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A Comprehensive Review of Green Nanotechnology and Nanodelivery Systems for Bioactive Compounds of Moringa oleifera

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Abstract

Moringa oleifera Lam. This multipurpose medicinal plant is one of the well-studied plants in pharmacognosy and phytochemistry known as Moringa, also called the "miracle tree," containing leaves, seeds, and pods loaded with flavonoids, phenolic acids, vitamins, carotenoids, glucosinolate, isothiocyanate (ITCs), alkaloids, and bioactive peptides with antioxidant-, anti-inflammatory-, antimicrobial-, anticancer-, hepatoprotective-, and cardioprotective effects. Great amounts of overviews at this time point of polyphenol-discussed extracts from Moringa plants, and lately it is a chock-all-natural program in which metal-metal-oxide nanoparticles are eco-friendly synthesizers. However, this unusual pharmacological chance is severely limited by physicochemical properties such as low aqueous solubility and chemical and thermal instability. Polyphenol redox chemistry provides a unifying mechanistic connection linking the contributions of bioactive compounds in M. oleifera to its therapeutic roles with those molecular processes involved in the biosynthesis and stabilization of nanoparticles, thereby establishing the plant as both a phytotherapeutic resource and green nanotechnology platform. At the biochemical level, they act on the liberation of free radicals via several mechanisms, namely through activating the NRF2 (Nuclear Factor Erythroid 2-Related Factor 2)/phase-II antioxidant enzyme axis (SOD, CAT, GPx) and inhibition of NF-κB (Nuclear factor kappa B)-mediated inflammatory signalling and metabolic modulation of enzymes such as α-amylase and α-glucosidase; moreover, nanocarrier systems exhibited enhanced stability with typical encapsulation efficiencies, which are reported to be 70–95%, along with controlled-release profiles, followed by green-biosynthesized nanoparticles (5–50 nm) marked by antimicrobial, photocatalytic, and cytotoxic properties due to equivalently acting electron-lending polyphenolic-hydroxyl groups prompting defence mechanisms against oxidative stress whilst simultaneously driving redox processes responsible for reducing/capping metal ions during synthesis. This review strives to present an integrated overview of Moringa through the incorporation of its phytochemical/pharmacognostic attributes, biochemical mechanisms, and nano-promoted bioactive components

Keyword : Flavonoids, Nrf2 pathway, nanoencapsulation, silver nanoparticles, oral bioavailability
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INTRODUCTION

Medicinal plants continue to be an important pillar of pharmacognosy and a fruitful avenue for new therapeutic opportunities, reflecting the fact that natural products continue to fuel the majority of newly approved drugs [1]. Among them, Moringa oleifera Lam. (family Moringaceae) is one of the most

investigated multipurpose medicinal trees, grown in Africa, Asia and Latin America and appreciated for many pharmacological activities [2]. Beyond its medicinal role, it is inexpensive and among the fastest-growing non-wood plants, widely available and socioeconomically important, particularly in low- and middle-income regions [3]. Nutritionally, its leaves, pods, and seeds possess extremely high concentrations of proteins, minerals, vitamins, and antioxidants, which both explain its widespread moniker as "the miracle tree." [4]. Its leaves in particular are rich in flavonoids, phenolic acids, carotenoids, glucosinolate, and vitamins that account for much of its bioactivity [5]. Nevertheless, many of these phytochemicals are characterized by poor aqueous solubility, chemical and thermal instability and high susceptibility to oxidation that restrict their practical formulation and storage [6]. In common with most dietary polyphenols, they are also rapidly metabolized and poorly absorbed in vivo, resulting in limited systemic bioavailability and a persistent gap between high activity in vitro and inconsistent in vivo efficacy [7]. Given the nutraceutical and pharmacological potential of M. oleifera across multiple organ systems, including antioxidant, anti-inflammatory, antidiabetic, hepatoprotective, and cardioprotective effects [8]. it is important to overcome these limitations in the most efficient way possible. Its low cost and ease of adaptation has already been a motivation for its incorporation into functional foods, dietary supplements, and value-added products [9]. By contrast, reliable delivery of its bioactive could result in major public-health and economic gains against the global burden of malnutrition and non-communicable disease, particularly in resource-limited settings [10]. Mechanistically, its pharmacological actions here are based on well-defined phytochemical–biochemical interactions as opposed to non-specific effects, though these mechanisms have rarely been explicitly linked to the delivery strategy [11]. Despite its rich polyphenol extracts also facilitating green synthesis of metal and metal-oxide nanoparticles, the phytotherapeutic and green-nanotechnology literatures have evolved mostly independently from each other, and so far, no review has woven together the biochemistry, nanodelivery and green nanotechnology of M. oleifera under one mechanism-based umbrella [12]. This review seeks to integrate these strands through a single mechanistic spine, polyphenol redox chemistry, and sequentially cover the phytochemical profile, biochemical mechanisms, bioavailability hurdles, green delivery systems and green synthesis as well as the biomedical prospect of M. oleifera environmental issues such as safety and regulations pertinent to translation [13].

