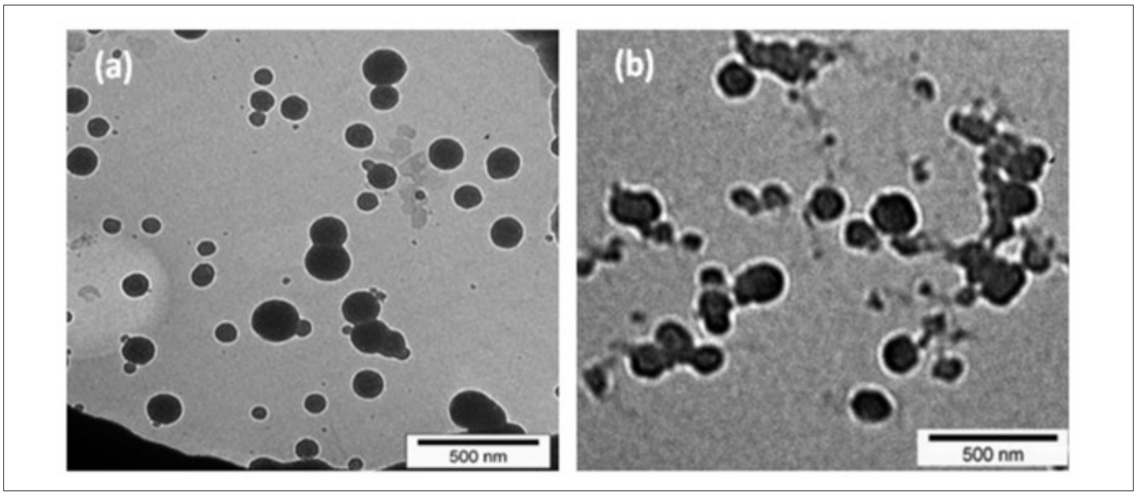

Fig. 8. TEM micrographs of Ca NPs were synthesized from the thermal decomposition method using two precursors. a) CaO powders after calcination (from precursor 1M NaOH) and b) CaO powders after calcinations (from precursor 2M NaOH) (37).

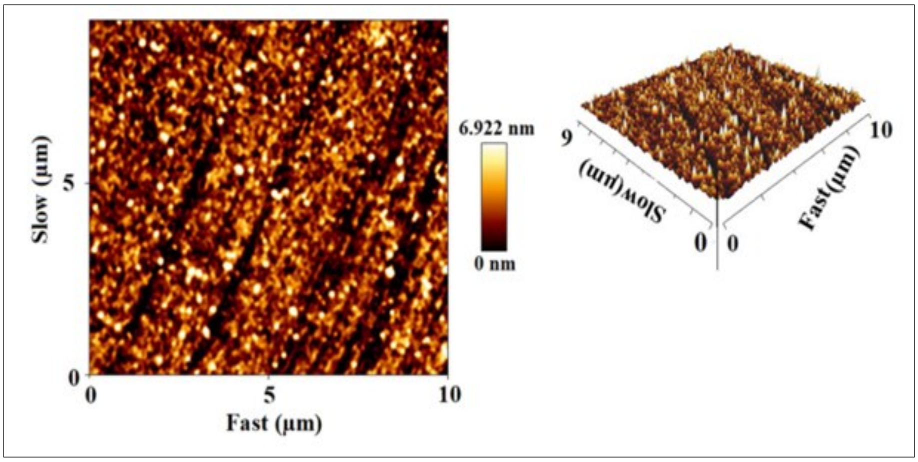

Fig. 9. AFM micrograph of synthesized Nano Ca powder (42).

Applications of calcium nanoparticles

Calcium nanoparticles are highly stable and widely used in agriculture and industries such as biosensing, drug delivery and manufacturing plastics, papers, paints, sealants and adhesives. Their high porosity, large surface area and easy production make them ideal for creating affordable and reliable biosensors, as shown in Fig. 10.

