WISELEAF SCIENTIFIC VENTURES

CHAPTER 6: Herbal Formulations and Novel Drug Delivery Systems

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Abstract

The phytochemicals of *Moringa oleifera* exhibit considerable therapeutic potential; however, conventional methods of administration suffer from drawbacks including inadequate solubility, limited bioavailability, chemical instability and non-targeted release. This chapter discusses the potential of *Moringa oleifera* bioactive chemicals and NDDS in association with drug delivery systems as efficient approaches to mitigate the limitations mentioned above. The chapter describes the main bioactive components of *Moringa oleifera*, including flavonoids (quercetin, kaempferol), phenolic acids, glucosinolate (isothiocyanates) and certain peptides linking their molecular structures to anti-inflammatory properties as well as antioxidant, antidiabetic, antimicrobial and neuroprotective activities. This chapter explores the ability of various nanotechnology-based carriers including polymeric nanoparticles, solid lipid nanoparticles (SLNs), nano emulsions and liposomes to entrap Moringa extracts thereby improving stability, mediating controlled release and enhancing cellular uptake. Also included are advanced applications like transdermal patches, implants and ligand targeting systems for localized treatment (e.g., cancer). This chapter provides a detailed conceptual framework for designing efficient *Moringa oleifera* based novel drug delivery systems integrating phytochemistry and pharmaceutical technology. This highlights the potential of these preparations to translate traditional ethnopharmacological knowledge into efficacious and reproducible treatment strategies with well-defined costs, thereby integrating herbal medicine within a novel framework of precision therapeutics.

Keywords: *Moringa oleifera*, herbal, nanoformulation, novel drug delivery systems, antioxidant, anti-inflammatory

1. Introduction

M. oleifera, also called the miracle tree, 'flourishes worldwide in tropical and subtropical areas, including Asia, Africa, Central America, and Madagascar (1). *M.oleifera*, the most thoroughly researched species of thirteen *M. oleifera* (*Moringa Rivae, Moringa arborea, Moringa rivae, (2) Moringa ruspoliana, Moringa ovalifolia, Moringa drouhardii, Moringa hildebrandtii, Moringa concanensis, Moringa borziana, Moringa longituba, Moringa pygmaea, Moringa peregrina, Moringa stenopetala*) with *M. oleifera* being notably recognized for its functions in nutrition, biogas, production, and fertilizer, among others (3). Herbal medicines are one of the oldest forms of healthcare and still hold an important place in modern therapeutics. Due to their various pharmacological activities, natural origin and good safety profiles, the herbal products are increasingly investigated as therapeutic agents for a wide range of disease prevention and treatment. Nevertheless, traditional herbal preparations usually face multiple obstacles such as poor water solubility, low bioavailability, instability of active ingredients, rapid degradation loss of efficacy and reduced specificity in targeting tissues. Such limitations may substantially diminish the clinical efficacy of herbal medications (4,5). New drug delivery systems (NDDS) are novel systems based on the recent advances in pharmaceutical technology that offer modern routes to surpass the challenges of conventional herbal formulations. TDDS including nanoparticles, liposomes, phytosomes, nanoemulsions, microspheres and transdermal systems have shown impressive capability in solubilising herbal bioactives with great enhancement in absorption and stability; delivery of these compounds as well as controlled release. Such systems can also enhance the pharmacokinetic and dynamic profiles of phytoconstituents, reduce side effects and improve adherence in patients (6). Compounds derived from plants have been used to treat human diseases for centuries, with their therapeutic applications supported by modern science and clinical trials. These formulations not only provide controlled and targeted drug delivery but also assist in the uniform quality control and marketing of herbal products. Hence, NDDS has made herbal formulations the subject of considerable interest in

pharmaceutical research and development (7). This chapter introduces the background of herbal formulations and their challenges, highlights new drug delivery systems for delivering herbal therapeutics, and focuses on the novel research directions currently being explored in this rapidly evolving field.

2. Herbal Formulation of *M. oleifera*

M. oleifera has become scientifically and economically important as a medicinal plant because of its high utility and pharmacological properties. In dosage forms, barks, leaves, roots, seeds and seed oil of *M. oleifera* have been formulated as capsules, powders, pills, syrups creams, teas suspensions etc. The formulations aim to increase the stability, therapeutic effectiveness, patient adherence and bioavailability of the phytoconstituents. Current developments are directed towards the application of nano-based delivery systems to overcome the limitations of conventional phytomedicines (8).