Pharmacognostic and Phytochemical Profile

Moringa oleifera Lam. (family Moringaceae), commonly called drumstick tree, horseradish tree, or moringa, is a fast-growing multipurpose tree native to the Indian subcontinent and widely naturalized in tropical and subtropical regions. seeds, bark, Leaves, pods, flowers, and roots are used as food and in traditional medicine.

Botanical identity

- Scientific name: Moringa oleifera Lam.
- Common names: Moringa, drumstick tree, horseradish tree, ben oil tree, mulangay (Philippines).
- Family: Moringaceae.
- Habit: Fast-growing deciduous tree up to 10–12 m; pinnate leaves, slender drooping branches, long tapering pods (drumsticks).
- Used Parts: Leaves (fresh/dried), leaf powder, pods (immature/ripe), seeds, seed oil, flowers, roots, bark
- Distribution: Native to South Asia and cultivated/naturalized throughout Africa, Southeast Asia the Caribbean and Central and South America; well-drained soils in tropical/subtropical climates.
- Collection: Most collections are done in the morning, young leaves/pods widely used. The variability of phytochemical content includes seasonal patterns, age of plant at harvest, cultivar and post-harvest handling.

Macroscopic (organoleptic) characteristics

- Leaves: Bipinnate; leaflets small, oblong to elliptic 1–2 cm long; fresh leaves green soft and aromatic with slight pungent cabbage-like taste sufficing a debris of leaves brittle olive to dark green dried leathery than pale yellow diagnostic.
- Leaf powder: Green pulverulent; finely to coarsely powdered; odour characteristic, taste slightly bitter to astringent.
- Pods (young drumsticks): Long, slender and green, reaching 30–50 cm with a soft inner mesocarp while they are young.
- Seeds: Almost spherical, 1–1.5 cm in diameter with a papery seed coat; kernels white.
- Flowers: Fragrant, small, whitish-creamy.

Microscopic (anatomical) features

- Leaf (common diagnostic characteristics detected in transverse sections and powder
- Dorsiventral leaf with thin cuticle.
- The cuticular micromorphology may include one or two different types of simple epidermis cells, with the unicellular non-glandular trichomes being rare and the anomocytic.
- Palisade and spongy mesophyll clearly demarcated; palisade is usually a single layer of elongated cells.
- Some accessions show the presence of both glandular and non-glandular trichomes.
- Well-developed collateral vascular bundles.
- Microscopy of powder: fragments of parenchyma, spiral and annular xylem vessels, fibers/fiber groups, stomatal fragments, pollen grains, and even calcium oxalate crystals (prismatic/druse) in some cases
- Stem/bark: Cortex with collenchyma, phloem fibers, and sclerenchyma; wood exhibits vessels, fibers, and parenchyma typical of dicotyledonous trees and the seed with endosperm [14].

Physicochemical parameters and quality tests

- Loss on drying/moisture content: fresh leaves are high (up to 75–80%); dried leaf powder should be low, ideally <8–10%, for storage stability.
- Total ash: averages ~6–12% (dependent on part and source).
- Acid insoluble ash: as a low fraction, this indicates there is low earthy contamination; typical values are ~0.5–2%.
- Water-soluble ash: Variable; done with total ash.
- Extractive values: Water extractive (hydrophilic constituents) and ethanol extractive (70% ethanol, routinely reported; percent yields depend on solvent and material (e.g., 10–30% w/w for leaves depending on method).
- Foreign matter: it should be at a very low level; the specification is usually <2% w/w.
- pH of aqueous extract: acidic to neutral based on preparation.
- Contaminants: for heavy metals (Pb, Cd, As, Hg)—from pharmacopoeial/regulatory limits, pesticide residues, and microbial burden.