Role of calcium nanoparticles in soil and plant physiology

Calcium nanoparticles can improve soil fertility, aid in the movement of specific trace mineral elements and potentially immobilize biologically irrelevant heavy metals (61, 62). Research indicates that $CaCO_3$ nanoparticles reduced nanocomposite film degradation in soil (63). Nano-calcium application causes changes in soil morphology, such as increased porosity and enhanced surface reactivity, thus improving water absorption and nutrient translocation (64, 65).

The evidence stated that nanoscale CaO nanoparticles could be easily transported across ionic channels in the plant system owing to their diminutive size, elevated surface area-to-volume ratio and continuous flow (66). The elevated electrochemical potential energy of nanoscale materials significantly influences the phloem transport of CaO NPs (67). Calcium ion (Ca^{2+}) movement in plant xylem vessels occurs in chelated form, with the velocity of water flow being a pivotal element. Moreover, apoplastic and symplastic routes enable Ca^{2+} transfer in fruit or leaf tissues (68). The uptake and translocation pathways of nano calcium carbonate (NCC) in plants remain unclear. Still, they could involve mechanisms such as endocytosis (64), carrier proteins (65), intercellular filaments (69), pore-forming behaviour (70), or cleavage patterns (71), influencing plant activities. NCC may boost photosynthetic performance by enhancing the D1 protein activity of photosystem II (72). NCC may also reduce ROS accumulation by elevating antioxidant enzyme activity, thus inhibiting D1 protein degradation. The up-regulation of necessary photosynthetic enzymes, including Rubisco and Rubisco activase, may cause increased photosynthetic efficiency through nanoparticles (73).

Role of calcium nanoparticles on crop management

Calcium nanoparticles have been shown to significantly enhance plant growth, yield and post-harvest quality by improving nutrient absorption and physiological processes. The following Tables 5 & 6 summarize the effects of different calcium nanoparticle applications on various crops.

Role of calcium nanoparticles on stress management

Application of Ca NPs at varying concentrations significantly improved the capacity to scavenge free radicals, phenolic

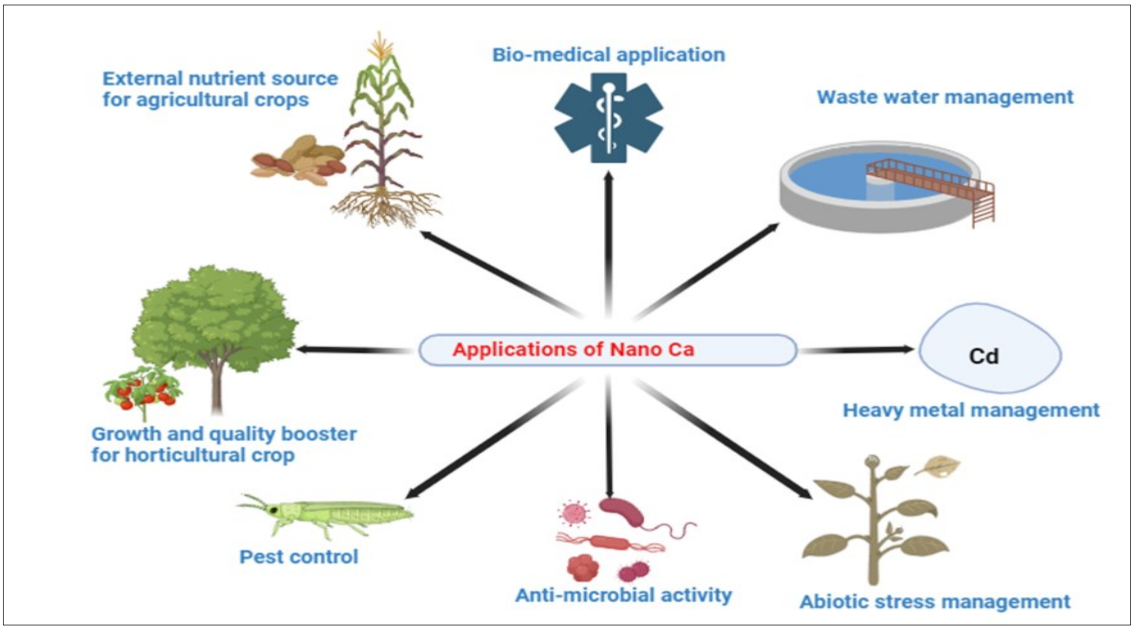

Fig. 10. Applications of Nano Ca.

