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Unexplored and Emerging Formulations of Moringa oleifera: Opportunities and Challenges in Nutraceutical Development

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Abstract: *Moringa oleifera, popularly known as the "miracle tree," has emerged as a promising candidate for nutraceutical study because to its high nutritional and phytochemical content. M. Oleifera contains approximately 110 bioactive chemicals, including flavonoids, phenolic acids, glucosinolates, alkaloids, terpenoids, and sterols, which provide a variety of health benefits such as antioxidant, anti-inflammatory, antidiabetic, hepatoprotective, cardioprotective, and neuroprotective effects. Traditional formulations, such as powders, teas, and capsules, have limitations due to poor solubility, low bioavailability, short shelf life, and disagreeable taste or odour. To address these issues, innovative formulations such as nanoparticles, nanoemulsions, oral thin films, hydrogels, biopolymer-based encapsulation, spray-dried powders, and functional meals have been investigated for improved bioavailability, stability, and patient compliance.Furthermore, topical and transdermal applications of Moringa extracts in creams, gels, and films offer new opportunities in the cosmetic and dermatological domains. Beyond its therapeutic applications, M. Oleifera shows potential in tailored nutrition, pediatric and geriatric formulations, and long-term nutraceutical creation via byproducts. However, challenges such as variability in phytochemical content, a lack of large-scale clinical trials, safety concerns, regulatory hurdles, and supply chain sustainability have yet to be tackled. This review critically examines M. Oleifera's phytochemistry, therapeutic properties, current and novel delivery modes, and future prospects, highlighting both opportunities and challenges in adapting its traditional use to modern nutraceutical advances.*

Keywords: Moringa oleifera, Phytochemicals, Nutraceutical formulations, Antioxidant activity, Bioavailability enhancement

I. INTRODUCTION

India is well-known for its Ayurvedic treatments. Various plants have been employed in Ayurvedic medicine to treat ailments from ancient times. According to the World Health Organization, over 80% of the world's population relies on traditional medicine for primary care. Traditional healers use these plants as an important part of their healing techniques. Herbalists are traditional healers with a deep awareness of medicinal plants and their therapeutic properties. Due to the presence of secondary metabolites, medicinal plants are the backbone in many rural communities for treating a variety of ailments. [1] Moringa oleifera is a rapidly growing tree native to South Asia and Africa that has long been prized for its high nutritional value and therapeutic benefits: Its leaves, seeds, and pods contain high levels of vitamins, minerals, amino acids, antioxidants, and phytochemicals such flavonoids and glucosinolates. Moringa is becoming more popular as a nutraceutical ingredient due to rising customer demand for plant-based and functional diets. However, traditional formulations frequently fail to address issues such as poor stability, unpleasant taste, and inadequate bioavailability, prompting further research into advanced and consumer-friendly delivery strategies. Secondary metabolites are chemicals produced by plant cells through metabolic pathways. Secondary metabolites have been shown to have a wide range of biological effects, providing a medical foundation for the use of herbs in traditional

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medicine in many ancient civilizations. They have antibacterial, antiviral, antifungal, and antioxidant activities, which can help plants avoid illness. Plants contain several secondary metabolites (such as phenolics, flavonoids, tannins, alkaloids, and steroids) that are concentrated in specific sections of the plant, such as flowers, leaves, bark, root, and seeds. [2]Natural substances with antioxidant properties, metal-chelating ability, protein interaction, methylglyoxal trapping, and/or blocking the receptor for advanced glycation end products may reduce the development of AGEs. C-phycocyanin from Spirulina platensis has antioxidative, antidiabetic, anti-inflammatory, and immune-regulating effects, making it a promising natural chemical for diabetic therapy. [3]Okra mucilage and pod extracts, both ethanolic and aqueous, have been shown to reduce blood glucose levels in alloxan-induced diabetes animals. Water-soluble extracts of okra seeds and peel inhibited α-glucosidase and α-amylase enzymes, which are necessary for carbohydrate digestion. Okra-derived biomolecules have been shown to reduce hyperglycemia and protect against diabetic nephropathy and oxidative stress, making it a promising nutraceutical for controlling diabetes and related problems. [4] Moringa oleifera, commonly known as "Moringa," is the most developed form within the Moringaceae family. Moringa is an extremely nutritious plant with numerous applications. [5] In India and Pakistan, M. oleifera is known as Sohanjna and has spread throughout the country. The leaves are high in iron, hence it is recommended for expecting mothers. [6]Three nonlegislative organizations, including Trees for All Occasions, Church World Service, and Scholarly Concerns for Hunger Organization, have supported Moringa as "natural nutrition for the tropics." Moringa leaves are commonly used in food and pharmaceutical purposes. Several organizations across the world manufacture various Moringa leaf products, including tablets, capsules, tea, leaf powder, cleansers, and face wash. [7] Moringa is known as the "Never Die" plant because of its adaptability to a variety of soil, climatic, and environmental circumstances. The power of Moringa to mitigate the effects of global climate change is incredible It holds 50 times more CO2 than the Japanese tree Cedar and 20 times that of typical vegetation[8].

