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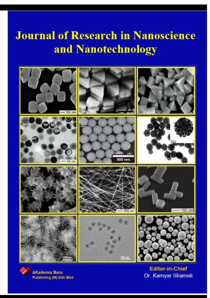

Green Synthesis of Nanoparticles using Dandelion Extract for Biomedical Applications

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ABSTRACT

The growing focus in green nanotechnology has focused research into botanically-based systems for the synthesis of nanoparticles (NPs) that have biomedical significance in a more environmentally sustainable way. *Taraxacum officinale (T. officinale)*, with the general name dandelion, is a medicinal herb that contains bioactive phytochemicals and serves as an exciting natural template for the biosynthesis of metal and metal oxide NPs and nanoemulsions. Since many phytochemicals, like many other natural products are chiral, these can also be used for the synthesis of chiral NPs (CNPs). This review highlights recent advances in the synthesis of dandelion extract mediated NPs, and their structure, mechanisms of synthesis, and surface functionalities associated with the phytocompounds. We will review the potential dandelion extract nanomaterials pose for medicinal use by focusing specifically on their antibacterial, antifungal, antiviral, and anticancer characteristics based on the referenced studies in this review. This study introduces methods through which dandelion phytochemistry, combined with structured nanomaterials, can produce stable scaffolds for future therapeutic applications and presents the potential challenges, possibilities, and future perspectives for dandelion as an environmentally friendly nanofactory for biomedical uses.

Keywords:
Dandelion extract, green synthesis, nanoparticles, antimicrobial activity, anticancer applications, phytochemical-mediated nanotechnology.

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1. Introduction

Green Nanotechnology is increasingly recognized as an essential element in creating the next generation of sustainable/green materials for both biomedical and industrial applications. In comparison to conventional methods of chemical or physical synthesis, Green Nanotechnology actively seeks to utilize renewable materials and non-toxic solvents in energy-efficient processes. Recent work in the area of biologically mediated synthesis of NPs, especially with plant extracts, has shown that these methods not only can bring down environmental impacts, they can also contribute to enhanced biocompatibility and therapeutic activity. This is evident when comparing the antibacterial activity and cytotoxicity of metal and metal oxide NPs produced from a Green route compared to chemically produced NPs, for example. This is a significant advancement in the safe use of nanomaterials in medicine [1,2].

Plants, particularly those rich in secondary metabolites, are increasingly recognized as natural nanofactories. Phytochemicals such as flavonoids, terpenoids, and phenolic acids can serve dual roles as reducing agents and stabilizers in the synthesis of nanoparticles (NPs). Given the widespread occurrence of chirality in phytochemicals, these also possess high potential for the synthesis of chiral NPs, which are receiving growing interest for applications in medicine [3,4], quantum technology [5], and spintronics in recent years [6,7].

Among medicinal plants, Taraxacum officinale (commonly known as dandelion) has attracted significant interest due to its strong antioxidant, anti-aging, antibacterial, and anti-inflammatory properties. Recent studies suggest that dandelion-mediated NPs exhibit promising surface functionalization, enabling more targeted therapeutic applications with reduced off-target effects [8]. In addition to their biomedical potential, a major advantage of biosynthesized NPs lies in their inherent dispersibility and stability attributed to natural capping layers formed by plant biomolecules both of which are critical for successful clinical translation [9,10].

With the growing body of research into dandelion-extract derived NPs, now is a timely opportunity to provide a unified overview of the synthesis, characterization, and biomedical applications. The aim of this review is to provide a systematic overview of the ways which metal and metal oxide NP and nanoemulsion formation can be facilitated by utilizing the *T. officinale* extract. The review will emphasize investigating the therapeutic potential of dandelion-based nanomaterials, and summarize recent development in antimicrobial (antibacterial, antifungal, and antiviral) and anticancer activity while highlighting the mechanisms of bioactivity attributable to phytochemical composition [11,12]. This review will also outline the physicochemical mechanisms of action by which these NPs exert their effects, assess the potential advantages of the dandelion-mediated NPs over conventional alternatives, and discuss barriers to commercialization such as scaling, reproducibility, and toxicity concerns [13].

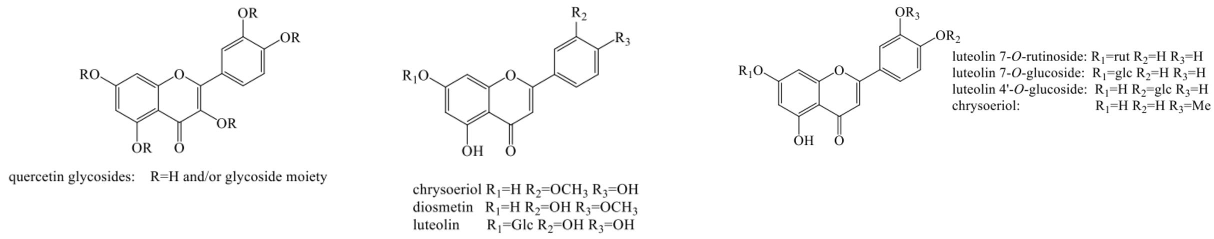
In summarizing contemporary understanding and identifying gaps, this review will help researchers and technologists interested in green nanotechnology in the area of biomedical applications to realize the full potential of dandelion-based nanomaterials for therapeutic purposes, while invoking the momentum towards compatible and sustainable nanotechnology solutions as a global priority. Ultimately, this will prepare the roadmap for future studies to develop safe and effective dandelion-based nanomaterials, or at minimum consider the novel capacity for engineered nanomaterials (biocompatible and bioactive agents) from this common weed.

