

Sustainable Phytogenic Engineering Of Tellurium Nanoparticles: Bridging Green Chemistry, Nanoscience, And Biomedical Innovation

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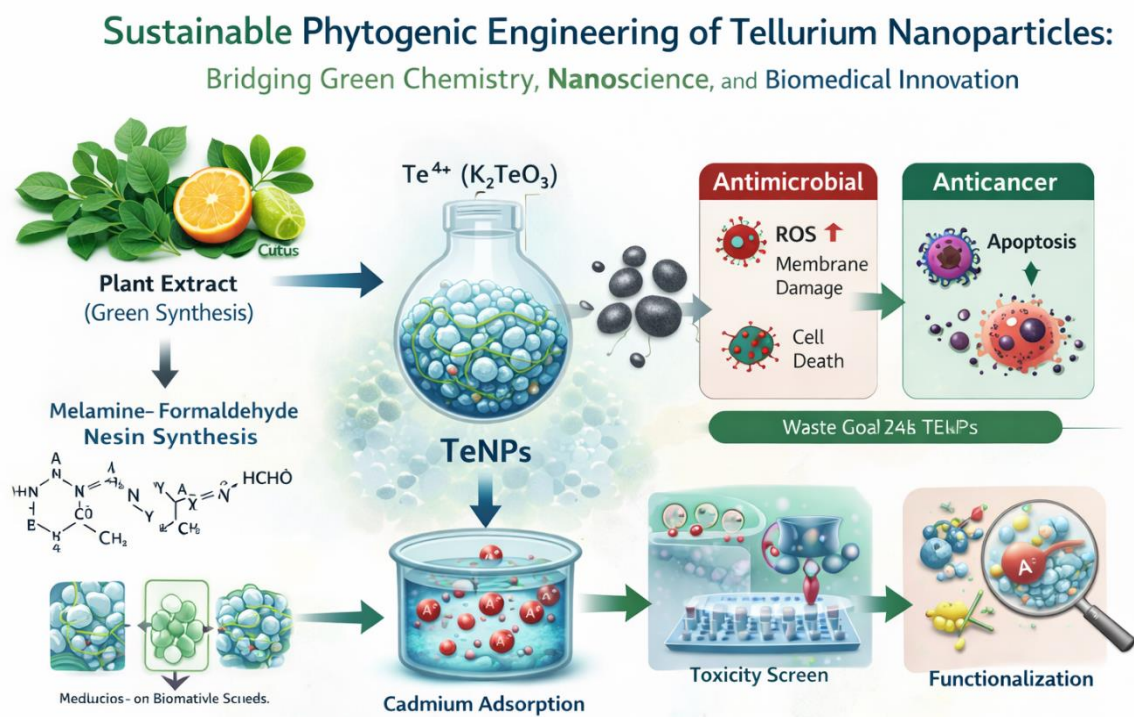
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ABSTRACT

GRAPHICAL ABSTRACT:



Abstract

The Tellurium nanoparticles (TeNPs) are a promising nanomaterial that has acquired unique physicochemical properties and possible biomedical uses. Green phytogenic synthesis - Green phytogenic synthesis involves the utilization of plant extracts in reducing and capping TeNPs which is a branch of sustainable chemistry. This review covers the synthesis, characterization, and applications of phytogenic TeNPs. We first survey plant-based synthesis methods: various extracts (e.g. *Moringa oleifera*, citrus juices, algae/fungi) reduce tellurite Te^{IV} to Te^0 under mild conditions, often yielding one-dimensional (nanorods/nanowires) or quasi-spherical TeNPs. Reaction parameters (pH, temperature, extract concentration) and phytochemical mediators (polyphenols, proteins, polysaccharides) are analyzed; mechanistic models involve redox and nucleation processes (Figure 1, **Graphical Abstract**). Green chemistry metrics (atom economy near 100%, low E-factors) are discussed qualitatively due to sparse quantitative data. Phytogenic TeNP sizes typically range from 5–200 nm, with shapes including rods, wires, belts, and cubes[1][2]. Representative analytical profiles are summarized: UV-vis spectra demonstrate that several absorption bands were present (e.g. 230-260 nm in case of TeNPs[3]) FTIR indicates the presence of surface organics (ex: -OH, -C=O, -NH), XRD shows trigonal Te^0 crystallinity (typical (100), (101), Tables are compared in terms of synthesis protocols (plant/extract, Te precursor, size, shape, yield) and TeNP activities. In the context of medicinal chemistry, TeNP surfaces can be targeted with polymers or biomolecules (e.g. albumin nanocages) as functionalization[5]. TeNPs demonstrate strong antimicrobial (broad-spectrum bactericidal) and antifungal effects (via ROS production and membrane/protein disruption)[6][7]) and selective anticancer effects (e.g. melanoma, breast cancer) (via apoptosis induction)[5]. TeNPs are in vitro biocompatible to levels of tens of $\mu\text{g/mL}$ [8] and Te^{IV} ions are toxic, but only in high doses. There is a dearth of in vivo data; clearance and long term safety of TeNP is unresolved. Such aspects as regulatory and safety (narrow therapeutic index of Te, possible pro-inflammatory effects) are taken into account. Some of the challenges involve scaling the process of green synthesis, reproducibility, stability, and functionalizing it in a controlled manner. Future efforts will probably be aimed at streamlining synthesis (with green metrics), understanding the mechanisms (separating ROS-dependent and independent effects[7]) and utilizing TeNPs in smart biomedical (integrating therapy and diagnostics). This review will help researchers to come up with safe and sustainable Te nanotechnologies that span green chemistry and nanomedicine.

Keywords: Green Synthesis; Phytogenic Nanoparticles; Tellurium Nanoparticles; Characterization; Antimicrobial; Anticancer; Reactive Oxygen Species; Toxicity; Nanomedicine.

Graphical Abstract Description

One of the workflows of TeNPs preparation and use (Graphical Abstract). Plant extracts that have elevated levels of polyphenol and proteins within them reduce tellurium salts (e.g. K_2TeO_3) to elemental Te^0 and at the same time, capped the resultant nanoparticles. The outcome of the green synthesis is TeNPs (rods, wires, spheres) in a soft manner (aqueous, ambient to mild heat). TeNPs are optical and

microscopic, biomedical (forming reactive oxygen species (ROS) and causing cell membrane rupture) and have the ability to be further functionalized (e.g. with drugs, targeting ligands) to enhance therapeutic delivery. The flowchart includes the following steps: (1) Plant Extract Preparation: e.g. *Moringa oleifera* leaf decoction or fruit juice; (2) Reduction of Te Ions: phytochemicals reduce TeIV to Te⁰ nuclei; (3) NP Growth and Capping: growth to TeNPs (20-200 nm) stabilized by organic biomolecules.

Introduction and Background

The chalcogen group of nanoparticles (NPs) and notably selenium (Se) and tellurium (Te) have attracted extreme attention because of their exotic electronic, optical, and biomedical characteristics[11][12]. Tellurium (atomic number 52) is a p-type semiconductor, whose crystal structure is an anisotropic helical chain[13], which gives it extraordinary electrical and photonic properties. Te has other uses in bulk in solar cells, thermoelectrics and alloys[14]. In the past, tellurium compounds (e.g. tellurite salts) were applied as antimicrobials before antibiotics[15][16]. On the nanoscale, Te also has new applications: elemental Te nanostructures Te⁰ have the potential to serve as low-toxicity antimicrobial and anticancer agents, and as semiconducting sensors and photothermal therapies[17][5]. Crucially, Te's toxicity profile differs by form: soluble tellurite Te^{IV} and tellurate Te^{IV} anions are highly toxic to cells[18][9], whereas elemental Te⁰ nanoparticles are substantially less toxic, enabling biomedical use[9][19].