Phytochemicals

Studies have discovered around 110 bioactive compounds in MO, each with a protective or therapeutic property. Table 1 shows that the phytonutrient composition varies across the tree. Aside from being a highly nutritious and versatile tree, MO is rich in phytonutrients that both prevent and treat ailments. Furthermore, the composition of the phytochemistry in the plant varies according to the portion of the tree and the abiotic variables of the ecosystem in which it grows [9].MO phytochemicals fall into six categories: flavonoids, phenolic acids, glucosinolates, terpenes, alkaloids, and sterols [10,11]. Phenolic components in MO mostly include of phenolics, flavonoids, and phenolic acids. Although such phytochemicals are found throughout the plant, the seeds are exceptionally high in phenolic acids and flavonoids, including the polyphenols gallic acid, ellagic acid, and quercetin [12]. Flavonoids are often found in flavanol and glycoside forms. Out of the 26 flavonoids found in Missouri, myricetin, rhamnetin, and kaempferol are among the most ambulant. Furthermore, the leaves of the genus contain eleven phenolic acids, including caffeic, chlorogenic, ferulic, and syringic acids. Both flavonoids and phenolic acids have been shown to have antioxidant, anti-photoaging, and anti-cancer effects. However, MO's high phenolic acid content is the primary driving force behind its excellent scavenging action, which contributes significantly to its overall antioxidant, anti-inflammatory, and hepatoprotective activities [13,14]. When a pyronase moiety is anomerically linked to O-sulfated (Z)-thiohydroximate, it yields glucosinolate. Glucomoringin (4-O-(-L-rhamnopyranosyloxy)-benzyl glucosinolate) is the most frequent glucosinolate in MO, and moringin is its isothiocyanate. When plant tissue is disturbed, myrosinase is released, which then attaches to a glucosinolate to generate an isothiocyanate [14].These Components have anti-inflammatory and antibacterial properties by stimulating detoxifying enzymes. Isothiocyanates also exhibit apoptotic properties, which act as an anti-cancer agent. Furthermore, glucosinolates and isothiocyanates protect against hyperglycemia [11]. Carotenoids are the principal tetraterpenoid category found in MO leaves, with lutein being the most abundant carotenoid. MO contains carotenoids such as eluteoxanthin, 15-Z-β-carotene, lupeol acetate, β-amyrin, α-amyrin, 13-Z-lutein, and all-E-zeaxanthin. Tetraterpenoids' antioxidant activities defend against a wide range of disorders by trapping free radicals, which can damage cell architecture and cause inflammation [13, 14]. Furthermore, these phytoconstituents contribute to MO's natural broad-spectrum antibacterial effects against common periodontal infections. This makes it an effective oral health therapy for reducing the progression of periodontal disease [15]. MO

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contains many alkaloids, including marumoside A, marumoside B, and pyrrolemarumine-4-O-α-L-rhamnopyranoside. Alkaloids, particularly N,α-L-rhamnopyranosyl, have been shown to protect the heart from hypertension [11]. Moringa oleifera's bark and leaves contain β-sitosterol-2-O-β-D-galactopyranoside and β-sitosterol, both of which have anti-inflammatory properties via decreasing inflammatory factor release [11,14]. Furthermore, β-sitosterol reduces dietary cholesterol absorption in the intestines [16]

Unexplored and Emerging Formulations of Moringa Oleifera

Moringa oleifera, also known as the "miracle tree," contains numerous bioactive components, including flavonoids, phenolics, isothiocyanates, vitamins, and minerals. While traditional formulations such as powders, teas, and capsules have been extensively examined, numerous developing and unexplored formulations show promise for improved bioavailability, stability, and therapeutic efficacy.

Nanoparticle-Based Delivery: Moringa bioactives are encapsulated in lipid, polymeric, or inorganic nanoparticles to protect sensitive chemicals from degradation and enhance absorption.

Potential benefits include increased bioavailability, targeted distribution, controlled release, and phytochemical stability.

Research Gap: Although Moringa nanoparticles have been employed in preclinical research for antioxidant and anti-inflammatory effects, clinical uses are mainly unknown [17,18].