1.1 Botanical Profile of T. officinale

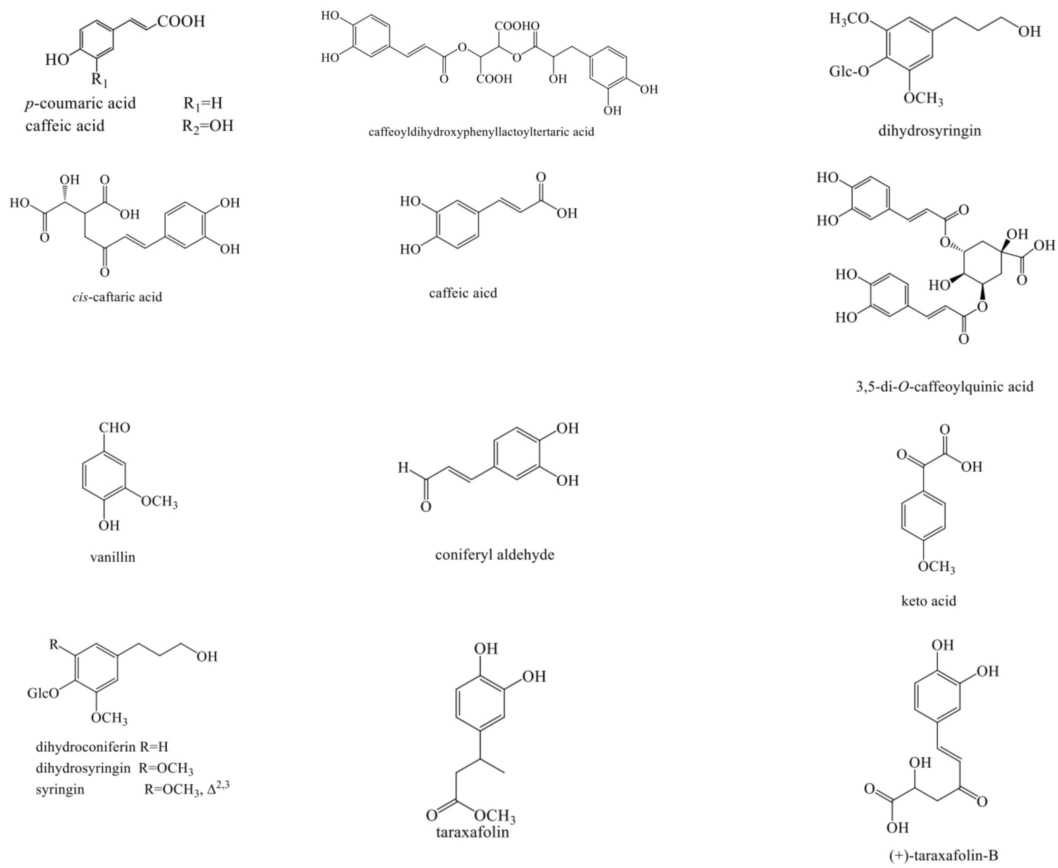
T. officinale, is a hardy, herbaceous perennial plant with a broad geographic distribution across temperate regions of Europe, Asia, and North America. For centuries, dandelion has played a significant role in various systems of traditional medicine. It has been used in European herbalism, Traditional Chinese Medicine (TCM), and other indigenous medical practices for its diuretic, digestive, anti-inflammatory, and liver-detoxifying properties. In several cultures, the plant has been included in remedies aimed at cleansing the blood, supporting bile flow, and improving metabolic function (Figure 1). The use of dandelion in spring tonics and detoxifying herbal mixtures remains common across many parts of the world, underscoring its global importance as a medicinal plant [8, 14].

Fig. 1. Image of dandelion (*T. officinale*) flowers and leaves, a medicinal plant traditionally used in various cultures for its therapeutic properties