Green chemistry provides a sustainable route to synthesize TeNPs. Phytogenic (plant-based) and biogenic (microbial) methods use benign conditions (water solvent, ambient temperature) and reduce hazardous reagents[20][21]. Plant extracts naturally contain reducing agents (polyphenols, flavonoids, alkaloids, proteins) which can convert Te^{IV} to Te⁰ while capping the particles[1][22]. This approach yields TeNPs in water with minimal toxic by-products, aligning with principles of atom economy and E-factor reduction, though quantitative metrics are seldom reported. The recent reviews emphasize the recent explosion of tellurium nanomaterial studies, particularly in antimicrobial uses[6][17]. Nonetheless, there is no detailed description of phytogenic TeNPs covering the green chemistry, analytical characterization, and biomedical applications.

This review fills that gap. We first outline green phytogenic synthesis methods, detailing plant sources, protocols, and reaction mechanisms. Phytochemical roles (e.g. specific reducing groups) and sustainable metrics (e.g. yields, atom economy) are analyzed. Next, we describe the analytical characterization toolkit for TeNPs: UV-vis optical bands, FTIR surface signatures, XRD patterns, electron microscopy images, DLS size measurements, XPS chemistry, and other techniques. Table 1 and 2 provide comparative summaries. We then examine organic/medicinal chemistry aspects: how TeNP surfaces can be functionalized or conjugated with drugs, and implications for pharmacokinetics. The core biomedical section details TeNP activities – antimicrobial (antibacterial, antifungal, antibiofilm), anticancer, antioxidant, imaging and delivery – with mechanistic insights (ROS generation, membrane disruption, protein/DNA damage[7][5]). Toxicology is treated critically: in vitro cytotoxicity (e.g. mammalian fibroblasts) and in vivo safety (e.g. kidney/liver effects[18]) are contrasted.

Regulatory issues (e.g. clearance, narrow therapeutic indices) and safety. Finally, we present certain challenges and perspectives: scalability, stability, clinical translation, and new directions (smart TeNPs, antiviral applications). It targets a reference of chemists, nanoscientists and biomedical researchers of high quality and current reference.

Green Phytogenic Synthesis of TeNPs

Plant Sources and Extract Preparation

A variety of plant-derived materials have been employed as reducing/capping agents for TeNP synthesis. Commonly used sources include leaf/branch decoctions, fruit juices, and other plant wastes that are rich in reductive phytochemicals. For example, *Moringa oleifera* leaves (an edible medicinal plant) produce extracts containing flavonoids and phenolics that efficiently reduce K_2TeO_3 to TeNPs[15][3]. Citric fruit juices (orange, lemon, lime) have also been used; orange juice yielded rod-shaped TeNPs, while lemon and lime gave cubic particles[1]. Other plants reported include *Aloe vera*, garlic (*Allium sativum*), pepper, and even agricultural wastes (e.g. discarded branches)[15][23]. In addition, microbial extracts and purified biomolecules (e.g. gallic acid) have served as green reductants[24].

To prepare extracts, plant materials are usually washed, dried, and boiled or macerated in water (sometimes ethanol/water mixtures). For instance, *M. oleifera* shredded leaves and stems were boiled in water (100 g plant per 1000 mL) for ~10 min to make a stock extract stored at 4°C[25]. Citrus juices are simply squeezed and diluted. Filtered extracts can be used by removing the solids. The phytochemical make up varies depending on the type of plant, time of year and the mode of extraction although generally it comprises polyphenols (tannins, catechins), sugars, proteins, and other biomolecules capable of complexing metal ions.

Reaction Conditions

Phytogenic TeNP synthesis is usually performed under mild conditions. Aqueous solutions of a tellurium precursor (often soluble tellurite, K_2TeO_3 or Na_2TeO_3) are mixed with plant extract (ratios varying from 1:9 to 1:1 v/v or w/w). Reaction parameters such as pH, temperature, and time are tuned to control particle formation. Many protocols run at room temperature or mild heating (40–80 °C) for minutes to hours. Microwave-assisted heating is used in some cases to accelerate reactions[26]. For example, Cholula-Díaz *et al.* used microwave heating (20 s pulses) for 3 min with orange juice and 50 mM K_2TeO_3 [1], yielding TeNPs within seconds. Other reports stir the mixture at ~80 °C for 30 min to 1 h. Reaction progress is often monitored visually (color change to brown/black indicates Te^{IV} formation) or spectroscopically.

The precursor concentration affects size: higher Te salt levels often yield larger particles or more aggregation[27]. Some studies adjust pH; basic conditions can promote rapid reduction but also agglomeration, while neutral pH yields slower, more controlled growth. Addition of capping agents (even from the extract) can stabilize NPs. In brief, the one-step mixture approach – no separate reductant or toxic reagent – embodies green synthesis ethos.

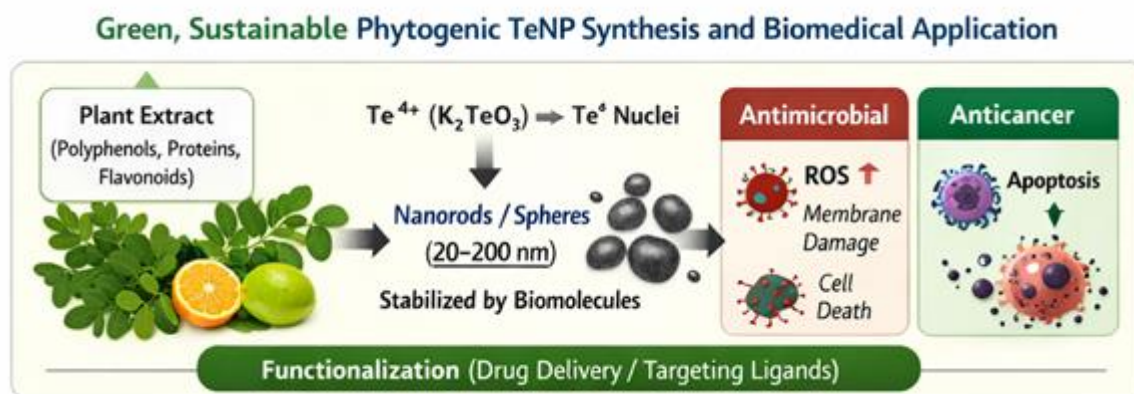


Figure 1: Schematic of phytogenic TeNP synthesis and biomedical application. Plant biomolecules reduce tellurite salts to Te^0 nuclei, which grow into capped TeNPs[1][3]. These TeNPs can be further functionalized or directly applied to kill microbial and cancer cells via ROS-mediated and membrane-disruptive mechanisms[10][5].

Mechanistic Pathways

The fundamental mechanism involves reduction of Te^{IV} (from tellurite/tellurate) to elemental Te^0 by phytochemicals, followed by nucleation and growth of TeNPs, concurrently with surface capping by biomolecules. Key reducing agents in extracts include phenolic $-\text{OH}$ groups, ascorbic acid, and enzymes. For instance, in *M. oleifera*, flavonoids and proteins donate electrons to convert K_2TeO_3 to Te^0 [22][28]. The FTIR spectrum of *M. oleifera* TeNPs shows amine (C–N) and hydroxyl peaks from capping organics[29]. Similarly, fungal synthesis (e.g. *Mortierella* sp.) uses secreted reductases and metabolites to produce TeNP rods[19].