2. Nanoemulsions & Self-Emulsifying Systems

Concept: Oil-in-water nanoemulsions containing Moringa seed oil or leaf extracts.

Potential benefits include increased lipophilic chemical solubility, improved gastrointestinal absorption, and the ability to use functional meals or beverages.

Research Gap: There are little investigations on the large-scale manufacture, shelf-life stability, and sensory acceptance of such formulations [19].

3. Biopolymer-Based Encapsulation Uses natural polymers like alginate, chitosan, or starch to make beads or microcapsules using Moringa extracts.

Potential advantages include controlled release, protection against stomach degradation, and gut-targeted administration.

Research Gap: Few studies have investigated the combination of polymer types and the adjustment of release kinetics for optimum therapeutic efficacy (20).

4. Functional foods and beverages.

Concept: Moringa leaf powder or extracts are added to fortified foods, smoothies, dairy products, and nutraceutical beverages.

Potential Benefits: Provides bioactive compounds in an accessible and appetizing form; promotes cardiovascular, metabolic, and immunological health.

Research Gap: More research is needed on consumer acceptance, stability during processing, and interactions with other food ingredients [21].

5. Transdermal and topical formulations.

Creams, gels, or patches containing Moringa extracts or oils for targeted anti-inflammatory, antioxidant, or antibacterial properties.

Potential benefits: Bypasses first-pass metabolism, improves skin penetration, and addresses dermatological issues.

Research Gap: There is little standardization of extract concentration, skin penetration examination, or clinical efficacy trials [22].

6. Moringa Thin Films and Lozenges: Oral films or lozenges that dissolve quickly.

Potential benefits include increased patient compliance, buccal absorption, and systemic administration of bioactives.

Research Gap: Limited investigation into flavour masking, mechanical characteristics, and stability [23].

7. Hydrogel-Based Delivery Systems: Hydrogels with Moringa extracts provide controlled and sustained release of active components.

Potential Benefits: Ideal for wound healing, topical anti-inflammatory treatments, and long-term therapeutic effects.

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Research Gap: The majority of studies are experimental, with no standardized goods available for clinical usage [24].

8. Combination Formulations: Synergistic formulations of Moringa with other plants or nutraceuticals.

Potential benefits include increased bioactivity, multi-target therapeutic potential, and complimentary health effects.

Research Needed: A thorough assessment of synergistic effects, pharmacokinetics, and safety [25].

9. Lyophilized powders and spray-dried extracts.

Concept: Extracts are freeze-dried or spray-dried to create very stable powders for usage in capsules, tablets, or functional meals.

Potential benefits include the preservation of bioactive substances, increased shelf life, and more precise dosing.

Research Gap: Optimizing processing parameters to retain maximum phytochemical activity is required [26].

Therapeutic Properties:

Anti-inflammatory.

M. oleifera leaves contain bioactive combinations with anti-inflammatory effects. Using M. oleifera leaf extract reduced the generation of human macrophage cytokines (tumour necrosis factor-alpha, interleukin-8, and interleukin-6) induced by tobacco smoke concentrate and LPS (lipopolysaccharide). [30] When M. oleifera leaves were employed, macrophage cells treated with bacterial LPS were found to suppress nitric oxide (NO) production. [31]

One study found that quercetin from M. oleifera leaf inhibited the start of neutral factor kappa-beta, preventing inflammation and subsequent processes. [32] A watery preparation of M. oleifera root in rodents weighing between 120 and 160 g was tested for anti-inflammatory effects. The aqueous root concentrate of M. oleifera at 750 mg/kg, standard drug indomethacin at 10 mg/kg, and refined water as control were administered 30 minutes before edema was induced in rodent paws via subcutaneous infusion of carrageenin.

Moringa oleifera administration at 750 mg/kg reduced edema progression at 1, 3, and 5 hours by 53.5%, 44.6%, and 51.1%, respectively. It also reduced carrageenan-induced edema to a similar extent as the strong anti-inflammatory medicine indomethacin. [33]

Antioxidant properties.

Moringa oleifera has many antioxidant-rich chemicals. [47] Moringa oleifera leaf quantities, both mature and tender, demonstrated high antioxidant activity against free radicals, decreased oxidative stress to important biomolecules, and protected against oxidative stress. [34] Indian-origin M. Oleifera freeze-dried leaves showed antioxidant activity of 66.8% in ethanol and 65.1% in methanol. Both 80% methanol and 70% ethanol solvents were reported to be excellent for the extraction of cell reinforcement (antioxidant) chemicals. [52] Fluid concentrations of M. oleifera seed, fruit, and leaf demonstrated antioxidant activity. M. Oleifera leaves shown cell reinforcing properties due to the presence of kaempferol. [2] M. oleifera leaf cell reinforcement was studied using various in vitro setups, including beta-carotene blanching, decreasing force, lipid peroxidation, ferrous particle chelation, and DPPH/hydroxyl/superoxide radical scavenging. The polyphenolic fraction was found to be the most effective. [35]

Antihyperglycemic or antidiabetic characteristics.