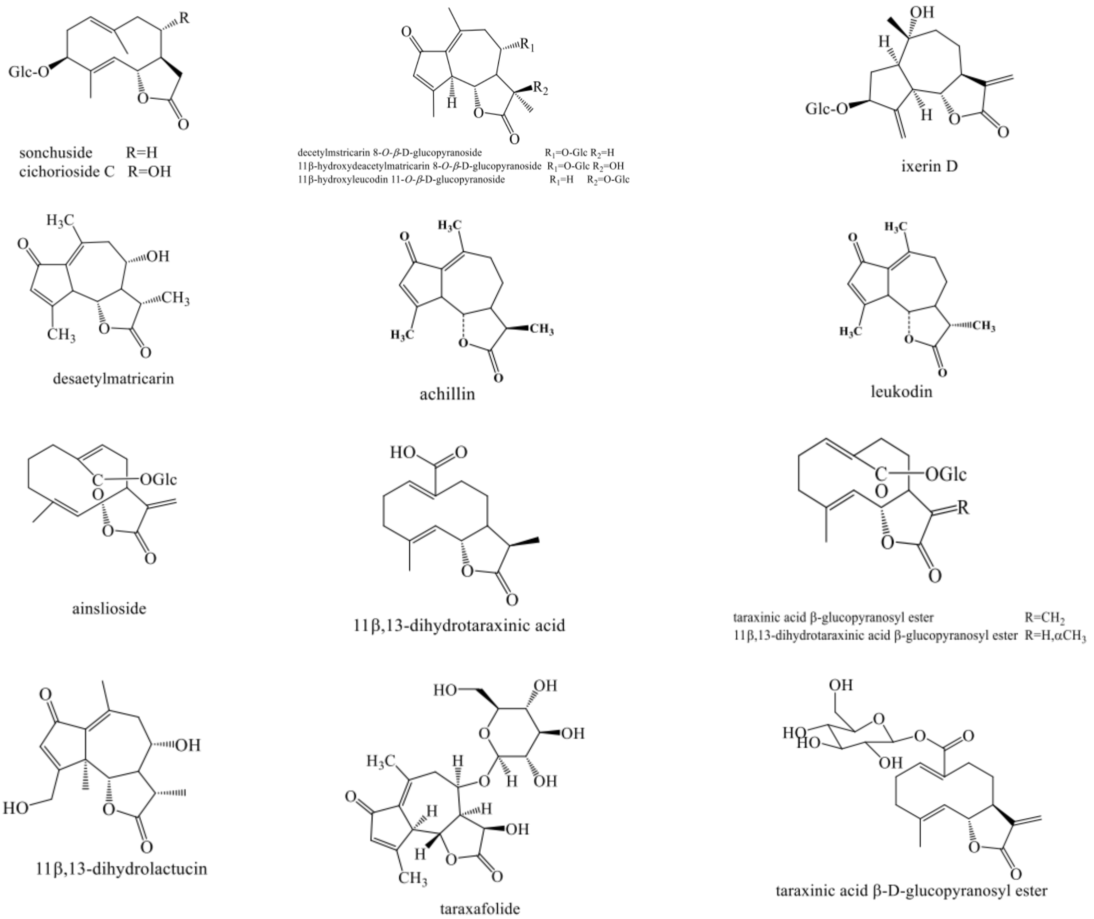
The medicinal and therapeutic value of *T. officinale* is attributed to its rich phytochemical composition. Key bioactive compounds found in various parts of the plant include flavonoids (e.g., luteolin, apigenin), phenolic compounds (such as chicoric and caffeic acid), sesquiterpene lactones, triterpenes, and polysaccharides, along with essential oils and minerals (Figure 2). Studies from different geographical regions have demonstrated that the chemical composition of dandelion varies depending on factors such as soil quality, climate, and harvest time [8,15]. This variability influences its pharmacological properties and has implications for its use in NP synthesis. In particular, phenolic-rich extracts derived from diverse ecological environments have shown notable antioxidant and metal-chelating abilities, making them suitable agents for stabilizing and reducing metal ions in green nanotechnology applications [16].