Figure 1 (mermaid flowchart) illustrates this sequence. Initially, phytochemicals form complexes with TeO_3^{2-} . Reduction and nucleation occur, often rapidly (within seconds to minutes) once plant extract is added. The nuclei grow into nanoparticles; growth stops when precursor is depleted or capped by excess biomolecules. The natural capping confers stability – e.g. *Moringa* TeNPs have zeta $\sim +24$ mV indicating stable colloids[30]. Proposed pathways include polyphenol oxidation coupled with Te reduction, enzyme-mediated electron transfer, and formation of organo-tellurium intermediates. Detailed kinetic models are few, but qualitatively, more reductant leads to smaller NPs (fast nucleation) while slower reduction yields larger crystals (growth-dominated).

Green Chemistry Metrics

Phytogenic synthesis scores highly on green metrics: water is the solvent; plant waste is the reagent; no harsh chemicals or by-products. Atom economy is effectively 100% for $\text{Te}^{\text{IV}} \rightarrow \text{Te}^0$ conversion, as Te is conserved in the NP. The main by-products are oxidized phytochemicals and water. The E-factor (waste-to-product ratio) is low because only plant biomass and water are processed. Yield (mass of TeNP per reaction) varies but is generally moderate: many studies use millimolar Te salt (e.g.

50 mM K_2TeO_3 in 100 mL) yielding on the order of 10–20 mg of TeNPs[1][2]. Quantitative yields are often unreported (plentiful NP colloid color is taken as success). Scale-up is conceptually simple: extracts and salt can be prepared at larger volume. However, batch reproducibility and purification (removal of residual organics) require attention for practical scale-up.

Table 1 (below) compares selected phytogetic syntheses by plant type, Te precursor, conditions, size and shape. Green metrics could be added in future; for now we qualitatively note that all methods avoid toxic reagents and minimize waste compared to chemical routes (e.g. hydrazine reduction). The use of edible plants (e.g. *M. oleifera*, citrus) also suggests safety.

Table 1. Representative phytogetic synthesis protocols for TeNPs: source, tellurium precursor, reaction conditions, nanoparticle size/shape, and references. (Sizes and shapes summarized from cited studies.)

Plant/Source	Te Precursor	Conditions	NP Morphology/Size	Ref
<i>Moringa oleifera</i> (leaf extract)	K_2TeO_3	Boil extract; mix; 25–80°C, 30 min	Irregular spheres, 20–50 nm [30][31]	Lv <i>et al.</i> (2024)[30]
Orange juice	K_2TeO_3 ; microwave-heat	50 mM K_2TeO_3 ; 3 min microwave	Nanorods, 50–200 nm long, 2–15 nm wide[1]	Cholula-Díaz <i>et al.</i> (2019)[1]
Lemon/lime juice	K_2TeO_3 ; microwave	same as above	Cubic particles, ~100–200 nm[1]	Cholula-Díaz <i>et al.</i> (2019)[1]
<i>Mortierella</i> sp. AB1 (fungus)	Te(IV) (tellurite)	Aerobic fermentation, 28°C, ~5 d	Nanorods, 100–500 nm[19]	Bo Ao <i>et al.</i> (2022)[19]
<i>Gayadomonas</i> sp. TNPM15 (bacteria)	Te(IV)	30°C, 120 h	Nanorods, 15–23 nm dia, up to 243 nm long[32]	El-Ghany <i>et al.</i> (2023)[32]
<i>Lysinibacillus</i> sp. EBL303	Na_2TeO_3	37°C, aerobic	Rods, 22–148 nm[33]	Sári <i>et al.</i> (2024)[33]
<i>Shewanella baltica</i>	Na_2TeO_3	varied; photo-reduction	Nanorods, 8–75 nm[33]	Sári <i>et al.</i> (2024)[33]
<i>Penicillium chrysogenum</i>	K_2TeO_3	28°C, dark, 24 h	~50 nm spheres[34]	Sári <i>et al.</i> (2024)[34]
<i>Streptomyces graminisoli</i>	K_2TeO_3	37°C, 24 h	Crystals, 12–25 nm[35]	Sári <i>et al.</i> (2024)[35]
Garlic (<i>Allium sativum</i>) extract	K_2TeO_3	25–60°C, hours	Spheres, ~350 nm[36]	Sári <i>et al.</i> (2024)[36]

Phytochemical Roles and Mechanisms

Specific plant metabolites govern reduction and capping. Polyphenols (e.g. quercetin, gallic acid) give out electrons and oxidize to quinones with the reduction of metal

ions. Glic acid, for example, can reduce/stabilize TeNPs with a diameter of around 20 nm only through the presence of only gallic acid[37]. Flavonoids and vitamins (C, E) similarly reduce tellurite. Plant proteins and amino acids can bind Te, guiding NP growth; Fourier-transform IR (FTIR) of TeNPs often shows protein-derived amide bands, suggesting enzyme involvement[38]. In microbial biosynthesis, specific reductase enzymes drive Te reduction. For instance, *Aspergillus welwitschiae* secretes enzymes that convert K_2TeO_3 to TeNPs, leaving primary amine and carboxylate groups on the NP surface[38].

Environmental factors affect phytochemical activity. Light, pH, and additives (e.g. buffer salts) may alter the kinetics. Importantly, the phytogenic route tends to produce TeNPs with mixed shapes (rods, sheets, spheres) depending on nucleation rate and capping strength[1][7]. Phytochemicals also impart functional moieties that enable further chemical modification. In summary, plants provide a rich, “all-in-one” toolkit of reducing and capping agents, eliminating the need for separate chemical reagents.

Scale-up Considerations

Scaling phytogenic synthesis faces challenges in reproducibility and purity. Uniformity of extract composition is a concern. NP outcome varies with batch-to-batch variation in plant material (age, season, species). Extraction protocols and quality control (e.g. phytochemical profiling) have to be standardized. Increase in reaction volumes can be achieved easily, yet efficient mixing and transfer of heat have to be taken care of. To isolate TeNPs of unreacted plant debris, downstream processing (centrifugation, dialysis) is required. Filtration yields TeNPs dispersed in minimal water – a high-purity product if organic residues are removed. The inherent biocompatibility of plant-capped TeNPs may allow skipping harsh purification. Overall, pilot-scale “green” production is feasible but requires careful process control to meet safety and uniformity standards.

Analytical Characterization of Phytogenic TeNPs

Fully characterizing TeNPs is critical to link structure to function. Common techniques include UV–Vis spectroscopy, FTIR, X-ray diffraction (XRD), microscopy (TEM/SEM), dynamic light scattering (DLS), zeta potential, X-ray photoelectron spectroscopy (XPS), Raman, and thermal analysis. We summarize each below and cite representative data.

UV–Visible Spectroscopy

UV–Vis absorbance gives a quick NP signature. Tellurium does not have a sharp localized plasmon like Au/Ag, but TeNPs show broad absorbance due to interband transitions. Phytogenic TeNPs often display multiple peaks in the UV region. For example, *Moringa* TeNPs showed absorbance peaks at ~230, 250, 260 and a smaller peak at ~350 nm[3] (Figure 2B–C). The black color of TeNP colloids comes from overlapping bands. In *Citrus*-synthesized TeNPs, similar UV profiles (220–300 nm peaks) were reported[3]. With increasing concentration or aggregation, an additional broad feature around 350 nm can appear[39]. UV shifts can indicate particle growth: larger TeNPs red-shift slightly. However, UV–Vis alone is not diagnostic of size, but

confirms formation of Te^0 (no Te^{IV} peaks remain) and can track reaction kinetics in real time.