2.1 Conventional and Herbal Formulations

Pharmaceutical forms of *M. oleifera* include tablets, powders, decoctions, syrup capsules, suspensions, lotions, ointments and herbal infusions. Typically, the leaves are dried and ground for oral consumption or mixed into other medicinal compounds. Taken together, these traditional dosage forms are widely used due to their ease of preparation, low cost and suitability for prolonged therapy (9). Due to the presence of proteins, vitamins, minerals, polyphenols, flavonoids, and antioxidants, a variety of leaf powder formulations have been advertised as nutritional supplements. Seeds' oil compositions have been incorporated into dermatological and cosmetic products for their emollient and anti-inflammatory properties. Formulations are prepared for antioxidant, antibacterial, antidiabetic, hepatoprotective and nutritive purposes (traditionally). However, barriers including poor water solubility, instability of phytoconstituents and low bioavailability, can limit their medicinal activity (10).

2.2 Powders and Capsules

Powder dosages are among the earliest and most common types of formulation of *M. oleifera*. The powdered form consists of dried whole plant material crushed into powder, with fresh leaves shade dried, then pulverized, sieved through a fine mesh sieve and packaged as bulk powders or encapsulated in hard gelatin capsules. Due to the higher content of proteins and

amino acids, iron, calcium, β-carotene, vitamin C, phenolic compounds and other components, Moringa leaf powder is widely used as a nutraceutical supplement (11).

Compared to bulk powders, capsule formulations are more consistent in dosage, more convenient and portable, and improve patient adherence. Many studies have shown that Moringa leaf extract can be encapsulated for its antioxidant and antidiabetic properties (12). Table 1 discusses about the powders and capsules made up of *M. oleifera.*

Table 1 *M. oleifera* Powders and Capsules

Dosage Form	Plant part	Method of Preparation	Uses	Reference
Leaf Powder	Leaves	Shade drying and pulverization	Nutritional supplement	13
Capsules	Leaf extract	Encapsulation of dried extract	Antioxidant and antidiabetic	14
Nutraceutical Capsules	Leaves	Standardized powder filling	Standardized powder filling	14

2.3 Tablets and Granules

M. oleifera is formulated into tablets using dried leaf powder/hydroalcoholic extracts and medicinal excipients, including microcrystalline cellulose, starch, lactose and binders. Better shelf-life, accurate dosage and easier patient compliance, travel-friendly are the advantages offered by tablets (15).

The granules are offered either as an intermediate for direct oral materials. Moringa pills are usually formulated through wet granulation or direct compression. Friability, hardness, dissolution & disintegration time and stability & weight fluctuation are evaluated for these formulations. Moringa capsules contain antidiabetic antioxidant, and nutritional supplementing capabilities supported by multiple investigations (16). Table 2 displays the tablets and granules.

Table 2 *M. oleifera* of Tablets and Granules

Formulation	Plant Part	Evaluation Parameters	Uses	Reference
Leaf powder tablets	Moringa leaf powder	Hardness, friability, dissolution	Nutritional supplement	17
Herbal granules	Leaf extract granules	Flow property, moisture content	Antioxidant activity	18
Effervescent tablets	Moringa extract	Disintegration and stability	Health supplement	19

2.4 Syrups and Suspensions

M. oleifera -derived suspensions and syrups are mainly developed for geriatric, paediatric and nutraceutical purposes. Syrups are mostly derived from aqueous or hydroalcoholic extracts along with their active ingredient, preservatives, sweeteners, modifiers, viscosity and flavouring substances (18).

Suspensions are prepared when solid plant materials need to be uniformly distributed within a liquid medium. Use of suspension forms improves taste-masking and the ability to take. Moringa syrups are marketed as dietary supplements for the treatment of anaemia, malnutrition and Vitamin deficiencies (19). Table 3 discusses the suspensions and syrups.