Preliminary phytochemical screening (qualitative)

- Flavonoids (quercetin, kaempferol glycosides) — strongly present.
    - Glucosinolates and isothiocyanates (nitrogen- and sulphur-containing secondary metabolites)—a typical feature for Moringa, especially leaves and seeds; characterized by pungent aroma but possessing many bioactivities.
    - One of the most important bioactive markers is alkyl glucosinolates (e.g., glucomoringin) and their enzymatic hydrolysis products (moringin, moringin isothiocyanate).
    - Abundant in vitamins (A, C, E), minerals (Ca, K®, Fe, Mg), and amino acids—especially in leaves.
    - Nonvolatile oil (present in seed): high level of oleic acid (ben oil).
    - Proteins: leaves protein-rich with amino acids [15].

Quantitative phytochemical determinations

- Total phenolic content: often expressed as mg GAE (gallic acid equivalents)/g of extract sep.
- Total flavonoid content: mg quercetin or rutin equivalents per g.
- Total alkaloids, saponins, and tannins: methods are varied; the report is done with a description of the assay.
- Specific marker quantification:

    - Marker used as chemotaxonomic / quality marker in some studies: Glucomoringin (and/or moringin) by HPLC/LC-MS;
    - Common flavonoid markers—HPLC quercetin and kaempferol glycosides.
    - Fatty acid profile of seed oil (GC/GC MS): oleic acid replaced by palmitic and behenic acids.
    - Assay selection (Minerals and Vitamins, AAS, ICP-MS, HPLC).

Chromatographic and spectroscopic profiling

- TLC fingerprinting: multi-solvent systems for bioactive compounds (flavonoids and glucosinolates; visualization under UV254/365 nm and spray reagents (e.g., NP/PEG for flavonoids; anisaldehyde or vanillin for terpenes.)
- Reversed-phase HPLC—UV detection for flavonoids and glucosinolates. Methanolic extracts of samples were utilized to analyze marker compounds, including quercetin-3-glucoside (QR), kaempferol glycosides (KGA), and glucomoringin (GMr). Retention Times and Calibration Curves.
- LC MS/LC MS/MS: for sensitive identification of glucosinolates, isothiocyanates, and minor compounds (4, 22), 25–29.
- GC/GC MS: Potent method for volatile fraction (flowers, leaves) and fatty acid-methyl ester (FAME) profiling of seed oil.
- NMR and IR for structural confirmation of the isolated compounds.

Extraction and isolation notes

- Common extraction solvents: water, ethanol (30–80%), methanol, ethyl acetate, and hexane (for lipophilic fractions).
- Leaves: aqueous/ethanolic extracts for nutraceuticals and flavonoid-rich fractions.
- Seeds: oil extraction by cold-pressing or solvent extraction; protein-rich press cake used for water purification (coagulant).
- Glucomoringin is water-soluble but may be extracted more efficiently with polar organic solvents followed by chromatographic purification.
- Enzymatic activity: myrosinase-like enzymes in Moringa convert glucosinolates to isothiocyanates upon tissue damage — important when processing (fresh vs. heat-treated) because heating can inactivate the enzyme and alter the profile of bioactive products [16].

Biochemical Mechanisms of Action

M. oleifera bioactives' pharmacological activities are supported by well-defined biochemical mechanisms [17]. Flavonoids and phenolic acids not only scavenge free radicals directly by donating hydrogen atoms from their phenolic hydroxyl groups to react with reactive oxygen and nitrogen species, but also enhance the expression of phase-II cytoprotective and antioxidant enzymes via up-regulating nuclear factor erythroid 2-related factor 2 (Nrf2)/antioxidant response element pathway as