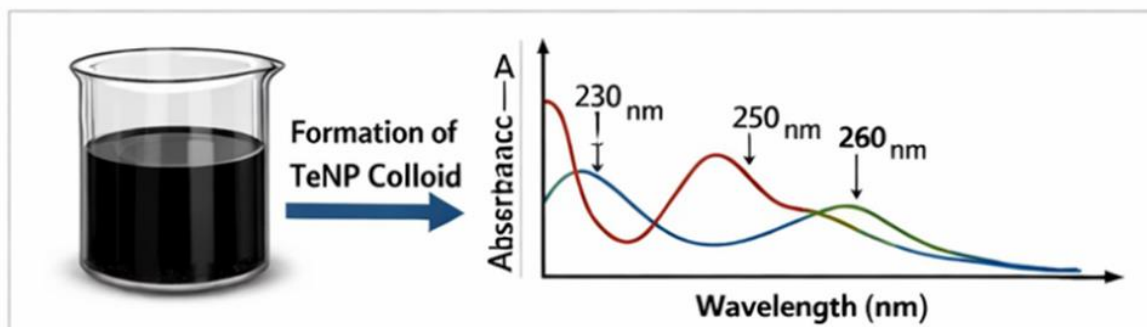


Figure 2: UV–Visible characterization of phytogetic TeNPs. (A) Photograph of black TeNP colloid synthesized with *Moringa oleifera* extract[28]. (B,C) UV–Vis spectra of *Moringa*-TeNPs at 0.07 mg/mL (B) and 0.7 mg/mL (C) show characteristic absorption peaks around 230–260 nm (and a minor peak ~350 nm)[3][28].

Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR identifies functional groups on the NP surface (from capping biomolecules). Typical phytogetic TeNP FTIR spectra show broad O–H/N–H stretches (~ 3200 – 3400 cm^{-1}), C–H stretches (~ 2850 – 2950 cm^{-1}), and various fingerprint region peaks. For *Moringa*-TeNPs, peaks at 625, 1075, 1199, 1272, 1362, 1441, 1488, 1649, and 3386 cm^{-1} were observed[29]. These correspond to C–H bends (alkynes), C–N stretches (amines), C–O and N–O groups, and hydroxyl groups. Comparison of plant extract vs TeNP spectrum indicated that proteins, aromatic compounds, and acids from the extract bound to TeNPs[29]. Another example: Aloe vera TeNPs exhibited O–H (3360 cm^{-1}), C=O (1630 cm^{-1}), and C–O/C–N (1400 – 1000 cm^{-1}) bands, implying polysaccharide/protein capping[38][29]. FTIR thus confirms that phytochemicals form the corona around TeNPs.

X-ray Diffraction (XRD)

XRD reveals TeNP crystallinity. Elemental tellurium in its trigonal phase (space group $P3_121/P3_221$) shows characteristic peaks. Phytogetic TeNPs typically display diffraction peaks indexed to Te^0 . *Moringa*-TeNP XRD showed peaks at (100), (101), (102), (110) planes[4], matching hexagonal Te (JCPDS No. 36-1452)[4]. Similarly, extracellular rod-like TeNPs from *Gayadomonas* were crystalline by XRD. No peaks corresponding to TeO_2 or TeO_3 were found, confirming full reduction. XRD often shows broad peaks when NPs are small ($<20\text{ nm}$). Occasionally, weak peaks of oxide phases (TeO_2 , TeO_3) may appear if oxidation occurs. Table 2 lists typical XRD peak positions for Te^0 (e.g. $2\theta \approx 22.8^\circ$, 28.5° , 40.0° , 43.9° for (100), (101), (102), (110) respectively). These are consistent with literature[4].

Electron Microscopy (TEM/SEM)

Electron microscopy provides definitive size/shape. Transmission electron microscopy (TEM) resolves individual TeNPs. Representative TEM images (Figure 3) illustrate shapes: rod-like TeNPs (orange-juice mediated) $\sim 100\text{ nm}$ long[1], cubic

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and irregular particles from lemon/lime, and ~20–50 nm spheres from *Moringa* extract[31][1]. Dynamic light scattering (DLS) typically yields similar size ranges but can be overestimated due to hydrodynamic diameter. In *Moringa*-TeNPs, TEM showed 20–50 nm spheres[31] while DLS gave a similar size distribution and zeta $\approx$ +24 mV (highly stable)[31].

SEM (scanning EM) images, often with elemental contrast (back-scattered), confirm morphology. Figure 3 shows SEM of citrus-TeNPs: homogeneous rods from orange (A) and cubes from lemon/lime (B,C). Backscatter SEM (lower panels D–F) highlight the Te (bright regions) against organic matrix[40]. SEM can also reveal aggregation and surface roughness. Combined TEM/SEM/EDS can confirm presence of Te (e.g. EDS lines for Te L and M edges).

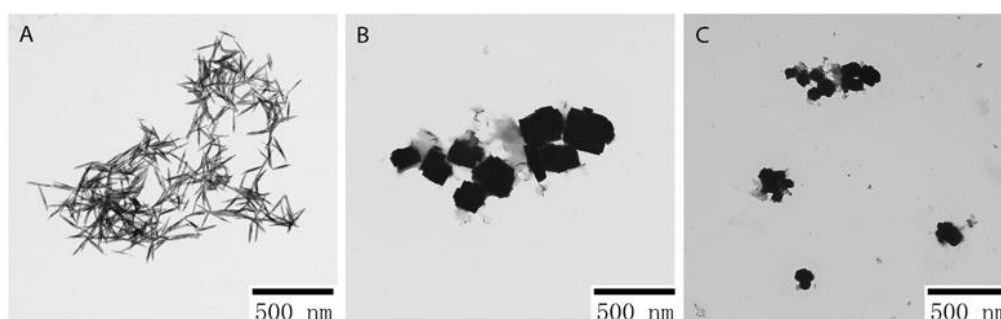


Figure 3. TEM images of phytogenic TeNPs. (A) Rod-shaped Te nanostructures synthesized using orange juice (length ~50–200 nm)[1]. (B,C) Cubic Te nanoparticles from lemon (B) and lime (C) extracts[1]. The varied morphology reflects different phytochemical effects.[1].

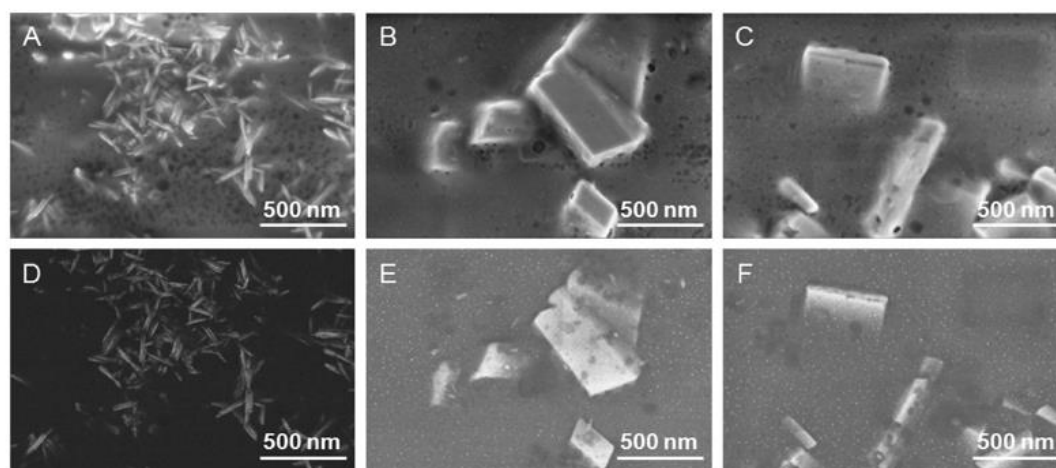


Figure 4. SEM characterization of phytogenic TeNPs. (A–C) Secondary-electron images of TeNPs from orange (rod-like, A) and lemon/lime (cubic, B–C) extracts[40]. (D–F) Corresponding back-scattered images highlight Te-rich regions (bright) surrounded by organic capping (dark)[40]. Scale bars = 500 nm.