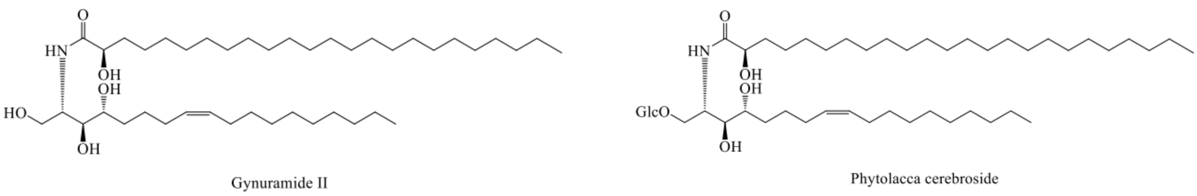
(a) Flavonoids from *Taraxacum* genus



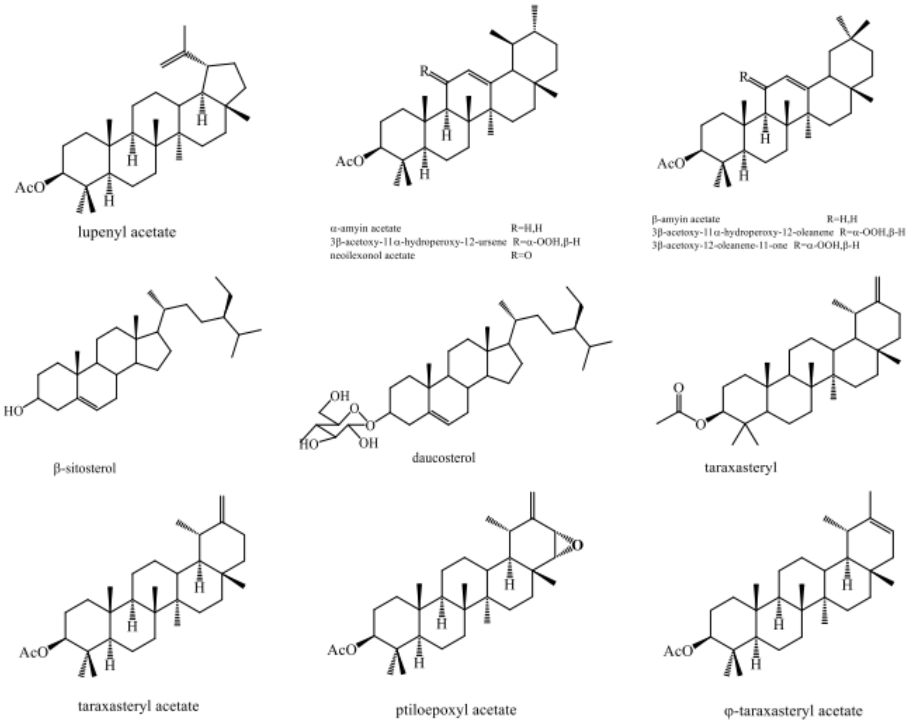
(b) Phenolic compounds



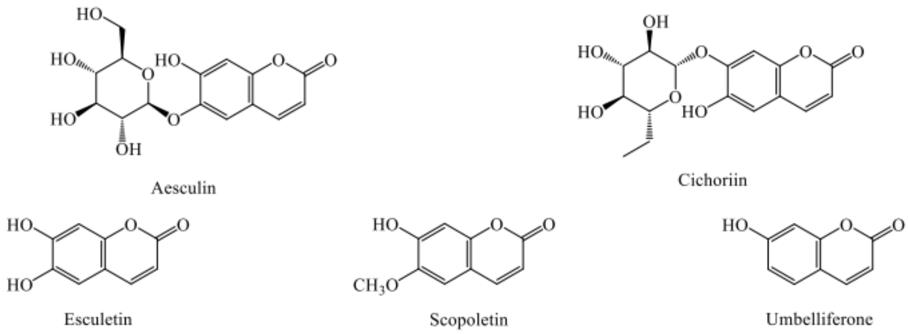
(c) Sesquiterpenoid compounds



(d) Sphingolipids



(e) Triterpenoids and Sterols



(f) Coumarins

Fig. 2. The molecular structures of (a) Flavonoids, (b) Phenolic compounds, (c) Sesquiterpenoid, (d) Sphingolipids, (e) Triterpenoids and Sterols, and (f) Coumarins isolated from *T. officinale* (dandelion) display a diverse array of bioactive chemical frameworks

The biosynthesis of NPs using plant extracts relies on the intrinsic chemical reactivity of phytochemicals, which serve as both reducing and capping agents [17,18]. In the case of *T. officinale*, phytoconstituents such as polyphenols, flavonoids, and terpenoids facilitate the formation of stable, biofunctional NPs [19,20]. Researchers from various scientific communities worldwide have successfully employed dandelion extract in the green synthesis of a wide range of NPs, including silver (Ag), zinc oxide (ZnO) [11,21,23-25], copper oxide (CuO) [9,12,22], and nickel-doped ZnO (Ni-ZnO) [13]. These NPs, synthesized through eco-friendly and cost-effective methods, have demonstrated significant biological activities, particularly antimicrobial and anticancer effects (Figure 3) [21]. The unique chemical makeup of dandelion extract not only governs NP morphology and stability but also contributes to their enhanced therapeutic efficiency [9,11,21-23]. As such, *T. officinale* continues to be explored as a valuable botanical source for the development of sustainable nanomaterials for medical and technological applications [22,26].

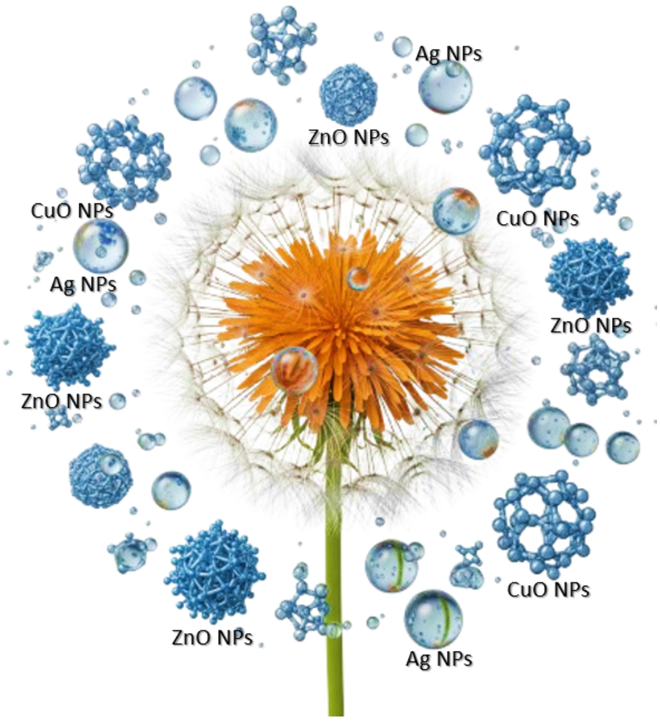


Fig. 3. A schematic illustrating the green synthesis of NPs such as Ag, ZnO, CuO, and Ni-doped ZnO using the aqueous extract of *T. officinale* (dandelion)

1.2 Green Synthesis of NPs using T. officinale Extract

The initial step in the biogenic synthesis of NPs utilizing *T. officinale* involves the extraction of bioactive phytoconstituents that act as reducing and stabilizing agents. Optimized extraction protocols, ranging from aqueous and methanolic maceration to advanced ultrasonic-assisted and reflux extractions, are employed to maximize yield and preserve the functional integrity of key phytochemicals such as polyphenols, flavonoids, and terpenoids [27]. Extraction parameters, including solvent polarity, temperature, pH, and duration [28], critically modulate the phytochemical profile and subsequently influence NP nucleation and growth kinetics [29]. Rigorous standardization of extraction procedures is imperative to ensure reproducibility and scalability for downstream nanomaterial fabrication.

Green synthesis of metal and metal oxide NPs using natural materials, such as biopolymers, honey, gelatin, and microorganisms, has been extensively studied [30]. Among these methods, the use of plant extracts has garnered special interest due to their high content of oxidizing phytochemicals, which play a key role in NP biosynthesis [31].

The green synthesis of metal and metal oxide NPs via *T. officinale* exploits the redox potential of its phytochemicals to convert metal ions into nanoscale zero-valent metals or oxides under mild conditions. The process typically involves the incubation of aqueous plant extracts with metal precursors, such as $AgNO_3$ for silver, $Zn(CH_3COO)_2$ for zinc oxide, and $CuSO_4$ for copper oxide, under controlled temperature and agitation regimes [30]. Phytochemical moieties act simultaneously as reductants and capping agents, driving controlled nucleation and growth while preventing agglomeration (Table 1). Recent advancements document successful synthesis of doped nanostructures, including Ni-doped ZnO, underscoring the versatility of dandelion-mediated routes. These biosynthetic strategies offer environmentally benign, energy-efficient alternatives to conventional chemical methods, minimizing hazardous byproducts and facilitating biomedical compatibility [32].