Moringa oleifera was widely used in the treatment of diabetes. The results of the examination revealed that M. oleifera significantly lowered the blood glucose level. [36] Moringa's isothiocyanates have been shown to reduce both insulin resistance in the body and the process of gluconeogenesis in the liver. [49] The concentrated Moringa dry powder contained N-benzyl carbamates, benzyl ester, N-benzyl thiocarbamates, and benzyl nitrile. This is attributable to increased insulin secretion from the rats' pancreas, as well as lipid peroxidation and cyclooxygenase suppression. [48]

According to reports, scientists engaged rats in diabetes research by injecting streptozotocin (STE) into their abdomens (intraperitoneally) at a dose of 55 mg/kg. After consuming 250 mg/kg of M. oleifera extract for a month, malonaldehyde levels fell and inflammatory cytokines improved. [37]

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Antimicrobial properties.

M. oleifera leaf ethanol extracts had the broadest antibacterial action, effectively inhibiting Pseudomonas aeruginosa, Staphylococcus aureus, Escherichia coli, and Enterobacter aerogenes. Meanwhile, chloroform from the leaf extracts was solely effective against Salmonella typhimurium and E. coli. According to the findings, ethanol extracts from Moringa seeds were found to be effective against S. aureus and E. coli. [38] Clinical studies has indicated that M. oleifera infuses the body with antibacterial protection for the liver. [50] A daily intake of 500 mg of ethanol and aqueous extract reduced S. aureus and E. coli infection by 65%-80%. Researchers discovered that supercritical carbon dioxide concentrate derived from M. oleifera leaves and seeds inhibits S. aureus biomass production. [39] The Moringa extract inhibited the growth of Basidiobolus ranarum, Trichophyton mentagrophytes, Basidiobolus haptosporus, and Trichophyton rubrum. Moringa ethanol concentrate was found to be effective against Klebsiella pneumonia, Candida albicans, Enterobacter spp., E.coli, Salmonella typhi, P. aeruginosa, S. aureus, Streptococcus, and Proteus mirabilis. [40]

Hepatoprotective characteristics.

Certain studies investigated Moringa's ability to treat liver infections. [35,41,42] Moringa leaf extracts reduced the toxicity of carbon tetrachloride in rodent livers, as evidenced by a significant decrease in lactoperoxidase and increased levels of antioxidants such as superoxide dismutase, glutathione catalase, reductase, peroxidase, and S-transferase. [42] An ethanolic concentrate of M. Oleifera leaves was tested for its hepatoprotective effects on the liver in rodents treated with antitubercular drugs such as rifampicin, pyrazinamide, and isoniazid. The oral administration of the concentrate demonstrated critical defensive activities, including glutamate oxaloacetate transaminase, alkaline phosphatase, glutamate pyruvate transaminase, lipids and lipid peroxidation levels in the liver, and bilirubin levels in the serum. [43] Furthermore, a hepatoprotective study administering 7 g/day of Moringa leaf powder over 12 weeks showed a 30% reduction in alanine transaminase levels and a 25% reduction in aspartate aminotransferase levels, alongside enhanced antioxidant activity and improved liver function, without adverse effects. [51] These findings emphasized Moringa's dual therapeutic potential against infections and liver impairment.

Cardiovascular and neuroprotective disease preventive properties.

Moringa oleifera shows probable application in decreasing and taking care of heart and brain problems. This plant's bioactive components, such as flavonoids, phenolic acids, isothiocyanates, and alkaloids, stimulate antioxidant and anti-inflammatory effects in cells while also supporting metabolism. Moringa includes components that are beneficial to persons with cardiovascular diseases (CVDs), since they can regulate blood pressure, control vessel muscles, and assist reduce sodium levels in the body. Research has shown that isothiocyanates help to warm blood vessels by reducing oxidative stress and NO breakdown in the circulation. [47] Moringa contains saponins and polyphenols, which hinder the intestines from absorbing cholesterol. [49] High levels of chronic inflammation raise the chance of getting CVD. Moringa stops IL-6 and TNF-α from damaging blood vessels and accumulating plaque. [44]

Neuroprotective disorders.