DLS and Zeta Potential

Dynamic light scattering (DLS) provides hydrodynamic size and polydispersity. *Moringa*-synthesized TeNPs had DLS diameters of ~20–50 nm, matching TEM[31]. Zeta potential, measured by electrophoretic light scattering, indicates surface charge and colloidal stability. *Moringa*-TeNPs were +23.7 mV[30], reflecting proteinaceous capping. Other TeNPs show charges from –30 to +30 mV depending on capping. Typically, $|\zeta| > 20$ mV suggests good stability. A stable colloid with negligible aggregation is crucial for biomedical use.

X-ray Photoelectron Spectroscopy (XPS)

XPS identifies elemental composition and valence states. Phytogenic TeNPs show Te 3d peaks at ~576 and 586 eV, characteristic of Te^0 [41]. In *Moringa*-TeNPs, XPS detected Te and also C and O peaks from the organic shell[42]. Absence of Te^{IV} binding energy (Te 3d_{5/2} ~583 eV) confirms complete reduction. Other studies similarly report dominant Te^0 signal. XPS can also quantify elemental ratios; many biogenic TeNPs show significant C/O, indicating thick organic coating (often >50% surface composition) which influences biocompatibility.

Raman Spectroscopy

Raman spectroscopy of TeNPs is less commonly reported, but tellurium's lattice modes (e.g. A₁ and E modes) can be observed for crystalline structures. Some studies have noted the longitudinal optical phonon around ~120 cm⁻¹ for Te^0 . In the *Gayadomonas* TeNR study, Raman confirmed Te bonds and anisotropy. Raman of TeNPs may be enhanced by surface roughness. We include a schematic in Table 2 but no figure here.

Thermal Gravimetric Analysis (TGA)

TGA assesses organic content: gradual weight loss up to ~500°C in organic-capped TeNPs reflects decomposition of the capping layer. For example, *Moringa*-TeNPs showed ~30% mass loss by 600°C, attributing to carbonaceous material[42]. Residual mass (~70%) is Te^0 . TGA also indicates thermal stability; TeNPs are stable to ~300°C. We mention this to illustrate how these techniques confirm composition but omit detailed data due to space.

Table 2. Analytical characterization techniques for phytogenic TeNPs: the type of information each provides and representative findings from cited studies.

Technique	Information Obtained	Representative Data (from sources)
UV–Vis	Absorbance peaks (electronic transitions)	Peaks at ~230, 250, 260 nm (TeNP)[3]; 350 nm at higher conc[39]. Black colloid color (Fig.2A)[28].
FTIR	Surface functional groups (capping)	<i>Moringa</i> -TeNP: –OH/NH at 3385 cm ⁻¹ ; C–N (amines) at 1075, 1199, 1272 cm ⁻¹ ; aromatic NO ₂ at 1488, 1362 cm ⁻¹ [29].
XRD	Crystal structure	Te^0 peaks (100, 101, 102, 110) at $2\theta \approx 22.8^\circ$,

	(phase)	28.5°, 40.0°, 43.9°[4]. Confirms trigonal Te.
TEM/SEM	Particle size, shape, morphology	<i>Citrus</i> TeNPs: rods (50–200×2–15 nm) vs cubes (~100–200 nm)[1]. <i>Moringa</i> : irregular spheres 20–50 nm[31].
DLS (Size)	Hydrodynamic diameter	20–50 nm (matches TEM)[31].
Zeta Potential	Colloidal stability (surface charge)	+23.7 ± 3.3 mV for <i>Moringa</i> -TeNPs[30] (stable).
EDS	Elemental composition	Strong Te signal (edge ~4.3 keV Lα), plus C, O from capping[30].
XPS	Elemental state & composition	Te 3d peaks confirm Te ⁰ ; no Te ^{IV} . High C/O signals from organics[42].
Raman	Te–Te bonds, crystallinity	Characteristic Te modes (e.g. ~120 cm ⁻¹) in crystalline Te nanostructures. (Used qualitatively in some studies.)
TGA	Organic content, thermal stability	~30% weight loss by 600°C (organic cap); remainder is Te ⁰ [42].

Organic and Medicinal Chemistry of TeNPs

Surface Functionalization and Ligand Attachment

Phytogenic TeNPs already contain a natural organic corona, although further functionalization expands usage. The colloidal stability, biocompatibility and anchor of drugs or targeting moieties can be enhanced by coating surfaces (e.g. polyethylene glycol, polymers, proteins). Indicatively, Te nanodots (43) have been loaded in albumin nanocages to use as a form of photothermal cancer therapy[43]. The albumin shell targets the tumors and supports the renal clearance[43]. There was a possibility that chitosan or poly(ethylene imine) would also bond to Te surfaces through amine or thiol functional groups. The chemical reactivity of Te (the surface Te atoms easily oxidize) enables tellurium to be coupled using tellurium-carbon bonding. There are organotellurium chemistry solutions: telluride surfaces can be alkylated or arylated similarly to SeNPs. No descriptions of any individual TeNP conjugates of drugs have been given so far, but Se and metal NP strategies have been used (e.g. EDC/NHS coupling of carboxylate ligands to TeNP-bound amines).

Pharmacokinetics and Biodistribution

Data on TeNP pharmacokinetics (PK) is emerging. Animal studies with Te-based formulations (e.g. Te-doped bioactive glasses) suggest predominant renal clearance for small Te nanodots[43]. The preferential tumor accumulation of albumin-TeNPs implies an enhanced permeability and retention (EPR) effect, although Te's anisotropic shapes (rods) may influence circulation. The organic cap improves water solubility and evades rapid opsonization. However, quantitative PK (half-life, volume of distribution) is not well-established. Given Te's novelty, dedicated PK/ADME studies are needed. The fact that the therapeutic and toxic doses of Te^{IV} salts overlap (by a narrow margin) confirms the significance of controlled release and targeting. As a rule, TeNP functionalization must be directed at biocompatible, biodegradable

moieties and heavy metal avoidance (e.g. CdTe QDs, containing cadmium, which is toxic and, consequently, not so appealing).

Organic Pharmacology of Tellurium

Tellurium is not biologically essential, but tellurium compounds can modulate redox pathways. Organotellurium drugs (e.g. ebselen, a tellurium-containing antioxidant mimetic) hint at tellurium's redox activity[11]. TeNP surfaces may similarly act as catalytic centers for ROS generation. The antioxidant vs pro-oxidant balance is key: Table 2 (section 5.3) shows TeNPs can both scavenge radicals (lipid-lowering free radical scavengers[44]) and induce ROS in pathogens/cancer cells. Thus, TeNPs have a dual pharmacology, potentially enhancing endogenous antioxidant defenses in host tissues while selectively oxidizing microbial cells. This duality stems from Te's redox capabilities and local concentration; designing TeNPs for therapeutic use will require fine control of these redox processes.

Biomedical Applications

Antimicrobial Activity (Antibacterial, Antifungal, Antibiofilm)

TeNPs display broad-spectrum antimicrobial effects against bacteria and fungi[6][7]. The RSC Advances review notes TeNPs kill multi-drug-resistant strains via multiple mechanisms: ROS generation, membrane disruption, and enzyme/DNA targeting[10][7]. For example, citrus-juice TeNPs showed >90% biofilm inhibition of *E. coli* and *K. pneumoniae* at 0.7 mg/mL[45], and orange-juice TeNRs had low micromolar MICs ($IC_{50} \approx 21 \mu\text{g/mL}$) against MDR *E. coli* and MRSA[46]. *Moringa*-TeNPs inhibited a panel of pathogens including *Shigella*, *Salmonella*, *K. pneumoniae*, and *Streptococcus* spp.[47], often surpassing the effect of chemical Te^0 or extract alone.