In addition to NP synthesis, *T. officinale* phytochemicals have been harnessed as natural emulsifiers for the fabrication of nanoemulsions, colloidal dispersions characterized by nanoscale droplet sizes that enhance solubility and bioavailability of hydrophobic therapeutic agents. Nanoemulsion preparation typically employs high-energy ultrasonication or low-energy phase inversion techniques, with dandelion-derived surfactant compounds stabilizing oil-in-water or water-in-oil systems. These green nanoemulsions present promising platforms for drug delivery and photodynamic therapy, leveraging improved pharmacokinetics and targeted bioactivity while maintaining biocompatibility [33].

Table 1
Summary of metal/metal oxide NPs synthesized using *T. officinale* and their applications

Author / Year	NPs	Chemical Precursor	Findings / Innovation	Ref.
Kasthuri et al. (2024)	ZnO-NPs	$ZnSO_4{\cdot}7H_2O$	Eco-friendly synthesis; significant antibacterial, antifungal, and anticancer activities.	9
Saratale et al. (2018)	Ag-NPs	$AgNO_3$	Potent antimicrobial and antioxidant properties; better than commercial Ag-NPs.	11
Abrica-González et al. (2023)	ZnO-NPs, CuO-NPs	Zn salt Copper salt	*T. officinale* as bioindicator for NP toxicity; assessed DNA damage and physiological effects.	13
Rasheed et al. (2017)	Ag-NPs	$AgNO_3$	Antibacterial and anticancer effects; potential against multidrug-resistant strains.	21
Aayasha et al. (2022)	ZnO-NPs	Likely Zn salt	Strong antibacterial, antioxidant, and dye degradation activities.	22
Fazle et al. (2024)	Ag-NPs	$AgNO_3$	Green synthesized Ag-NPs with antibacterial and antifungal activity.	23
Yousefzadeh et al. (2023)	Ag-NPs	$AgNO_3$	Green Ag-NPs showed superior antioxidant, antimicrobial, and α-glucosidase inhibition.	24
Saratale et al. (2018)	Ag-NPs	$AgNO_3$	Green Ag-NPs showed enhanced efficacy against phytopathogens and HepG2 cells	25
Mustafa et al. (2022)	Ni–ZnO-NPs	$Zn(NO_3)_2$ + Ni^{2+}	Applied in solar cells; enhanced crystallinity and light-harvesting.	26

1.3 Physicochemical Characterization of Dandelion-Mediated Nanomaterials

Comprehensive physicochemical characterization is fundamental for correlating NP structural attributes with their biological function. Electron microscopy techniques, Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM), and Atomic Force Microscopy (AFM), are routinely applied to elucidate NP morphology, size, and surface topography, revealing predominantly spherical to branched "dandelion-like" architectures facilitated by phytochemical templating. X-Ray Diffraction (XRD) provides definitive crystallographic fingerprints confirming phase purity and crystallinity of metal and metal oxide NPs. Detailed size distribution analyses via dynamic light scattering (DLS) complement microscopy data, offering insights into colloidal stability in suspension [33].

Surface characterization using Fourier Transform Infrared Spectroscopy (FTIR), X-ray Photoelectron Spectroscopy (XPS), and Ultraviolet–Visible (UV-Vis) spectroscopy enables identification of specific phytochemical functional groups adsorbed onto NP surfaces [34]. These bioorganic ligands, hydroxyl, carboxyl, and amine moieties, play a crucial role in steric and electrostatic stabilization, as quantitatively assessed by zeta potential measurements. The phytochemical corona not only imparts colloidal stability but also modulates NP interactions with biological milieus, influencing cellular uptake and bio-distribution (Figure 4).

The intrinsic phytochemical capping of dandelion-derived NPs serves as a biofunctionalization strategy that enhances their therapeutic efficacy and biocompatibility. Surface-bound flavonoids, phenolic acids, and terpenoids act as active interfaces facilitating targeted interaction with microbial membranes or cancerous cells through mechanisms such as reactive oxygen species modulation and receptor-mediated endocytosis. This biomimetic functionalization differentiates dandelion-mediated NPs from their synthetic analogs by reducing cytotoxicity while improving specificity and therapeutic index. Harnessing this natural biointerface engineering holds significant promise for the rational design of next-generation nanomedicines with tailored pharmacodynamics and minimized off-target effects [35].

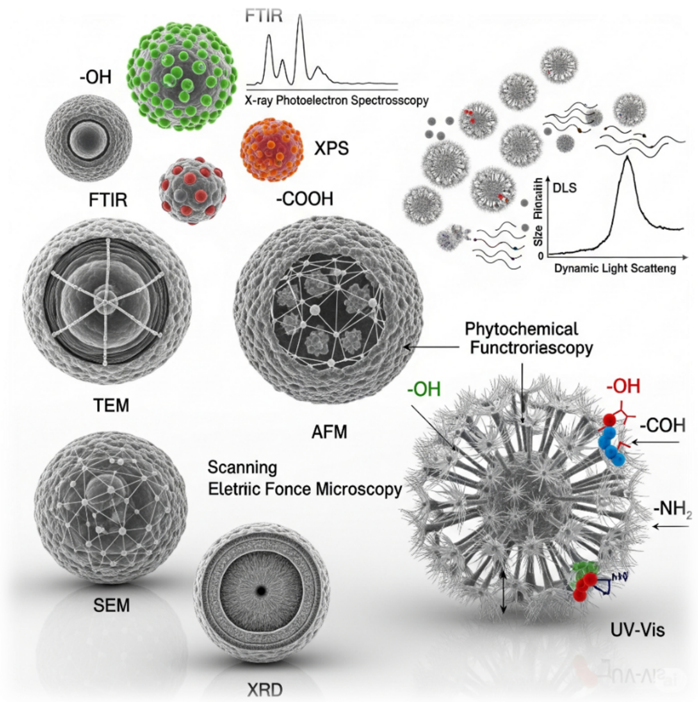


Fig. 4. Characterization of the physicochemical properties of metal and metal oxide NPs synthesized via green methods is performed using a wide range of analytical techniques, including TEM, SEM, AFM, XRD, DLS, XPS, FTIR, and UV-Vis spectroscopy