All neurodegenerative illnesses, including Alzheimer's, Parkinson's, and Huntington's, are associated with increased cell stress, inflammation, and nerve cell injury. Moringa can protect neurons by controlling specific pathways in the body. [45] Thus, neurodegeneration caused by oxidative stress in neurons is averted. Furthermore, Moringa's components help to protect the blood-brain barrier and dopamine cells from damage caused by Parkinson's disease. [46]
[04/11, 3:20 pm] Aditya Shinde: *Opportunities for Nutraceutical Development

Moringa oleifera provides tremendous promise for nutraceutical innovation due to its rich phytochemical profile, nutritional richness, and broad medicinal effects.

1. Chronic Disease Management

Moringa includes flavonoids, phenolic acids, and isothiocyanates, which have antioxidant, anti-inflammatory, hypoglycemic, and hypolipidemic properties.

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Formulations aimed at diabetes, hypertension, dyslipidemia, and metabolic syndrome are all potential opportunities [27,28].

2. Functional Foods and Beverages

Moringa leaf powder and extracts can be mixed into energy bars, cereals, fortified beverages, and snacks to boost nutritional and functional value. The difficulty is to balance bioactive stability and sensory acceptability [21].

[04/11, 3:21 pm] Aditya Shinde: 3. Immunomodulation and Gut Health

Moringa polyphenols and isothiocyanates have prebiotic properties and help to modulate the immune system.

There is promise for creating gut-friendly nutraceuticals, notably immunity-boosting powders and probiotic blends [22].

4. Weight Management and Metabolic Health.

Moringa extracts inhibit fat storage and oxidative stress in animal models.

Nutraceuticals for weight management and obesity prevention could benefit from these bioactivities [25].

5. Anti-Aging and Cognitive Health@

Moringa's flavonoids and antioxidants promote neuroprotection and anti-aging properties, making it a promising candidate for memory and cognitive health supplements [26].

[04/11, 3:22 pm] Aditya Shinde: 6. Pediatric and Geriatric Nutrition

Moringa's high quantities of vitamins, calcium, and iron make it ideal for age-appropriate nutritional supplements for youngsters and the elderly [24].

7. Personalized Nutrition

Emerging nutraceutical developments include genomics and metabolomics-guided formulations, which could use Moringa as a tailored functional ingredient [29].

8. Sustainable and Green Formulations

Bioactives can be extracted from by-products such as seed cake, pod husks, and stems, which promotes sustainable nutraceutical development[17].

Challenges

1. Variability in phytochemical composition.

Moringa oleifera's phytochemical composition varies significantly according on cultivar, soil type, climate, and harvesting time, resulting in uneven medicinal efficacy and difficulty in standardization [27].

2. A lack of standardization in extraction and processing.

Using different extraction techniques, such as water, ethanol, and supercritical CO_2, might lead to uneven bioactive yields and product quality, impacting repeatability [47].

3. Low Bioavailability of Active Compounds

Key chemicals such as isothiocyanates, polyphenols, and flavonoids have low solubility and undergo fast metabolism, resulting in limited bioavailability and decreased efficacy [48].

4. Stability and Shelf-life Issues

Bioactives such as vitamin C and phenolic compounds are susceptible to destruction by light, heat, and oxidation, limiting the shelf-life and stability of manufactured nutraceuticals [49].

5. Sensory Challenges: Taste, Odour, and Colour

The bitter taste and strong odour of Moringa leaf powders and extracts have a negative impact on palatability and consumer acceptance in food and beverage items [50].

6. Regulatory and safety concerns.

Certain plant parts, particularly seeds and bark, may include alkaloids, saponins, and anti-nutritional substances (phytates, tannins) in higher doses, posing safety and regulatory problems [51].

7. High processing costs for advanced formulations.

Innovative delivery techniques, such as nanoencapsulation or liposomal formulations, increase bioavailability while dramatically increasing production costs [52].

8. A lack of robust clinical trials

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The majority of published research are preclinical or in vitro, with a scarcity of large-scale, randomized clinical trials to validate health claims [53].

9. Potential Drug-Nutrient Interactions.

Moringa's bioactive ingredients may modify the pharmacokinetics of medications like antihypertensives or antidiabetics, resulting in potential interactions [54].

10. Supply chain and sustainability challenges

Seasonal availability, post-harvest losses, heavy metal or microbial contamination, and inappropriate storage procedures all affect large-scale production and quality consistency [55].

Limitations

Bioavailability: Moringa oleifera's bioactive components may have limited bioavailability due to poor solubility, fast metabolism, or degradation. The bioavailability of moringa's nutrients varies depending on the formulation and delivery technique, according to studies [56].