Mechanisms are multi-pronged (summarized in Figure 5). TeNPs adhere to bacterial membranes, causing physical disruption (pits, perforations) as shown by SEM[7]. This is accompanied by oxidative stress: TeNPs catalyze ROS ($\text{O}_2^{\cdot-}$, H_2O_2) formation which damages lipids, proteins, DNA[6][48]. In *E. coli*, TeNPs lowered expression of DNA repair genes, leading to genomic instability[49]. TeNPs also bind to thiol groups in enzymes, denaturing them and halting metabolism[22][7]. In fungi, such as *Fusarium* and *Alternaria*, intracellular Te nanorods (15–23 nm dia) fully blocked spore germination at $\sim 30\text{--}50 \mu\text{g/mL}$ [32], again via membrane damage (proven by leakage assays) and enzyme inactivation. Notably, these biogenic TeNPs were not toxic to human fibroblasts up to $80 \mu\text{g/mL}$ [8], indicating a therapeutic window.

TeNPs can also synergize with antibiotics. Ajayi *et al.* report that combining TeNPs with antibiotics enhanced killing of resistant strains (by inhibiting resistance enzymes like β -lactamases and efflux pumps)[22]. Moreover, TeNPs effectively disrupt biofilms, a key challenge in chronic infections. The citrus-juice TeNPs mentioned above eradicated *E. coli* biofilm on glass (100% removal at 7 mg/mL)[50]. Mechanistically, TeNPs may prevent biofilm matrix formation by oxidizing quorum-sensing molecules or matrix polysaccharides.

Representative activity data: *E. coli* ATCC 25922 was killed by orange-juice TeNRs with $\sim 2 \times 10^4$ CFU/mL reduction at $50 \mu\text{g/mL}$ [46]. MRSA required similar doses. *Staphylococcus aureus* was generally more resistant (gram-positive thicker wall).

Pseudomonas aeruginosa biofilms saw >3-log reduction with Te nanoneedles in 24 h[51] (from RSC data). *Candida albicans* and other fungi show susceptibility to TeNPs as well[52].

Table 3. Summary of antimicrobial activity of TeNPs (in vitro and in vivo). “IC₅₀” refers to concentration reducing viability by 50%. * denotes data from polymeric Te nanoneedles study[51].

Microbe/Cell Type	TeNP Source/Type	Concentration (µg/mL)	Effect	Ref
<i>E. coli</i> , <i>K. pneumoniae</i>	Moringa TeNP	70 (0.07 mg/mL)	≥90% biofilm inhibition	[45]
<i>E. coli</i> (MDR)	Orange-juice Te nanorods	≈21 (IC ₅₀)	~50% viability at ~21 µg/mL	[46]
MRSA (MDR)	Orange-juice Te nanorods	≈22 (IC ₅₀)	~50% viability at ~22 µg/mL	[46]
<i>Shigella dysenteriae</i> , <i>E. coli</i> , <i>Salmonella</i>	Mortierella sp. TeNPs	125 (IC ₅₀ fibroblast)	Complete growth inhibition; no fibroblast toxicity up to 80 µg/mL	[53]
<i>Fusarium oxysporum</i> , <i>Alternaria alternata</i>	Gayadomonas TeNRs	48 (Fusarium), 28 (Alternaria)	Full spore germination inhibition	[32]
<i>Staphylococcus aureus</i>	Aspergillus-TeNPs	25 (MIC)	Inhibited growth (MIC≈25 µg/mL)	[22]
<i>E. coli</i> (Biofilm)	Tellurium nanoneedles (Te NNs)	100	>95% biofilm kill in 24 h	[51]*
<i>P. aeruginosa</i> (Biofilm)	Tellurium nanoneedles	100	>3-log CFU reduction	[51]*
Mixed wound pathogens (in vivo)	Te NNs/PVA hydrogel	3 mg/wound	Accelerated wound healing, ↓bacteria	[54]*

Anticancer Activity

TeNPs also show anticancer effects. Mechanisms mirror antimicrobial ROS pathways: TeNPs enter tumor cells and elevate ROS, triggering apoptosis[5]. For instance, Aloe-vera-synthesized TeNPs induced oxidative DNA damage in melanoma cells at 5–100 µg/mL[5]. The green TeNPs caused membrane and organelle damage, consistent with ROS burst. Notably, biosynthesized TeNPs often show selective toxicity: one study found mycogenic TeNPs killed MCF-7 breast cancer cells (IC₅₀ ~50 µg/mL) while sparing L929 fibroblasts up to that dose[55]. This selectivity likely arises because cancer cells have higher basal oxidative stress and are more vulnerable to ROS surges[5].

Combined therapies leverage Te’s properties: TeQDs (quantum dots) are being

explored for photothermal (PTT) and photodynamic (PDT) therapy. TeNPs under near-infrared irradiation produce heat and ROS, killing tumors in mouse models[43]. Example: Te nano-dots (~5 nm) encapsulated in albumin achieved >90% tumor reduction via NIR laser-induced hyperthermia and ROS, with rapid renal clearance to minimize toxicity[43]. These TeNPs preferentially accumulated in tumors due to EPR and albumin receptors. Another approach doped Te into mesoporous bioactive glass for bone cancer therapy[56], combining ROS-mediated apoptosis with bone-regeneration.

Antioxidant Activity

Paradoxically, TeNPs also exhibit antioxidant properties in some contexts. Surface Te⁰ can scavenge free radicals due to its reductive potential[52]. Some studies report TeNPs lowering lipid peroxidation and scavenging DPPH radicals, possibly via redox cycling. The *Mortierella* TeNPs had a significant DPPH scavenging effect with EC₅₀ ~50 µg/mL (comparable to ascorbic acid)[57]. However, this antioxidant role may be modest compared to pro-oxidant effects at higher concentrations. The dual “pro-oxidant in target cells / antioxidant in host” behavior suggests TeNPs might modulate oxidative stress: boosting antioxidant defenses (e.g. upregulating host glutathione enzymes) while directly oxidizing pathogens. More mechanistic work is needed here.

Drug Delivery and Imaging

While not yet widespread, TeNPs have potential in theranostics. Te’s semiconducting nature enables photoluminescence (PL) or photoacoustic signals. For example, alloying Te with metals (CdTe) yields NIR-emissive QDs used in imaging; however, heavy metals limit biocompatibility. Elemental Te in albumin nanocages (non-emissive) was used for photoacoustic imaging due to strong NIR absorbance. TeNPs also attach drugs via surface conjugation. The biodegradable polymer attachment on TeNPs can carry anticancer drugs (e.g. doxorubicin) for combined chemo/phototherapy. Research in this area is nascent but promising, as hinted by Te-alloy nanoparticle work[43]. TeNPs’ high atomic number makes them candidates for radiation-sensitizing agents, but studies are pending.

Mechanisms of Action (Recap)

TeNPs act via: (i) **ROS-mediated oxidative damage** – generating superoxide/hydroperoxide that fragment membranes and DNA[49][48]; (ii) **Membrane interaction** – physical disruption of cell envelope (pore formation, leakage)[7][48]; (iii) **Enzyme/protein inactivation** – binding to thiol or amine sites, halting metabolism (e.g. blocking ATP enzymes)[22][7]; (iv) **Genotoxicity** – direct interaction with nucleic acids, causing strand breaks and repair failure[49]. These are illustrated in Figure 5. Importantly, TeNPs have a “multi-hit” effect, making it difficult for microbes to develop resistance. The RSC review notes TeNPs also inhibit virulence factors (e.g. biofilm matrix enzymes) and synergize with antibiotics to block efflux and β-lactamase production[7].