Table 5. Effects of calcium nanoparticles on growth and yield on field crops

Ca particle used	Crop	Key findings	Reference
50 % calcium nitrate + 50 % nano-calcium	Groundnut	The combination of 50 % calcium nitrate with 50 % nano-calcium mixture improved pod and seed production, 100-seed weight, pod yield, seed yield, shelling percentage and nutrient uptake.	(51)
Nano CaO (500 ppm)		Increased calcium content in stems (36.4 %) and leaves (61.5 %) compared to control plants.	(52)
Nano-Ca + Humic Acid		Improved seedling growth, increased biomass and enhanced nutrient content (Ca, N, P, K) in shoots and roots.	(10)
Gypsum + 714.28 mg ha^{-1} Nano calcium nitrate		Increased growth parameters and yield.	(53)
20 mg/L nano CaO	Mung bean	Enhanced plant height by 27.4 %, boosted stomatal conductance and transpiration rate, leading to enhanced gas exchange.	(54)
Nano calcium carbonate 100 ppm	Rice	Improved growth, seed quality and reduced time for 50 % flowering.	(55)
Nano calcium carbonate 200 ppm	Wheat	Enhanced root length, surface area, diameter, volume, dry biomass, antioxidant enzyme activities and photosynthetic parameters.	(56)
Nano-Ca 500 ppm + Potassium Humate (K-H)	Cotton	Improved growth, yield and fibre quality.	(57)
Nano fertilizers (Ca, humic acid)		Increased seed cotton yield.	(58, 59)
Calcium phosphate nanoparticles	*Zea mays*	Increased chlorophyll content and enhanced plant vitality.	(60)

Table 6. Effects of calcium nanoparticles on growth, yield and post-harvest quality of various horticultural crops

Ca particle used	Crop	Key findings	Reference
CaNPs - 75 and 100 mg L^{-1}	*Moringa oleifera L*	Increased shoot and root lengths, germination percentage, leaf number, relative water content, carotenoid content and nutrient absorption in roots.	(74)
		Increased crude fibre, ash, K and Ca while reducing toxic heavy metals. Additionally, they improved antioxidant activity, reduced oxidative stress and lowered cancer risk by 50 %.	(75)
ZnO + CaO NPs (50 ppm)	*Solanum lycopersicum*	Increased shoot number, leaf area, fresh weight, yield per plant, fruit diameter and fruit weight.	(76)
Nano Ca fertilizer (2.5 mg L^{-1})	Potato	Increased cortex layer thickness compared to the control.	(77)
Nano Ca fertilizer (2 mg L^{-1})	Gerbera flower	Improved flower quality, vase life and reduced stem curvature.	(78)
CaO NPs 2500ppm (foliar application)	cherries, apples, peaches, pears, tomatoes, grapes, Paraguayan and apricots	Increased Ca^{2+} ions in fruit peel, enhanced fruit diameter and yield and reduced fruit cracking by strengthening tissue.	(79)
Nano calcium (0.1 %) + nano-boron (10 ppm)	Pomegranate	Enhanced shoot length, leaf number, leaf area, aril percentage, fruit weight, TSS, sugars, vitamin C and anthocyanin content while reducing total acidity.	(80)
Nano-Ca (foliar application) (250 mg L^{-1})	Mango	Compared to conventional calcium treatment, there is increased calcium concentration in shoots (3.0 %) and roots (2.8 %).	(81)
Calcium Phosphate NPs (30 mg L^{-1})	Avocado	Enhanced physiological response and seedling development.	(82)
Nano-Ca + $CaCl_2$ (Pre-harvest spray)	Apple	Reduced weight loss during storage by maintaining membrane integrity, increasing firmness and minimizing moisture loss.	(83, 84)
Nano calcium treatment	Apple, strawberry, fleshy fruit	Decreased activity of cell wall enzymes (PG, PME, β-Gal), leading to greater fruit firmness during storage.	(85-87)