Table 3 Suspensions and Syrups of *M. oleifera*

Dosage Form	Plant part	Application	Advantages	Reference
Herbal syrups	Aqueous leaf extract	Nutritional supplement	Improved palatability	8
Oral suspension	Extract dispersion	Paediatric administration	Easy swallowing	19
Nutritional tonics	Leaf extract with vitamins	Malnutrition therapy	Enhanced patient compliance	20

2.5 Topical Gels and Creams

Topical gels and creams obtained from *M. oleifera* have been substantially studied for their antioxidant, anti-inflammatory, antibacterial, injury repair, and cosmetic qualities. Seed oils and Leaf extract are the predominant components in topical preparations. Gels are often formulated using hydroxypropyl methylcellulose, carbopol or sodium alginate as gelling agents. Creams are composed of hydrophilic emulsion or lipophilic emulsions that include *Moringa* leaf extract and seed oil (21). Various research exhibit that *Moringa* based creams have anti-inflammatory and moisturizing properties attributed to tocopherols, flavonoids, and fatty acids. *Moringa* topical preparations have antibacterial properties against skin infections and facilitates wound contraction and tissue regeneration (22). Table 4 portrays the various topical formulations of this plant.

Table 4 Topical Formulations of *M. oleifera*

Formulation	Plant Part	Application	Reference
Herbal gel	Leaf extract	Wound healing	21
Anti-inflammatory cream	Seed oil	Skin inflammation	22
Cosmetic cream	Seed oil and antioxidants	Moisturising and antiageing	23
Antimicrobial ointment	Leaf extract	Skin infections	24

3 Fundamental Challenges in Herbal Drug Delivery

3.1 Poor Solubility of Herbal Bioactives

A significant portion of bioactive phytochemicals especially polyphenols, flavonoids, and terpenoids demonstrate inadequate hydrophilicity. Compounds including kaempferol, quercetin, resveratrol, and curcumin are poorly soluble in water, limiting their solubility in gastrointestinal fluids. Inadequate solubility directly reduces the amount of the active chemical available for absorption across the intestinal epithelium (25).

3.2 Chemical Instability and Degradation

Some methods predict the deterioration of herbal medicine therapy. Many alkaloids are heat sensitive; therefore, prolonged boiling or decoction can result in their degradation, as these

phytochemicals are thermolabile. This degradation reduces the number of bioactive compounds and can also generate potentially toxic breakdown products (26).

Beyond their sensitivity to temperature, phytoactive agents degrade during storage and gastrointestinal passage. Factors leading to instability encompass:

Oxidation: Many flavonoids and phenolic compounds are susceptible to oxidative degradation when exposed to air and light.

pH sensitivity: Before reaching the small intestine, gastric acidity can degrade acid-labile agents in the blood stream.

Enzymatic degradation: Digestive enzymes along the length of the gastrointestinal tract can metabolise specific phytochemicals

Photodegradation: The storage of photosensitive substances is greatly affected by light exposure.

3.3 High molecular weight and lipophilic Profile

Many bioactive phytochemicals have molecular characteristics that prevent passive diffusion across biological membranes. Those include high molecular weight, strong hydrogen bonding and extremely high polarity, which may restrict diffusion through the paracellular pathway or transcellular transport. Some compounds act as efflux transporter substrates, particularly the P-glycoprotein (P-gp), which actively extrudes orally administered toxicants into the intestinal lumen and reduces their bioavailability (27).

4. Introduction of Nano formulations

These nanoformulations are drug delivery systems that are carefully designed at the nanoscale (1-1000 nm) based on their ability to encapsulate, protect, and transport therapeutic molecules to desired sites in the body. Nanoformulations offer an innovative approach to addressing the challenges posed by crude plant extracts and isolated bioactive compounds in herbal medicines and phytopharmaceuticals. The integration of nanotechnology with traditional herbal medicine has led to the emergence of “nano phytomedicine,” an innovative discipline that aims to enhance the therapeutic efficacy of naturally occurring phytochemicals and minimize their adverse effects (28).

4.1 Nanoformulation of *M. oleifera*: Need

Despite the great therapeutic potential of *M. oleifera* as a free radical scavenger, inflammation fighter, glucose lowering therapy, antineoplastic, cardioprotective and antibacterial agent, there are a number of complex biopharmaceutical challenges associated with its clinical utility for the bioactive compounds (29).

Enhanced Solubility: The micelles formed by the introduction of lipophilic compounds into amphiphilic nanocarrier matrices can increase apparent aqueous solubility between 10 and 1000 times.

Protection against degradation: Sensitive chemicals are protected from enzymatic degradation and acidic hydrolysis by encapsulation within nanoparticles.

Controlled Release: Because of the slow-release characteristics of nanoparticle matrices, it is possible to decrease the frequency of dosage and maintain therapeutic drug concentrations.