1.4 Therapeutic Applications

Dandelion extract-mediated NPs exhibit robust antibacterial properties against a diverse array of clinically significant Gram-positive and Gram-negative bacteria. The nanoscale dimensions confer enhanced surface reactivity, facilitating effective interaction with bacterial cell envelopes. The conjugated phytochemicals act synergistically, disrupting membrane integrity, perturbing intracellular enzymatic functions, and inhibiting essential metabolic pathways. These biohybrid nanomaterials, particularly silver and metal oxide NPs synthesized via *T. officinale*, demonstrate promising efficacy against antibiotic-resistant strains, positioning them as viable alternatives or adjuncts in combating persistent bacterial infections and biofilm-associated complications in medical implants [9,11-13].

The antifungal efficacy of *T. officinale*-derived NPs is primarily mediated through their ability to breach the complex fungal cell wall and membrane systems, inducing structural disintegration and metabolic dysfunction. ZnO and Ag NPs, biofabricated using dandelion phytochemicals, have shown potent fungicidal activity against opportunistic and pathogenic fungi such as Candida spp. and Aspergillus spp. The mechanistic basis involves both direct physical interactions and the generation of oxidative stress, which collectively inhibit fungal growth, spore germination, and biofilm formation, highlighting their potential for therapeutic and agricultural antifungal interventions [9,21,23].

Although still emerging, the antiviral potential of dandelion extract-mediated NPs is gaining significant attention. These nanostructures interfere with viral life cycles by binding to viral surface proteins, obstructing host-cell receptor engagement, and impairing viral entry and replication. Metal NPs functionalized with dandelion phytochemicals demonstrate inhibitory activity against enveloped viruses, suggesting applications in prophylactic antiviral coatings and novel therapeutic formulations. Continued elucidation of antiviral mechanisms and spectrum is warranted to harness these biogenic NPs fully [24,25].

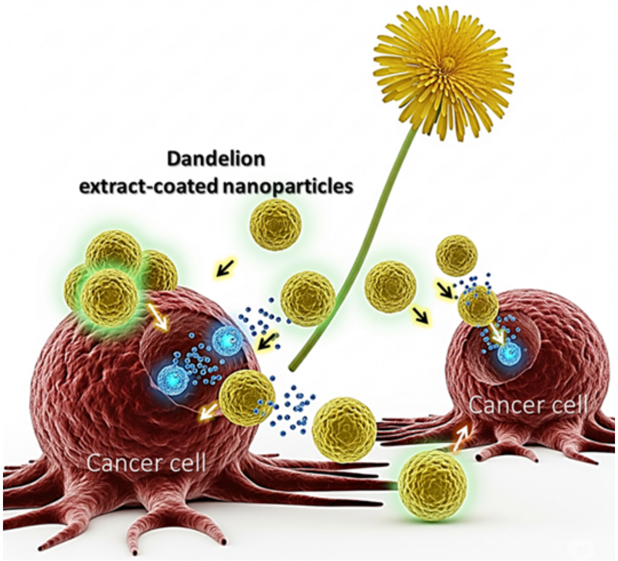


Fig. 5. A schematic illustration depicting the role of biosynthesized NPs in assessing anticancer activity by selectively targeting and eliminating malignant cells

Dandelion-mediated NPs present a multifaceted anticancer modality by integrating nanoscale physical properties with the intrinsic bioactivity of phytochemicals (Figure 5). Enhanced cellular internalization coupled with localized ROS generation induces oxidative stress, DNA fragmentation, and apoptosis selectively in malignant cells. Furthermore, these NPs modulate oncogenic signaling pathways, suppress tumor proliferation, and sensitize cells to chemotherapeutic agents. Their biomimetic surface functionalization mitigates off-target toxicity and improves tumor microenvironment targeting, underscoring their potential as nanoplatforms for precision oncology, including synergistic photodynamic and chemotherapeutic regimens [13].

2. Mechanisms of Action

The primary antimicrobial mechanism involves electrostatic and hydrophobic interactions between NPs and microbial membranes. The phytochemical-functionalized NP surfaces facilitate strong adhesion to the negatively charged bacterial and fungal cell envelopes, causing membrane destabilization, pore formation, and increased permeability. This interaction results in leakage of cytoplasmic contents and loss of membrane potential, effectively compromising cell viability. The tailored surface chemistry of dandelion-derived nanomaterials optimizes these interactions, enhancing specificity and potency (Figure 6).

A critical bioactive mechanism of dandelion-mediated NPs is the induction of reactive oxygen species (ROS), which exceed cellular antioxidant capacity leading to oxidative damage. In pathogens, this manifests as lipid peroxidation, protein denaturation, and nucleic acid damage, culminating in cell death. In cancer cells, ROS accumulation triggers mitochondrial dysfunction and activates intrinsic apoptotic cascades via cytochrome c release and caspase activation. This controlled oxidative stress, modulated by phytochemical capping, enables selective cytotoxicity while preserving normal cells, a key attribute for therapeutic applications [36].