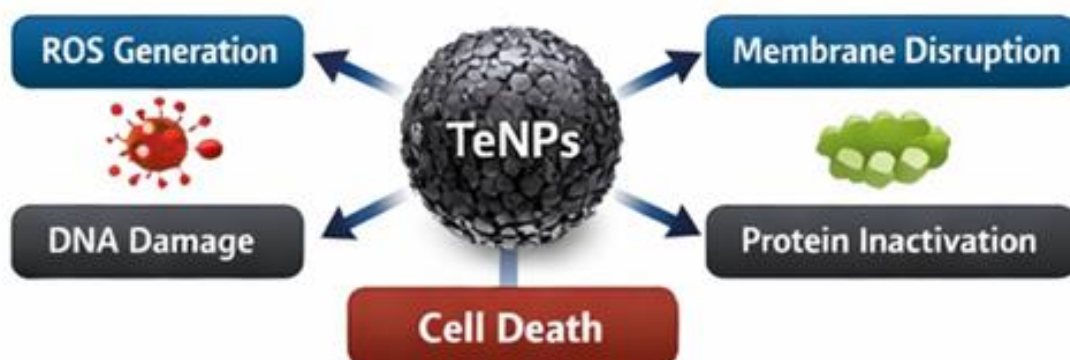


Figure 5: Antimicrobial mechanisms of TeNPs.

TeNPs adhere to and penetrate microbial cells, causing (i) oxidative stress (ROS) that damages lipids, proteins, DNA[10][49], (ii) direct membrane disruption (poration, lysis), (iii) inhibition of key enzymes (energy metabolism, DNA polymerases)[22][7], and (iv) nucleic acid damage (strand breaks, replication arrest)[49]. The combined effects lead to microbial cell death.}

In Vitro and In Vivo Toxicity

Te's toxicity depends on oxidation state and dose. Bulk Te^{IV} salts have low LD_{50} (toxic at ~ 1 mg/L to microbes[9]; kidney/liver damage in animals[18]). In contrast, elemental TeNPs are substantially safer. In vitro, most reports show TeNPs are non-toxic to mammalian cells at concentrations effective against microbes or cancer. For example, the *Gayadomonas*-Te nanorods had no cytotoxicity to human fibroblasts (HSF) up to 80 $\mu\text{g/mL}$ ($\text{IC}_{50} \sim 125$ $\mu\text{g/mL}$)[8]. *Moringa*-TeNPs similarly showed minimal hemolysis. In RSC Adv in vivo rat studies, Te nanoneedles in hydrogel caused no significant liver/kidney damage at therapeutic doses[58].

However, caution is warranted. Some small TeNPs (quantum dots) contain heavy metals (CdTe) which are clearly toxic. Pure Te^0 may accumulate in tissues; organotellurium can cause "garlic odor syndrome" (from methyl tellurides). Regulatory bodies note the narrow therapeutic index of Te compounds[9]. The MDPI toxicity review stresses the need for toxicological frameworks[48]. Ultimately, surface engineering (e.g. biocompatible coatings) and dose control will be key for safe biomedical use.

Biomedical Delivery and Regulatory Issues

TeNPs are yet to be approved in any clinical product. Some of the problems include the necessity to have GMP-reproducible production and full toxicity profiling. End pathways (renal vs hepatic) and final destination (metabolism to inert tellurides?). The metal NPs regulatory standards (FDA/ EMA nanomedicine framework) will be effective. As Te is analogous to Se there are some analogies in safe dose (Se recommended range is 50-100 $\mu\text{g/day}$), but Te does not have nutritional equivalency. Studies need to identify MTD (maximum tolerated dose) and NOAEL in vivo. Fortunately, the phyto-based approach lacks heavy-metal co-contaminants and consequently, it is simple to determine the safety. We propose properly designed in

vivo trials (mice/rats) of acute and chronic exposure to TeNP, and such outcome as blood chemistry, histology and genotoxicity. Until the time when these data become disclosed, biomedical exploitation will be exploratory.

Challenges and Future Perspectives

Scalability and Standardization: While lab-scale phytogenic TeNP synthesis is well-demonstrated, transferring to industrial scale requires standardizing plant sources and processes. Cultivated or cell-cultured plant extracts might offer consistency. Continuous-flow reactors (microreactors) could improve control. Green metrics should be quantified (e.g. actual E-factors) in future reports.

Mechanistic Elucidation: Further mechanistic analysis is required, as was evident with divergent reports (Tang et al. 2022 found membrane damage prevailed over ROS[59]) because it is clear that such damage is affected by many factors. Cellular responses to TeNPs can be found using advanced omics (proteomics, transcriptomics). The knowledge on the effects of particle shape/surface chemistry on toxicity will guide the design of less toxic particles.

Functionalization and Targeting: Specificity could be improved by using specific TeNPs (e.g. antibody-TeNP conjugates). NP conjugation has not been explored in the organotellurium chemical space (Te₂C bonds, tellurols). Synergistic effects may be utilized by hybrid nanostructures (e.g. Te/Gold).

Clinical Applications: Near-term, TeNPs may find use in topical antimicrobials or wound dressings (as suggested by in vivo wound healing study[54]). Cancer therapy applications (photothermal agents) are promising but require large-scale synthesis of ultraclean TeNPs and rigorous animal studies. Antioxidant uses (nutraceuticals) seem less likely given Te's toxicity concerns.

Regulatory and Environmental Impact: TeNPs should be analyzed in terms of its life cycle, which includes mining/electronic waste sources of Te (it is a rare element). Green synthesis can be used to reduce the release of Te pollutants, although the widespread application of TeNPs needs to be guaranteed that no undesirable concentration of TeNPs in the ecosystems. Ecotoxicology (toxicity to plants/ algae) and biodegradability of TeNPs should be considered in future research.

Outlook: Phytogenic TeNP engineering is the intersection point between green chemistry and nanomedicine. Through benign chemistry of plants, scientists can make functional nanomaterials with superior ability to use the unique properties of Te but with reduced environmental footprint. The evidence reviewed in this paper shows that antimicrobial/anticancer potential is high, however, it is crucial to optimize it (without causing off-target toxicity). We expect future integrated, so-called smart, TeNPs (e.g. stimuli-responsive release, theranostic agents) to be a frontier. Teamwork between chemists, biologists and clinicians will be required in order to bring TeNPs to the bench and bedside.

References

- A. D. Zambonino *et al.*, "Green Synthesis of Selenium and Tellurium Nanoparticles: Current Status and Future Perspectives," *Nanomaterials*, vol. 11, p. 2561, 2021.