Translocation across physiological barriers (such as the intestinal epithelium and blood-brain barrier): The biodistribution of nanomaterials can differ considerably due to their dimensions (generally ~50–300 nm) which can enhance permeation.

Targeted Delivery: Passive targeting by increased permeability and retention effect in pathological tissues, or active targeting through surface functionalization with specific ligands.

Improved Cellular Uptake: Nanoparticles are taken up by endocytic pathways, bypassing efflux mechanisms such as P-glycoprotein.

4.2 The Benefits of Nanoformulation for Moringa Bioactives

The following functions of nanoencapsulation of Moringa extracts and their bioactives extracts directly address these restraints. Table 5 discusses the benefits of nanoformulations prepared from this plant.

Table 5 Benefits of Nanoformulations for Moringa Bioactives

Advantage	Mechanism	Therapeutic Benefit	Reference
Enhance Solubility	Embedding lipophilic molecules into amphiphilic nanocarrier frameworks	Improved dissolution and absorption	30
Protection from degradation	Physical encapsulation can protect labile compounds from acidic hydrolysis and enzymatic digestion	Extended half-life and stability	31
Controlled Release	Nanoparticle-based matrix allows sustained-release profiles	Reduced dosing frequency, maintained therapeutic levels	32
Enhanced Permeability	Nanoscale size enables transport across biological obstacles	Enhanced oral bioavailability; possible CNS targeting	33
Targeted Delivery	Passive targeting by means of the EPR effect or active targeting using ligands	Higher therapeutic index (TI), lower apoptosis	34

Improved Cellular Uptake	Internalization of endocytic by bypassing P-gp efflux	Higher intracellular concentrations	35

4.3 Classification of Nanoformulations for *M. oleifera*

A thorough examination of current research on nanoformulations for *M. oleifera* into three principal types: Polymeric Nanoparticles, Lipid Based Nanocarriers, and Green Synthesized Metallic Nanoparticles. Emerging systems such as nanoemulsions and quantum dots constitute more specialized categories.

4.3.1 Polymeric Nanoparticles

Polymeric nanoparticles are colloidal systems made of biodegradable natural or synthetic polymers that encapsulate therapeutic compounds inside a polymer matrix (nanosphere) or encased by a polymer membrane (36).

4.3.2 Chitosan Nanoparticles

Chitosan nanoparticles; those sub-microscopic carriers composed of chitosan which is a natural polysaccharide polymer biocompatible and biodegradable and obtained from shells provided by the exoskeleton of crustaceans such as shrimp, crab, etc. They are very safe, non-toxic and biocompatible, so they can be easily utilised as "nanovehicles" for the delivery of drugs/proteins/genes to the body (37).

4.3.3 PLGA and PLA Based Nanoparticles

Poly (lactic-co-glycolic acid) and poly (lactic acid), as synthetic biodegradable polyesters approved by the FDA, are routinely used as drug delivery systems.

4.3.3.1 PLGA-Chitosan Hybrid Nanoparticles: PLGA chitosan nanoparticles loaded with Moringa extract promoted higher death of HepG2 liver cancer cells than the free extract (38).

4.3.3.2 Targeted PLA-PEG-FA/Chitosan PLA Nanoparticles: Towards a dual polymer system with folic acid conjugation, in the targeting of breast neoplasm cells (BT-549) by means of active focusing on folate receptors able to raise by up to 3.8-fold cytoplasmic bioavailability against non-targeted nanoparticles (39).

4.3.4 Other Polymeric Systems

4.3.4.1 Moringa Gum Based Nanogels: pH-responsive nanogels were prepared using Moringa gum as the polymer matrix which have 98% drug loading efficiency for doxorubicin through functionalization of morpholino group, and compounds developed were found to have pH-dependent release characteristics and negligible effect at pH 7.4. Rendering dopamine-like response from potential dopaminergic neurons (40).

4.3.4.2 Lipid Based Nanocarriers

Lipid based solutions exploit the biocompatibility and absorption promotion properties of lipids to increase the oral bioavailability of Moringa bioactives (41).

4.3.5 Phytosomes

Phytosomes are molecular complexes between phospholipids, usually phosphatidylcholine and polyphenolic compounds formed by hydrogen bonding. Unlike liposomes, the phytosome is not a vesicle but is a solid-state complex (42).