contents and flavonoid contents and enhance nutritional quality in *M. oleifera* than water and calcium nitrate application, as well it reduce the oxidative stress biomarker (MDA) levels in CaNPs-amended soil (75). $Ca_3(PO_4)_2$ nanoparticles enhanced root and shoot growth, increased antioxidant enzyme activities and lowered lipid peroxidation levels in rice (88). The activity of antioxidant enzymes such as phenyl ammonia lyase and catalase was increased by applying 20 mg/L CaO NPs and 2 % FM and decreased malondialdehyde and hydrogen peroxide (54). Moreover, CaO NPs decreased the soil cadmium acquisition (31) by the mechanism of cation exchange sites of Ca^{2+} and Cd^{2+} through facilitating calcium membrane channels, decreasing Cd uptake and supporting normal growth and metabolism (89, 90).

Effect of calcium nanoparticles on pest control

Nano $CaCO_3$ can control oriental fruit flies (*Bactrocera dorsalis*) and California red scale (*Aonidiella aurantii*) in Tankan leaves (*Citrus tankan*). It reduced 75 % of the population and prolonged cleaning behaviour in flies and it also increased Ca content to 13 times higher than the colloidal Ca treatment (91). The damage caused by gall midge, leaf mites, stem borers and paddy bugs was much lower in foliar application of nano calcite at 160 ppm than control plants (55).

Antimicrobial activity of calcium nanoparticles

The primary role of calcium hydroxide as a standard intracanal medicament is to deliver antimicrobial efficacy, which has led researchers to investigate the role of Ca nanoparticles as antimicrobial agents against fungi and bacteria. A brief overview of the antimicrobial activity of Ca nanoparticles is given in Table 7.

Conclusion

Nano calcium is of significant interest due to their adjustable properties. They are typically synthesized and characterized through various methods and show great potential in transforming agriculture by enhancing plant growth, soil fertility and crop yields. It also offers eco-friendly alternatives to traditional fertilizers. Their antimicrobial properties make

Table 7. Brief overview of antimicrobial properties of Ca nanoparticles

Form of Nano Ca	Antimicrobial properties	Reference
CaO	*Escherichia coli, Streptococcus mutans, Proteus vulgaris.*	(2)
$Ca(OH)_2$	*Enterococcus faecalis* (*E. faecalis*)	(92)
CaO	*Escherichia coli*	(27)
CaO	*Candida albicans*	(32)
CaO	*Escherichia coli, Pseudomonas aeroginosa*, *Streptococcus* mutans and *Staphylococcus aureus*	(27)
$Ca_3(PO_4)_2$	*Streptococcus mutans* *Enterococcus faecalis*	(29)
Strontium-substituted calcium-deficient hydroxyapatite	*Escherichia coli, Staphylococcus aureus*	(24)
CaO	*Bacillus subtilis, Staphylococcus aureus* *Pseudomonas aeruginosa, Escherichia coli*	(30)
CaO	*Lactiplantibacillus plantarum*	(93)

them helpful in managing infectious diseases, purifying water and eradicating plant pathogens. However, their application beyond the lab requires further research. Since no single method is perfect, there are challenges in terms of scalability, cost-efficiency and ecological considerations that must be resolved before the widespread adoption of nanoparticles. Additionally, the potential environmental and health impacts of Ca NPs necessitate investigations into their accumulation and mechanism of action within the human body. Continued research and collaboration are crucial to unlock its full potential for sustainable agriculture and global food security.

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Authors' contributions

KM prepared the manuscript. SA and SK helped to collect articles. SN, RSK, RK and RR participated in the sequence alignment and drafted the manuscript. VV quoted the references. All authors read and approved the final manuscript.

Compliance with ethical standards

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