they promote the gene/protein expressions of superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase(GPx) [18]. While bioactive compounds derived from M. oleifera such as the isothiocyanate moringin (generated enzymatically from glucomoringin via myrosinase) directly activate Nrf2 and inhibit nuclear factor-κB (NF-κB) signalling to down-regulate the expression of inflammatory mediator genes, including TNF-α, IL-6, inducible nitric oxide synthase (iNOS) and cyclooxygenase 2 (COX-2) [19]. Reductions in postprandial blood glucose are partly ascribed to inhibition of α-amylase and α-glucosidase, the carbohydrate-hydrolysing enzymes that slow postprandial glucose release, whereas metabolic effects in lowering lipids and myocardial cardio-protection also involve modulation of lipid-metabolizing enzymes and angiotensin-converting enzyme (ACE) [20]. Biochemical mechanisms underlying anticancer activity include induction of intrinsic (mitochondrial) apoptosis, caspase activation, cell-cycle arrest, and modulation of redox balance [21]. Importantly, this same redox chemistry of phenolics therefore also dictates green nanoparticle synthesis: Hydroxyl groups found in polyphenols reduce ($Ag^{3+} \rightarrow Ag^{o}$) and phytochemicals and proteins serve structural capping and stabilizing agents via a mechanism confirmed spectroscopically by FTIR shifts corresponding to O–H, C=O and C–O functional groups [22]. Figure 1 conceptually summarizes the dual role, and Table 1 provides a mechanistic mapping with representative constituents.

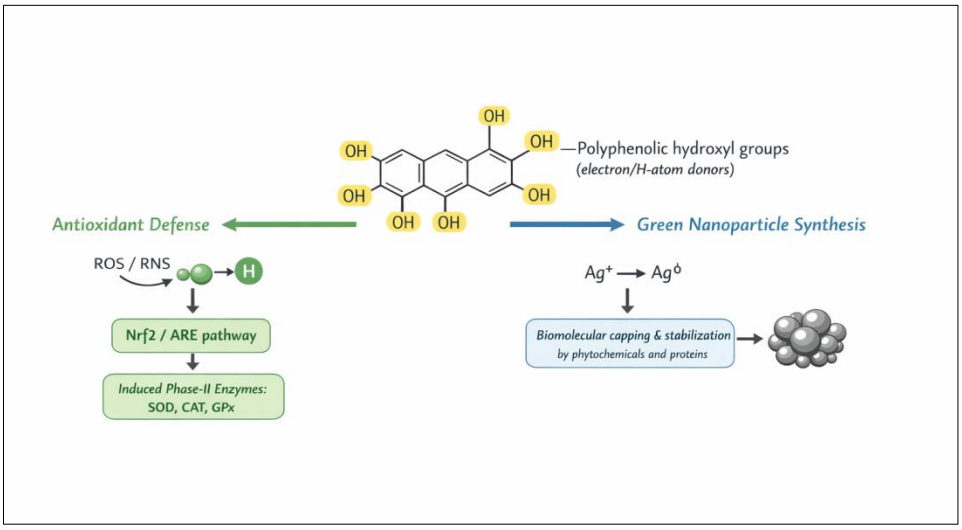

Figure 1. Unifying biochemical mechanism

Table 1. Biochemical mechanisms of representative M. oleifera bioactive constituents

Bioactive constituent	Biochemical target / pathway	Biochemical effect	Ref.
Quercetin, kaempferol (flavonoids)	Nrf2/ARE axis; ROS; SOD, CAT, GPx	Radical scavenging; induces antioxidant enzymes	[16]
Chlorogenic / caffeic acid (phenolics)	α-amylase, α-glucosidase; lipid enzymes	Antihyperglycaemic; hypolipidaemic	[4]
Moringin / glucomoringin (isothiocyanate)	Nrf2 activation; NF-κB inhibition	Anti-inflammatory (↓TNF-α, IL-6, iNOS, COX-2)	[17]
Bioactive peptides / proteins	ACE; oxidative-stress markers	Antihypertensive; antioxidant	[1]
Flavonoid/phenolic aglycones (in extracts)	Mitochondrial apoptosis; caspases; cell cycle	Pro-apoptotic; antiproliferative	[22]
Polyphenol hydroxyl groups (synthesis role)	Metal-ion redox reduction; biomolecular capping	Green nanoparticle formation and stabilization	[2]

Bioavailability Barriers

A substantial proportion of the phytochemical derived from Moringa oleifera M. oleifera phytochemical, have poor biopharmaceutical properties like water solubility decreases dissolution and absorption; chemical and thermal instability, which is due to oxidation and degradation of polyphenols through processing, storage and digestion [18], first-pass metabolism results in a reduction of systemic exposure. The inconsistent responses are compounded by the changing composition of crude extracts depending on plant part, harvest and solvent [19]. These restrictions account for the frequently large difference between activity in vitro versus in vivo and provide a strong justification for developing nanoscale delivery strategies [9].