4.3.6 Niosomes

Niosomes are vesicular systems based on non-ionic surfactants and offer advantages over liposomes, as they possess better chemical stability (phospholipid oxidation). They are less expensive and easier to manufacture (43).

4.3.7 Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs)

SLNs and NLCs possess a solid lipid structure at physiological temperatures, with NLCs integrating both solid and liquid lipids to improve drug loading capacity. *M. oleifera* mucilage as a natural mucoadhesive polymer for the treatment of Alzheimer's disease. The refined formulation demonstrated (44).

4.3.8 Lyotropic Liquid Crystals (LLCs)

LLCs are sophisticated self-assembled mesophase structures (lamellar, cubic, hexagonal) that arise from the interaction of amphiphilic molecules with polar liquids. An oily phase and a medicinal agent indicate the use of Moronga fixed oil in LLC formation. Moringa oil served as both an organic scaffold and a bioactive source, respectively. Hexagonal phase compositions demonstrated suitable topical pseudoplastic (shear-thinning) rheological properties (45).

4.3.9 Green Synthesized Metallic Nanoparticles

Moringa extracts serve as natural reducing, stabilizing, and capping agents in eco-friendly production of metal nanoparticles, thereby eliminating the need for toxic chemical reagents. Table 6 displays the synthesis parameters and outcomes of this plant.

Table 6 Synthesis Parameters and outcomes of *M. oleifera*

Moringa Part	Size Range	Shape	Applications	Reference
Leaves (fresh)	9 nm	Spherical	Antimicrobial	46
Leaves (freeze dried)	11 nm	Spherical	Antibacterial	
Flowers	8 nm	Spherical	Antibacterial	
Stem Bark	40 nm	Spherical/Pentagon	Anticancer	
Seeds	15.5 ± 4.5 nm	Spherical	Heavy metal modulation	

4.3.10 Gold Nanoparticles (AuNPs)

Moringa extracts from leaves, pods, gum, and flowers were used to synthesize gold nanoparticles (AuNPs) which also have applications in bioimaging, photothermal treatment and biosensing (47).

4.3.11 Metals and Metal Oxide Nanoparticles from other types

4.3.11.1 Zinc Oxide Nanoparticles (ZnO NPs)

Moringa-derived zinc oxide nanoparticles (ZnO NPs) are ultrafine particles of ZnO made via eco-friendly "green synthesis." A scientist blends zinc with Moringa oleifera (plant) extract instead of using irritant chemicals. The plant's natural compounds serve as the "reducing agent," which converts zinc ions into solid particles, and the "stabilizing agent" which prevents the particles from clumping (48).

4.3.11.2 Iron Oxide Nanoparticles (Fe_3O_4 NPs)

Iron Oxide Nanoparticles (IONPs) consist of nanoscale magnetite (Fe_3O_4) or maghemite (γ-Fe_2O_3) structures, 10–100 nm in size. These materials are commonly used in the medical field

due to their superparamagnetism and biocompatibility, making them perfect candidates for applications such as drug delivery, cancer treatments and diagnostic imaging (49).

4.3.11.3 Titanium Dioxide nanoparticles (TiO_2 NPs)

Titanium Dioxide nanoparticles (TiO_2 NPs, typically < 100nm in size) are used for their unique optical, UV-absorbing and photocatalytic properties. Gel particles, which are made up of clear Polystyrene or associated with natural polymeric E-Waste, and that easily act as an anchor vacuum in jets, etc., from UV rays (50).

4.3.12 Nanoemulsions

Nanoemulsions are heterogeneous systems with nanodroplet sizes (10–20 nm) in which one liquid phase is dispersed in another intrinsically immiscible liquid.

4.3.12.1 Hypogylcemic peptide delivery: Hypoglycemic peptide *M. oleifera* histine protein peptide-2 (MoHp P-2) was formulated as an emulsion by high-speed homogenous emulsification of Moringa seed.

4.3.12.2 Quantum Dots

Quantum dots are 2-10 nm nanoparticles that are the zero-dimensional semiconductor nanoparticles with special optical and electrical properties.

Silver Quantum Dots (Ag QDs) based on Moringa seeds and leaves: Silver Quantum Dots (Ag QDs) synthesized using Moringa seed and leaf extracts via green synthesis exhibit distinct quantum-tunnelling properties compared to larger Ag nanoparticles. These specific features render them potential candidates for biosensing, bioimaging, targeted drug delivery and theranostic applications (52,53). Table 7 shows a comparative summary of various nanocarriers.