The capping of NPs with *T. officinale* phytochemicals confers multifunctional bioactivity beyond mere stabilization. These ligands modulate NP biodistribution, cellular uptake pathways, and intracellular trafficking, enhancing target specificity and therapeutic efficacy. Additionally, their intrinsic pharmacological properties, anti-inflammatory, immunomodulatory, and enzyme inhibitory activities, act synergistically to potentiate antimicrobial and anticancer effects [37]. This biomimetic biointerface engineering reduces systemic toxicity and facilitates translational potential in nanomedicine.

The biosynthesis of NPs using *T. officinale* extract involves a green synthesis approach, where phytochemicals in the plant act as both reducing and capping agents. While exact mechanisms vary with metal ions and plant composition, here are generalized and plausible reaction mechanisms. Metal ions such as Ag+, Zn2+, and Cu2+ are reduced to their zero-valent forms (Ag^0, ZnO, CuO) in aqueous solutions. This reduction is facilitated by secondary metabolites present in *T. officinale* extracts, including flavonoids, phenolic compounds, terpenoids, ascorbic acid, etc. [38].

The synthesis of Ag-NPs involves the donation of electrons from hydroxyl groups in flavonoid or phenolic compounds, where Ar–OH acts as a reducing agent and is oxidized to a quinone-like structure (Ar=O). This mechanism serves as a representative example for the green synthesis of metallic NPs (Eqs. 1 and 2).

$$Ag^+ + \text{Phytochemical (Red-OH)} \rightarrow Ag^0 + \text{Oxidized phytochemical} \quad (1)$$

$$Ag^+ + Ar\text{–}OH \rightarrow Ag^0 + Ar{=}O + H^+ \quad (2)$$

Once metal ions are reduced to atoms, they undergo nucleation and growth to form NPs. During nucleation, the reduced atoms cluster together to form a stable nucleus, which serves as the foundation for further growth. In the growth phase, additional atoms are deposited onto this nucleus, leading to the formation of NPs of increasing size. [39, 40] This process is significantly influenced by factors such as pH, temperature, and the concentration of metal ions and phytochemicals. Following formation, NPs are stabilized through capping, where phytochemicals adsorb onto the NP surface to prevent aggregation. [41] This stabilization is facilitated by functional groups such as hydroxyl (–OH), carboxyl (–COOH), carbonyl (–C=O), and amino ($-NH_2$), which interact with the NP surface through hydrogen bonding, electrostatic interactions, and chelation, ensuring the NPs remain dispersed and stable in solution (Eq. 3).

$$\text{Ag-NP} + \text{Ar–OH/–COOH/–C=O/–NH}_2 \rightarrow \text{Ag-NP@Capped layer}^+ \quad (3)$$

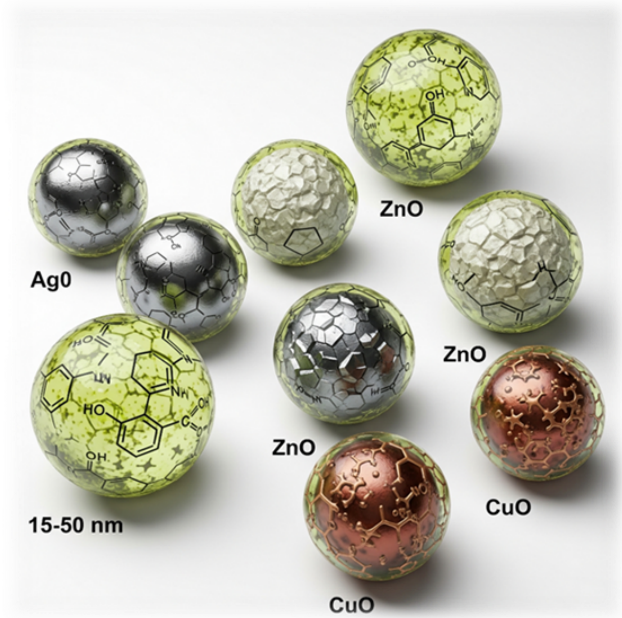


Fig. 6. A comprehensive evaluation of the role of plant-derived organic compounds in the surface capping and controlled synthesis of metal and metal oxide NPs utilizing plant extracts, with a detailed mechanistic insight into the biogenic synthesis pathways, as elucidated within ROS-mediated membrane disruption hypothesis

3. Challenges and Limitations

One of the foremost challenges in harnessing dandelion extract-mediated NPs lies in ensuring reproducibility and stringent standardization across synthesis batches. The complex phytochemical milieu of *T. officinale* is inherently variable, influenced by factors such as geographic origin, seasonal variation, and extraction protocols. This variability translates into inconsistencies in NP size, morphology, surface chemistry, and ultimately, bioactivity. Establishing standardized cultivation, harvesting, and extraction procedures alongside validated analytical methodologies is critical to achieving reproducible physicochemical characteristics and therapeutic outcomes, thereby advancing these nanomaterials toward clinical viability [42].

Despite the green synthesis approach and natural capping by phytochemicals, comprehensive toxicological profiling remains imperative. The interplay between NP physicochemical properties and biological systems can yield unanticipated cytotoxicity, immunogenic responses, or off-target effects, especially with prolonged exposure or systemic administration. Detailed mechanistic studies employing in vitro cellular models and in vivo animal systems are essential to delineate dose-dependent toxicity profiles, bio-distribution, metabolism, and clearance pathways. Such insights will inform rational NP design to maximize therapeutic efficacy while minimizing adverse effects, a cornerstone for regulatory approval and clinical translation [43].