Nanodelivery Approaches for Bioactives from M. oleifera

Nanodelivery enhances solubility, stabilizes labile compounds, and tailors the release profile [20]. High better encapsulation efficiency (reported to be ≈85–90%) allowing a controlled release under conditions mimicking gastrointestinal ones was achieved, by alginate/chitosan nanocapsules of an antioxidant-rich fraction obtained from roasted M. oleifera leaf extract [21]. Although the high encapsulation of bioactives from leaf extract was obtained in composite polymeric nanoparticles, e.g., PCL/montmorillonite [22], Chitosan-based mucoadhesive carriers lengthened the retention in mucosae [23], mucosae retention time lengthened using chitosan-based mucoadhesive carriers. and flexible M. oleifera-encapsulated nanoliposomes displayed cell-penetrating ability as evidenced by their anti-photoaging activity employing UVB-exposed HaCaT cells [24]. Hydrophobic constituents are the properties of solid lipid nanoparticles and nanostructured lipid carriers [25]. When carriers protect the labile phenolic groups from oxidation, they preserve the biochemical (redox and enzyme-modulating) activity of encapsulated bioactives, frequently enhancing activity at lower doses than provided by their respective conventional extracts [26]. Table 2: Comparison of representative carrier systems.

Table 2. Comparison of representative nanocarrier systems for M. oleifera bioactives [27]

Nanocarrier type	Encapsulated cargo	Typical size / EE*	Release / functional outcome
Alginate/chitosan nanocapsules	Antioxidant-rich roasted-leaf fraction	~200–400 nm; EE ~85–90%	Sustained GI release; preserved antioxidant activity
Chitosan mucoadhesive nanoparticles	Leaf bioactives / extract	~150–300 nm; EE ~70–85%	Prolonged mucosal residence; enhanced uptake
Flexible nanoliposomes	M. oleifera isothiocyanate (moringin)	~80–150 nm; EE ~75–85%	Improved intracellular delivery; anti-photoaging (HaCaT)
Solid lipid NPs / NLC	Hydrophobic constituents	~50–200 nm; EE variable	Controlled release of lipophilic bioactives
PCL/montmorillonite composite NPs	Leaf-extract bioactives	Sub-micron; high EE	High-efficiency encapsulation; thermal protection
Maltodextrin/gum-arabic micro/nano	Leaf phenolics	Micro–nano range	Enhanced thermal / storage stability

**EE = encapsulation efficiency. Values are representative ranges from the cited primary studies and should be verified against original sources*

Green Synthesis of M. oleifera-Mediated Nanoparticles and Their Biomedical/Environmental Applications

M. oleifera is widely used as a green nanofactory platform, and its extracts containing polyphenols are mostly utilized for reducing, capping and stabilization agents [28]. Spherical AgNPs (5--50 nm) synthesized from leaf extracts/methods/status are highly effective as antimicrobial and catalytic agents [29]; plant based anti-cancer activity of AgNPX through Apoptosis inducing selective cytotoxicity on

carcinoma cell lines has been reported previously [30]. Iron nanoparticles based on green processes have been proposed as sustainable platforms that could be relevant in low- and middle-income settings [31], while M. oleifera-based synthetic routes yielded ZnO nanoparticles with well-defined physical properties and formation mechanisms [32]. Likewise, fabricated palladium and TiO_2 NPs by M. oleifera extracts to be used in antibacterial and larvicidal and photocatalytic activity applications, respectively. The basic biochemical mechanism underlying these reactions—redox reduction of metal ions by polyphenol hydroxyls and biomolecular capping [33] (Figure 1)—supports both uses attributed to M. oleifera: being a source of phytotherapy and a green nanotechnology platform.

This illustrates the biomedical–environmental continuum of these functional biogenic nanoparticles held together through a shared redox chemistry engendered by polyphenols, where we know that polyphenol-rich extracts maintain high amounts of antioxidants over time [28]. From a biomedical perspective, together with the strong antimicrobial activity reported for AgNPs and similar nanoparticles supporting surface coatings and wound care applications as well as disinfection selected nanoparticles also induce selective cytotoxicity against cancer cell lines which relates to the well-characterized antiproliferative effect of M. oleifera extracts. Nanoparticles containing its bioactive compoutds stimulate antioxidant biotype responses and modulate inflammatory as well. On the environmental view point, it is in this same chemistry direction to be employed on a water treatment and/or degradation of dye or vector control applications [34], since both processes explicitly mentioned lie within this path due to common factor type mix of nature based reduction/capping active as opposed to the more traditional separate/mix /technology branch [25]. Finally, the broad pharmacological properties of this plant—namely hepatoprotective, cardioprotective, antidiabetic and neuroprotective activities—constitutes the biomedical end of this continuum [1].