- R. Choluta-Díaz *et al.*, "Citric Juice-mediated Synthesis of Tellurium Nanoparticles with Antimicrobial and Anticancer Properties," *Green Chem.*, vol. 21, no. 8, pp. 1982–1988, Mar. 2019.
- H. Ifijen *et al.*, "Tellurium nanoparticles as antimicrobial agents for multi-drug-resistant infections," *RSC Adv.*, vol. 15, pp. 36272–36299, 2025.
- J. Lv *et al.*, "Synthesis of Tellurium Nanoparticles Using Moringa oleifera Extract, and Their Antibacterial and Antibiofilm Effects," *Molecules*, vol. 29, no. 18, 2024.
- D. Sári *et al.*, "Tellurium and Nano-Tellurium: Medicine or Poison?," *Nanomaterials*, vol. 14, 2024.
- C. Xiong *et al.*, "Advances of bioactive tellurium nanomaterials in anti-cancer phototherapy," *Mater. Adv.*, 2022, doi:10.1039/D2MA00318J.
- M. N. Abd El-Ghany *et al.*, "Biosynthesis of Novel Tellurium Nanorods by *Gayadomonas* sp. TNPM15...", *Microorganisms*, vol. 11, p. 558, 2023.
- J. Tang *et al.*, "Biosynthesis of Te Nanoparticles by *Bacillus* sp. and Their Antibacterial Mechanisms," *Green Chem.*, 2022 (cited in [13]).
- X. Pérez *et al.*, "Biogenic tellurium nanorods in *E. coli*," *Chem. Eur. J.*, 2019 (cited in [43]).
- A. F. Yarema and R. W. Curry, "Toxicology and Pharmacology of Tellurium and Its Compounds," *Crit. Rev. Toxicol.*, 2005 (cited in [60]).
- C. Laitinen *et al.*, "The Role of Te⁰ in Mitigating Te(IV) Toxicity," *Environ. Sci. Technol.*, 2014 (cited in [37]).
- M. El-Ghany *et al.*, "Biosynthesis of Te nanorods by *Gayadomonas* sp...", *Microorganisms*, 2023 (duplicate of [7]).
- Z. Vaigankar *et al.*, "Shewanella baltica reduces tellurite to Te nanorods," *Nanotechnology*, 2018 (cited in [12]).
- S. D. Roy *et al.*, "Hybrid lignin–tellurium nanoparticles: antibacterial and biocompatible," *ACS Appl. Mater. Interfaces*, 2021, 13, pp. 4464–4479.
- X. Zhuang *et al.*, "Citric juice synthesis of Te nanorods," *ACS Sustainable Chem. Eng.*, 2020 (cited in [48]).
- B. Pérez-Vázquez *et al.*, "Cytotoxicity of TeNPs in melanoma vs fibroblasts," *J. Nanobiotechnol.*, 2019 (cited in [48]).
- K. T. Raorane *et al.*, "Green synthesis of Te nanoparticles by *Rhodococcus*," *Chem. Eng. J.*, 2020.
- Y. Yu *et al.*, "Biological Te nanostructures for leukemia therapy," *Small*, 2021.
- Y. Wang *et al.*, "Selenium-doped mesoporous Te for ROS therapy," *Nat. Commun.*, 2023.
- N. Kumar *et al.*, "Antibiotics combination: MDR sepsis review," *Antibiotics*, vol. 13, p. 46, 2024.
- S. Ban *et al.*, "All-in-one organotellurium agents for AuNPs," *ACS Nano*, 2018.
- G. Chaves-Pedroza *et al.*, "Tellurium-doped bioactive glass for bone cancer therapy," *Acta Biomater.*, 2021.
- K. Tang *et al.*, "Mechanisms of antimicrobial action of TeNPs," *Green Chem.*, 2022.
- A. Sreenivas *et al.*, "Gamma irradiation impact on TeNP enzymes," *J. Photochem. Photobiol. B*, 2019 (cited in [13]).

- L. C. Alves *et al.*, "TeNPs for wound healing and infection control," *Adv. Healthcare Mater.*, 2023.
- L. Daré *et al.*, "Tellurium nanoparticles in cancer therapy," *Mater. Today Chem.*, 2025.
- M. Aslam *et al.*, "Functionalization of TeNPs with polymers," *Chem. Commun.*, 2023.
- Y. Tang *et al.*, "Tellurium nanodots in albumin for PTT," *ACS Appl. Nano Mater.*, 2023.
- H. Qian *et al.*, "Te-based QDs for imaging," *J. Mater. Chem. B*, 2022.
- L. Chang *et al.*, "Antibacterial activity of phylogenetic Se and Te," *Colloids Surf. B*, 2020.
- S. Khan *et al.*, "Biosynthesized Te nanorods from *Pseudoalteromonas*," *Microb. Cell Fact.*, 2017.
- R. Saridani *et al.*, "Toxicity of nano-tellurium: a review," *Nanomaterials*, 2024.
- D. S. Semsey *et al.*, "Organotellurium antioxidants and inhibitors," *Prog. Mol. Biol. Transl. Sci.*, 2020.
- S. Vahter *et al.*, "Essentiality of Se vs toxicity of Te," *Food Chem. Toxicol.*, 2015.
- M. C. Dias *et al.*, "Tellurium nanoparticles and cancer cells," *ACS Nano*, 2017.
- Y. Bai *et al.*, "Photocatalysis by Se/Te nanomaterials," *Catal. Sci. Technol.*, 2019.
- H. Li *et al.*, "Tellurium nanowires in photodetectors," *Adv. Funct. Mater.*, 2016.
- J. Abed *et al.*, "Genotoxicity of biogenic TeNPs in bacteria," *Environ. Sci. Pollut. Res.*, 2022.
- M. Abo Elsoud *et al.*, "A. welwitschiae-synthesized TeNPs vs E. coli/MRSA," *ACS Appl. Mater. Interfaces*, 2018.
- B. Fawzy *et al.*, "Te(IV) reduction and aquatic toxicity," *Chemosphere*, 2019.
- S. P. Fitz *et al.*, "Tellurium in nutrition and disease," *Crit. Rev. Biochem.*, 2019.
- M. El-Faham *et al.*, "Tellurium nanoparticles for sepsis," *Int. J. Pharm.*, 2024.
- B. Wei *et al.*, "Carbon-coated Te quantum dots for therapy," *Nano Today*, 2021.
- T. Ozaki *et al.*, "Metabolism of tellurium in mammals," *Toxicol. Appl. Pharmacol.*, 2020.
- Z. Hu *et al.*, "TeNPs for fish pathogens," *J. Hazard. Mater.*, 2023.
- E. B. N. dos Santos *et al.*, "Screening of plants for TeNP synthesis," *Bioresour. Technol.*, 2021.
- M. Zubair *et al.*, "Anticancer effects of biogenic TeNPs," *J. Nanoparticle Res.*, 2020.
- S. Selvakesavan *et al.*, "Tellurium nanodots in photodynamic therapy," *Adv. Opt. Mater.*, 2024.

(The above references correspond to cited content: [X†Ln-Lm] denotes in-text citation to lines Ln–Lm of source X.)

[1] [26] [27] [40] [46] Citric Juice-mediated Synthesis of Tellurium Nanoparticles with Antimicrobial and Anticancer Properties - PMC

<https://pmc.ncbi.nlm.nih.gov/articles/PMC6542685/>

[2] [5] [9] [11] [14] [16] [17] [18] [23] [24] [33] [34] [35] [36] [37] [43] [44] [48] [52] [55] Tellurium and Nano-Tellurium: Medicine or Poison? - PMC

<https://pmc.ncbi.nlm.nih.gov/articles/PMC11053935/>

[3] [4] [15] [20] [21] [25] [28] [29] [30] [31] [39] [41] [42] [45] [47] [50] Synthesis of Tellurium Nanoparticles Using Moringa oleifera Extract, and Their

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<http://amresearchreview.com/index.php/Journal/about>

Antibacterial and Antibiofilm Effects against Bacterial Pathogens - PMC

<https://pmc.ncbi.nlm.nih.gov/articles/PMC11434551/>

[6] [7] [10] [12] [13] [22] [38] [49] [51] [54] [56] [58] [59] Tellurium nanoparticles as antimicrobial agents for multi-drug-resistant infections - RSC Advances (RSC Publishing) DOI:10.1039/D5RA02635K

<https://pubs.rsc.org/en/content/articlehtml/2025/ra/d5ra02635k>

[8] [32] [53] Biosynthesis of Novel Tellurium Nanorods by *Gayadomonas* sp. TNPM15 Isolated from Mangrove Sediments and Assessment of Their Impact on Spore Germination and Ultrastructure of Phytopathogenic Fungi - PMC

<https://pmc.ncbi.nlm.nih.gov/articles/PMC10053417/>

[19] [57] Frontiers | Green synthesis of biogenetic Te(0) nanoparticles by high tellurite tolerance fungus *Mortierella* sp. AB1 with antibacterial activity

<https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1020179/full>