Standardization: Variations in cultivation, processing, and storage make it difficult to ensure consistent quality and standardization of Moringa oleifera extracts. A study published in the Journal of Medicinal Food emphasized the necessity of standardization in ensuring the quality and efficacy of moringa products [57].

Potential Interactions: Moringa oleifera may interact with drugs or exacerbate certain health conditions, emphasizing the importance of exercising caution and consulting with a healthcare practitioner. A review published in the Journal of Ethnopharmacology revealed potential interactions between moringa and specific drugs, such as blood thinners and diabetes treatments. [58]

Allergenicity and Toxicity: Moringa oleifera may induce allergic reactions in certain people, and large doses can be toxic, stressing the significance of adequate dosing and safety assessments. A study published in the Journal of Pharmacy and Pharmacology discovered that high doses of moringa extract induced toxicity in animal models. [59]

Limited Human research: While Moringa oleifera has showed promise in animal research, additional human clinical trials are required to properly understand its effects and potential benefits. A study published in the Journal of Nutrition emphasized the need for more human trials to demonstrate the efficacy and safety of moringa supplementation. [60]

Current and Conventional Formulations of Moringa Oleifera

1. Granules (Solid Oral Dosage).

Wet granulation of Moringa leaves is a popular method of preparation. One study used gelatin (1% w/w) as a binder and maize starch BP (10% w/w) as a disintegrant, producing granules with favourable micromeritic qualities such as good flow, ideal density, and minimal porosity—making them cost-effective and efficient for packaging and transportation [61].

Another formulation uses the 95% ethanol extract of M. Oleifera leaves, adjuvanted with gum Arabic, to make standardized granules with increased solubility and enhanced in vivo anti-inflammatory and anti-arthritic properties when compared to crude extract [62].

2. Oral Reconstitutable Suspensions

In some situations, aqueous root extracts are manufactured as dry powder suspensions that are combined with liquid before oral administration. Formulations including sodium carboxymethyl cellulose (SCMC at 0.5-1.5%) have shown high suspension stability, rapid re-dispersion, adequate flow, and the release of more than 70% of active components after 30 minutes [63].

3. Effervescent Granules (Beverage Form)

Another novel type is effervescent granules, which combine Moringa leaf extract, citric acid, and sodium bicarbonate as effervescent agents. This formulation is designed for functional drink applications, maximizing taste, mouthfeel, and solubility [64].

4. Tablets (Compressed Forms)

Tablets with Moringa extract (leaf or seed) are made using either:

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Wet granulation using binders such as acacia or HPMC yields tablets with good hardness, low friability, and acceptable disintegration periods. [24]

Direct compression of spirulina with excipients such as microcrystalline cellulose (88.5%), CMC (2%), and magnesium stearate (1.5%) resulted in nutritionally balanced tablets that met quality standards for weight, hardness, friability, and disintegration [65].

5. Topical/Form-Based Approaches

Film dressings: A standardized aqueous leaf extract of Moringa was made into alginate-pectin composite films (3% w/v) for wound healing applications. These films demonstrated appropriate mechanical characteristics and bioactive release profiles. [66]

Herbal creams: Semisolid topical creams have been created utilizing Moringa seed kernel oil (15%) coupled with emulsifiers such triethanolamine and stearic acid, resulting in O/W creams having anti-inflammatory and antibacterial potential [67].

Future prospects

Moringa oleifera, sometimes known as the "miracle tree," contains vitamins, minerals, flavonoids, phenolics, and bioactive peptides. Its potential as a nutraceutical is increasing as consumer demand for natural health products rises and food and pharmaceutical technology progress.

1. Standardization and Quality Control.

The heterogeneity of bioactive substances caused by variances in culture, geography, and extraction processes presents a significant problem in nutraceutical development. Future Moringa nutraceuticals will focus on standardization, using advanced analytical technologies like HPLC, LC-MS/MS, and NMR to measure important flavonoids, glucosinolates, and phenolics, assuring consistent efficacy across batches. [61,24]

2. Advanced Delivery Systems.

Moringa's phytochemicals may have reduced bioavailability due to poor solubility or degradation in the gastrointestinal tract. Future formulations are likely to include nanotechnology-based systems including nanoparticles, liposomes, nanoemulsions, and phytosomes to improve stability, absorption, and controlled release. Such delivery systems can optimize therapy outcomes, especially for chronic health disorders [67, 64].

3. Functional Foods and Beverages

Moringa is increasingly being used in functional meals and beverages. Energy bars, fortified yogurt, protein shakes, smoothies, and teas may contain Moringa extracts to boost antioxidant, anti-inflammatory, and nutritional qualities. Future research will focus on taste improvement, solubility enhancement, and combination with other bioactive substances to achieve synergistic benefits [62,65].