Safety, Regulatory, and Translational Considerations

Despite this trend, many obstacles remain before mass adoption is achieved. The long-term toxicity, immunogenicity, off-target effects, and biodistribution of M. oleifera-derived nanocarriers and biogenic nanoparticles are still not fully understood [31]. Plant source, extraction, and synthesis parameters are variable to inconsistent particle size, shape, and surface chemistry that greatly affect activity and safety. Nanomaterials undergo a considerably more rigorous regulatory process than conventional herbal products, and scalable, reproducible manufacturing with adequate quality assurance is still in its infancy. There are, so far, no clinical trials of nanoformulated bioactives of M. oleifera.

DISCUSSION

Moringa oleifera is a one-of-a-kind medicinal plant; it possesses an unparalleled nutritional density and extreme phytochemical diversity, can be globally sustainably cultivated, and is culturally ubiquitous, yet it ironically embodies the biopharmaceutical challenges common throughout almost all other green medicine paradigms. In this context, the current synthesis adds to these efforts, that is, mapping every clinical endpoint where a positive pharmacological effect has been reported in the literature with respect to some particular biochemical target (Section 4; Figure 1) that supports an overarching rationale for nanotherapeutics: nanoencapsulation protects polyphenolic bioactives from oxidation or thermal degradation [35]. which are critical mechanisms of attenuation of redox- and enzyme-modulating activity. All these observations concur with the previously available data showing that nanosizing M. oleifera extracts (~100 nm) greatly increases the bioavailability and therapeutic efficacies of their phytoconstituents versus conventionally processed crude formulations (microns).

Importantly, while previous reviews have separately analyzed the therapeutic nanoencapsulation of M. oleifera bioactives and various green-synthesis applications as distinct pathways of bioactive cargo, this analysis demonstrates that a single polyphenol-driven reduction–capping pathway common to both applications governs their installation together in ways not previously articulated in the literature. The strategic convergence of mechanisms offers an integrative theoretical framework with translational applications where advances in chemical stabilization strategies for the rational production of standardized nutraceuticals and a broad category of engineered biogenic nanoparticles for

environmental applications may benefit from reciprocal knowledge. Therefore, nanodelivery and green nanoparticle synthesis should now be nominated as non-competitive technology but more like complementary/mechanistically coherent (yet divergent) biotic inputs to some intrinsic bioavailability hurdles faced by plants.

Nonetheless, those advancements have not (as yet) resolved some critical gaps. There are gaps in a direct pharmacokinetic comparison between nanoformulations and conventional formulations, limited capacity of bioavailability studies derived from solid predictive in vivo models, lack of systematic evaluation of toxicity, genotoxicity, and immunotoxicity potential, and absence of clear regulatory guiding principles. These issues, which would include but are not limited to the intrinsic variability of plant-based metabolites, lack of standardized procedures, and limited toxicological information, have regularly been cited as primary barriers towards the reproducible and safe-to-scale delivery of Moringa-derived nanomaterials [36].

CONCLUSION

From a biochemical perspective, Moringa oleifera provides a multifaceted experimental platform: its abundant and chemically diverse phytochemicals interact with central enzyme and gene pathways, which helps explain its reported antioxidant, anti-inflammatory, and antidiabetic actions. As many of these bioactives are chemically labile and possess low bioavailability—a generalized feature of botanical medicines—the M. oleifera model is well positioned to screen delivery strategies that aim to stabilize and boost activity. Importantly, polyphenolic hydroxyl groups that activate cellular antioxidant defenses also have had active chemical functions in metal ion reduction and nanoparticle capping during green synthesis. Thus, nanoencapsulation and green biosynthesis mediate retention of labile chemistry as well as the emergence of new desirable properties (amines, agglomerates, and micronized forms convert 5–50 nm nanoparticles to potent antimicrobial/antiviral photocatalytic activity) in otherwise unreactive chemical systems unique to the specific sources of nucleic acids. This review integrates biochemical data on M. oleifera into a mechanistic framework, providing this just-in-time due to the parallel development of moringa-derived nanoformulations. Hence, the role of the prioritization towards developing nanodelivery techniques in stabilizing and standardizing nutraceuticals and therapeutics derived from moringa is to utilize green synthesis with particular relevance to scalable, eco-friendly antimicrobial and water treatment applications (particularly for LMICs); pursue reproducible pharmacokinetic, in vivo, and toxicological studies within multidisciplinary consortia that enable transparent regulatory pathways and industrial-level manufacturing quality. However, we note that the vast majority of the available evidence is at a preclinical level, and translational and clinical research are needed before confirming safety and efficacy.