Transitioning from bench-scale biosynthesis of dandelion-mediated NPs to scalable, reproducible industrial production poses multifaceted challenges. Maintaining phytochemical integrity and bioactivity at scale demands optimization of extraction and synthesis conditions, along with stringent process control. Economic feasibility, process robustness, and compliance with Good Manufacturing Practices (GMP) must be prioritized. Additionally, developing scalable purification and formulation strategies that preserve NP stability and functionalization is critical for downstream clinical applications. Bridging these gaps requires interdisciplinary collaboration integrating nanotechnology, process engineering, and regulatory science.

4. Future Perspectives

Emerging trends point toward the development of sophisticated, multifunctional nanoplatforms derived from dandelion extracts, capable of integrated diagnosis and therapy (theranostics). By synergizing the intrinsic pharmacological activities of phytochemicals with tunable NP architectures, these systems can enable stimuli-responsive drug release, enhanced imaging contrast, and combinatorial therapeutic modalities such as photodynamic, chemo-, and immunotherapy. Such platforms promise to revolutionize personalized nanomedicine by offering precision targeting and real-time therapeutic monitoring [27].

Future advancements should focus on conjugating dandelion-derived NPs with active targeting moieties (e.g., antibodies, peptides, aptamers) and stimuli-responsive carriers to enhance specificity and controlled payload delivery. Exploiting the natural affinity of *T. officinale* phytochemicals toward cellular receptors and tumor microenvironments could potentiate receptor-mediated endocytosis and improved intracellular trafficking [43]. This strategic integration will reduce systemic toxicity and enhance therapeutic index, essential for clinical translation in antimicrobial, antiviral, and oncological applications.

As these biogenic NPs advance toward clinical and commercial use, it is imperative to address regulatory frameworks encompassing safety, efficacy, and manufacturing standards. Harmonized guidelines tailored for green-synthesized nanomaterials are required to streamline approval processes. Concurrently, comprehensive environmental impact assessments, including NP fate, persistence, and eco-toxicity, are essential to ensure sustainable development [30]. The eco-friendly nature of dandelion-mediated synthesis aligns with global sustainability goals; however, systematic studies on environmental biodegradability and bioaccumulation must underpin responsible innovation.

5. Conclusion

Dandelion extract-mediated NPs represent a compelling convergence of green nanotechnology and phytomedicine, offering a sustainable and biocompatible platform for the development of advanced therapeutic nanomaterials. Leveraging the rich phytochemical repertoire of *T. officinale*, these biosynthesized nanostructures exhibit multifunctional bioactivities, including potent antibacterial, antifungal, antiviral, and anticancer effects, which are intricately modulated by the natural capping and reducing agents intrinsic to the plant extract. The integration of these bioactive molecules not only enhances NP stability and dispersibility but also facilitates targeted interactions with pathological cells, enabling selective cytotoxicity and reducing off-target effects. Despite the promising therapeutic potential demonstrated by numerous in vitro and preliminary in vivo studies, several critical challenges remain to be addressed to fully harness the translational value of dandelion-derived nanomaterials. Key hurdles include achieving reproducible synthesis with standardized phytochemical profiles, comprehensive toxicological evaluations to establish safety margins, and the scale-up of green fabrication methods under regulatory-compliant manufacturing conditions. Addressing these issues will require interdisciplinary collaborations bridging phytochemistry, nanotechnology, pharmacology, and regulatory science. Looking forward, the strategic functionalization of dandelion-mediated NPs with targeting ligands and stimuli-responsive elements holds great promise for the design of personalized and precision nanomedicines. Moreover, their potential as theranostic agents underscores their versatility in future biomedical applications. Ensuring rigorous environmental and safety assessments alongside regulatory harmonization will be paramount to advancing these bio-nanoplatforms from laboratory research into clinical and commercial realms. In summary, *T. officinale*-based nanotechnology exemplifies a paradigmatic shift toward eco-friendly, biocompatible, and efficacious nanotherapeutics. This natural nanofactory approach aligns with global sustainability initiatives while offering innovative solutions to pressing medical challenges. Continued research and development in this domain will pave the way for novel, safe, and effective green nanomedicines, establishing dandelion-mediated NPs as vital contributors to the future landscape of therapeutic nanobiotechnology.

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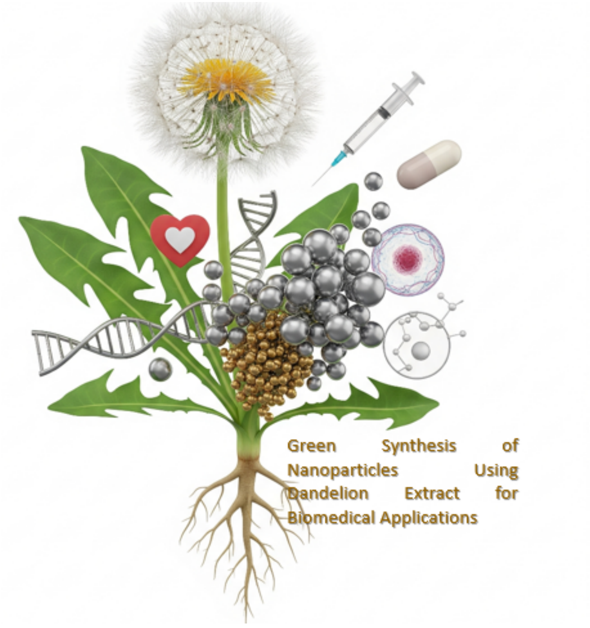

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