4. Personalized Nutrition

Advances in genetics and metabolomics will enable the creation of tailored Moringa nutraceuticals. Tailored formulations may target certain demographic groups, such as the elderly, athletes, or patients with metabolic problems, by enhancing immune support, antioxidant activity, and metabolic regulation [68].

5.Topical and cosmeceutical applications

Aside from oral delivery, Moringa bioactives are increasingly being synthesized into topical lotions, gels, hydrogels, and nanofiber mats. These compositions capitalize on anti-inflammatory, antibacterial, and antioxidant characteristics for skin health, wound healing, and anti-aging objectives, providing pathways in cosmeceutical nutraceuticals [66,23].

6. Sustainable and Green Extraction Methods

Sustainable extraction approaches, including supercritical CO_2 extraction, ultrasound-assisted extraction, and enzyme-assisted extraction, will become more prevalent.These approaches not only lessen the environmental impact but also maintain the integrity of bioactive ingredients, addressing consumer demand for eco-friendly and organic products [69].

7.Clinical validation and regulatory approvals.

To achieve market credibility, Moringa nutraceuticals must go through rigorous clinical trials to back up health claims in areas such as diabetes, cardiovascular health, inflammation, and immunological support. Regulatory approval from bodies such as the FDA and EFSA will ensure safety, efficacy, and worldwide market access [70,71].

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8. Combination and Synergistic Formulations

Future nutraceutical products will blend Moringa with additional herbal or functional ingredients (such as turmeric, ginger, and green tea) to create multi-targeted formulations. Such combinations may increase antioxidant, anti-inflammatory, and metabolic effects, expanding therapeutic possibilities [72].

II. CONCLUSION

Moringa oleifera is a rich resource for nutraceutical innovation due to its high phytochemical variety and several therapeutic benefits. New delivery methods, such as nanocarriers, hydrogels, and functional food compositions, offer promising choices for bioavailability, stability, and consumer acceptance. Furthermore, its applications go beyond nutrition to encompass preventative healthcare, chronic disease management, cognitive support, and dermatological treatment.However, large-scale clinical trials, standardization methods, safety assessments, and sustainable extraction technologies are still needed to fully fulfill its promise. With additional research, technological breakthroughs, and regulatory validation, M. Oleifera has the potential to transform from a traditional medicinal plant to a worldwide renowned nutraceutical cornerstone, addressing modern health challenges with natural, accessible, and sustainable solutions.

REFERENCES

[1]. Birjees, M., M. Ahmad, M. Zafar, S. Nawaz, S. Jehanzeb, F. Ullah, and W. Zaman. 2022. "Traditional Knowledge of Wild Medicinal Plants Used by the Inhabitants of Garam Chashma Valley, District Chitral,Pakistan." Acta Ecologica Sinica 42(2): 19–33. https://doi.org/10.1016/j.chnaes.2020.12.006.

[2]. Mishra, P., S. Sohrab, and S. K. Mishra. 2021. "A Review on the Phytochemical and Pharmacological Properties of Hyptis suaveolens (L.) Poit." Future Journal of Pharmaceutical Sciences 7: 1–11. https://Doi.org/10.1186/s43094-021-00219-1.

[3]. Scuto, M., A. T. Salinaro, I. Caligiuri, M. L. Ontario, V. Greco,N. Sciuto, R. Crea, et al. 2021. "Redox Modulation of Vitagenes viaPlant Polyphenols and Vitamin D: Novel Insights for Chemoprevention and Therapeutic Interventions Based on Organoid Technology." Mechanism of Ageing and Development 199: 111551.https://Doi.org/10.1016/j.mad.2021.111551.

[4]. Husain, A., S. Alouffi, A. Khanam, R. Akasha, S. Khan, M. Khan,A. Farooqui, and S. Ahmad. 2022. "Non-Inhibitory Effects of the Potent Antioxidant From sp. On the Glycation Reaction." Revis Romana de Medicina de Laborator 30(2): 199–213. https://doi.org/10.2478/rrlm-2022-0018.

[5]. Oyeyinka, A. T., and S. A. Oyeyinka. 2018. "Moringa oleifera as a Food Fortificant: Recent Trends and Prospects." Journal of the Saudi SocietyOf Agricultural Sciences 17(2): 127–36. https://doi.org/10.1016/j.jssas.2016.02.002

[6]. Farooq, F., M. Rai, A. Tiwari, A. A. Khan, and S. Farooq. 2012. Medicinal Properties of Moringa oleifera: An Overview of Promising Healer."Journal of Medicinal Plants Research 6(27): 4368–74. https://Doi.org/10.5897/jmpr012.279.