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مراجعة شاملة لتقنية النانو الخضراء وأنظمة توصيل النانو للمركبات النشطة بيولوجيا في نبات المورينجا أوليفيرا

الملخص

يعد نبات المورينغا أوليفيرا نبات طبي متعدد الاستخدامات من أكثر النباتات دراسةً في علم العقاقير والكيمياء النباتية، ويعرف أيضًا باسم "شجرة المعجزة". يحتوي أوراق هذا النبات وبذوره على نسبة عالية من الفلافونويدات والأحماض الفينولية والفيتامينات والكاروتينات والجلوكوزينولات والإيزوثيوسيانات (ITCsوالقلويدات والببتيدات النشطة بيولوجيًا ذات التأثيرات المضادة للأكسدة والالتهابات والميكروبات والسرطان. وقد أُجريت العديد من الدراسات حول مستخلصات البوليفينول من نبات المورينغا، ومؤخرًا أصبح برنامجًا طبيعيًا بالكامل يُستخدم فيه جسيمات أكسيد المعادن النانوية كعوامل تركيب صديقة للبيئة. مع ذلك، فإن هذه الإمكانية الدوائية الفريدة محدودة بشدة بسبب خصائصها الفيزيائية والكيميائية، مثل انخفاض ذوبانها في الماء وعدم استقرارها الكيميائي والحراري. توفر كيمياء الأكسدة والاختزال للبوليفينول رابطًا آليًا موحدًا يربط بين مساهمات المركبات النشطة بيولوجيًا في المورينغا أوليفيرا في أدوارها العلاجية والعمليات الجزيئية المشاركة في التخليق الحيوي واستقرار الجسيمات النانوية، مما يجعل النبات مصدرًا للعلاج النباتي ومنصة لتكنولوجيا النانو الخضراء. على المستوى البيوكيميائي، تعمل هذه المركبات على تحرير الجذور الحرة عبر آليات متعددة، وتحديدًا من خلال تنشيط محور إنزيم مضادات الأكسدة) NRF2العامل النووي المرتبط بالخلايا الحمراء 2)/المرحلة الثانية (SOD، CAT، GPx) وتثبيط الإشارات الالتهابية التي يتوسطها) NF-κBالعامل النووي كابا ب) والتعديل الأيضي للإنزيمات مثل ألفا-أميليز وألفا-جلوكوزيداز؛ علاوة على ذلك، أظهرت أنظمة النواقل النانوية استقرارًا مُحسَّنًا مع كفاءة تغليف نموذجية تتراوح بين 70 و95%، إلى جانب خصائص إطلاق مُتحكَّم بها. وتليها جسيمات نانوية مُصنَّعة حيويًا (5-50 نانومتر) تتميز بخصائص مضادة للميكروبات، ومحفزة ضوئيًا، وسامة للخلايا، وذلك بفضل مجموعات الهيدروكسيل متعددة الفينول التي تعمل بشكل متكافئ، والتي تُحفِّز آليات الدفاع ضد الإجهاد التأكسدي، بينما تُحفِّز في الوقت نفسه عمليات الأكسدة والاختزال المسؤولة عن اختزال/تثبيت أيونات المعادن أثناء عملية التصنيع. تسعى هذه المراجعة إلى تقديم نظرة عامة متكاملة عن نبات المورينجا من خلال دمج خصائصه الكيميائية النباتية/الدوائية، وآلياته الكيميائية الحيوية، ومكوناته النشطة بيولوجيًا المُعزَّزة بتقنية النانو.

الكلمات المفتاحية: الفلافونويدات، مسار Nrf2، التغليف النانوي، جسيمات الفضة النانوية