Table 7 Comparative Summary of *M. oleifera* Nanoemulsions

Category	**Subtype**	**Size range (nm)**	**Applications**
Polymeric	Chitosan	100-150	Oral nutraceutical, wound healing
	PLGA/PLA NPs	200-300	Cancer therapy
	Moringa gum nanogel	100-200	Targeted drug delivery

Lipid Based	Phytosomes	250+300	Cancer therapy
	Niosomes	180-200	Cardiovascular disease
	SLNs/NLCs	200-270	CNS disorders, topical
	Lyotropic LLCs	Mesophase	Topical delivery
Metallic	AgNPs	5-100	Antimicrobial, wound healing
	AuNPs	5-80	Diagnostics, therapy
	ZnO, Fe_3O_4, TiO_2	10-100	Photocatalytic, magnetic, wound healing
Emerging	Nanoemulsions	160-210	Functional foods, water treatment
	Quantum dots	2-10	Biosensing, imaging

Conclusion

Nanotechnology connects M. oleifera derived traditional herbal remedies with precision medicine by improving the efficacy, bioavailability, and targeted delivery of bioactive compounds. Collective data clearly show the effectiveness of nanoformulation strategies in bypassing the critical biopharmaceutical bottlenecks (insolubility, chemical instability, suboptimal bioavailability and biodistribution and poor release profiles) that have limited the clinical utility of this exceptional medicinal plant. This new field bridges the gap between nanotechnology and *M. oleifera* based therapeutics, creating a budding population of nanophytomedicine that converts herbal medicine from a highly practised discipline into an engineering discipline with well-defined pharmacokinetic characteristics, reproducible efficacy, and predictable safety profiles. Polymeric nanocarriers (natural, chitosan, lipids synthetic) usually have a better safety profile than other cargo carriers while metal-based nanoparticles need to be further evaluated for bio-security, as metal accumulation may raise concerns over long-term toxicity. The ability of *M. oleifera* phytochemicals to act primarily as natural reducing agents, stabilizing and capping agents for the green synthesis of metallic nanoparticles provides a unique advantage as they are widely used in green chemistry and sustainable pharmaceuticals. This characteristic makes *M. oleifera* an exceptionally versatile nanoscale "green tool," eliminating the need for hazardous chemical reducing agents in

nanoparticle synthesis. In conclusion, the nanoformulation of bioactives from *M. oleifera* is a Science-based formulation that carefully links ancient healing practices with modern pharmaceutical development to unleash the therapeutic potency of these miracle tree-derived molecules for future precision therapeutics.

Future Perspectives

However, many important gaps remain despite the great advances achieved. This includes mechanistic elucidation of intracellular trafficking pathways, nanoparticle-biofilm interactions and systems-level modulation of interconnected signaling networks (Nrf2-Keap1, NF-κB, MAPK, PI3K/Akt) which can be achieved using transcriptomics, proteomics and metabolomics-based approaches. Secondly, transitioning to a clinical study needs GMP-compliant scalable manufacturing systems and thorough ADME profiling followed by systematic toxicological assessment in accordance with international regulatory guidance (OECD, ICH, FDA, EMA) leading into a First-in-Human Stage Phase I trial for priority indications, such as early breast cancer (phytosomes). Thirdly, next-level targeting strategies such as ligand-conjugated nanoparticles (folate, transferrin, antibodies), stimuli-responsive systems (pH-sensitive, redox-sensitive, enzyme-responsive, thermosensitive) and multi-targeting should be further developed to improve therapeutic index and overcome tumor heterogeneity. Fourth, personalized nanomedicine strategies based on patient stratification biomarkers, theranostic nanoparticles (i.e., therapy plus diagnostic imaging), and pharmacogenomic factors will provide individualized selection of patients for immune-based therapies and active monitoring of therapeutic response in real-time. Lastly, given the importance of nanomedicines, considerations should instead be directed towards affordable and low-cost materials suitable for local sourcing with simplified downstream processing to facilitate technology transfer in LMICs together with capacity building and research networks within *M. oleifera* -endemic regions. If supported by ongoing investment in mechanistic research, scalable manufacturing, regulatory science and clinical development, *M. oleifera* nanomedicines may represent a new class of therapeutics that respects the thousands-year-old legacy of the "miracle tree" whilst meeting modern twenty-first-century standards for precision medicine.

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