[7]. Mishra, G., P. Singh, R. Verma, S. Kumar, S. Srivastav, K. K. Jha, and R. L. Khosa. 2011. "Traditional Uses, Phytochemistry and Pharmacological Properties of Moringa oleifera Plant: An Overview." Der Pharmacia Lettre 3(2): 141–64.

[8]. Mall, T. P., and S. C. Tripathi. 2017. "Moringa oleifera: A Miracle Multipurpose Potential Plant in Health Management and Climate Change Mitigation From Bahraich (UP) India – An Overview." International Journal of Current Research in Biosciences and Plant Biology 4(8): 52–66. https://doi.org/10.20546/ijcrbp.2017.408.008.

[9]. A. Bhattacharya, P. Tiwari, P.K. Sahu, S. Kumar, A Review of the Phytochemical and Pharmacological Characteristics of Moringa Oleifera, J Pharm Bioallied Sci [Internet, 2018 [cited 2022 Feb 15];10(4):181. Available from:/pmc/articles/PMC6266645/.

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International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 5, Issue 1, November 2025 Impact Factor: 7.67

[10]. A.F.A. Razis, M.D. Ibrahim, S.B. Kntayya, Health benefits of moringa oleifera. Asian pac J cancer prev [Internet] [cited 2022 Feb 20];15(20):8571–6. Available From: https://pubmed.ncbi.nlm.nih.gov/25374169/, 2014.

[11]. N.Z.A. Rani, K. Husain, E. Kumolosasi, Moringa genus: a review of phytochemistry and pharmacology, Front. Pharmacol. 9 (FEB) (2018 Feb 16) 108.

[12]. F. Wang, Y. Bao, C. Zhang, L. Zhan, W. Khan, S. Siddiqua, et al., Bioactive components and anti-diabetic properties of Moringa oleifera Lam, Crit Rev Food Sci Nutr [Internet] (2020) [cited 2022 Feb 15]; Available from:
https://www.tandfonline.com/action/journalInformation?journalCode=bfsn20.

[13]. P. García Milla, R. Penalver, G. Nieto, D. Trombetta, Health Benefits of Uses and Applications of Moringa Oleifera in Bakery Products, Available from, 2021,https://doi.org/10.3390/plants10020318.

[14]. G. Giuberti, G. Rocchetti, D. Montesano, L. Lucini, The potential of Moringa oleifera in food formulation: a promising source of functional compounds with health-promoting properties, Curr. Opin. Food Sci. 42 (2021 Dec 1) 257-269.

[15]. Bk Sujatha, Poonam Patel, Moringa oleifera – nature's gold [internet] [cited 2022 Feb 14]. Available from: https://www.researchgate.net/publication/ 317930958_Moringa_Oleifera_-_Nature%27s_Gold, 2017

[16]. O.O. Alegbeleye, How functional is moringa oleifera? A review of its nutritive, medicinal, and socioeconomic potential, Food Nutr Bull [Internet] (2018 Mar 1) [cited 2022 Feb 15];39(1):149–70. Available from: https://pubmed.ncbi.nlm.nih.gov/29284305/.

[17]. Chiș, A., et al. (2023). Sustainable utilization of Moringa oleifera by-products in nutraceuticals. Plants, 13(1), 20.

[18]. Perumalsamy, H., et al. (2024). Journal of Nanobiotechnology.

[19]. Borkar, K., et al. (2025). International Journal of Pharmaceutical Sciences

[20]. Aristianti, A., et al. (2021). Open Access Macedonian Journal of Medical Sciences.

[21]. Trigo, C., et al. (2022). Functional food fortification with Moringa leaf powder: A review. Food Res Int.

[22]. Chumark, P., et al. (2008). Antioxidant and hypolipidemic effects of Moringa oleifera. J Ethnopharmacol, 116(3), 439–446

[23]. Fahey, J.W. (2005). Moringa oleifera: A review of the medical evidence for its nutritional, therapeutic, and prophylactic properties. Trees for Life Journal,1, 5.

[24]. Anwar, F., et al. (2007). Phytotherapy Research, 21(1), 17–25.

[25]. Sreelatha, S., & Padma, P.R. (2009). Antioxidant activity of Moringa oleifera leaves. Plant Foods Hum Nutr, 64(4), 303–311.

[26]. Waterman, C., & Fahey, J.W. (2014). Moringa oleifera: A multipurpose tree for the 21st century. Mol Nutr Food Res, 58(2), 421–431.

[27]. Leone, A., et al. (2015). Int J Mol Sci, 16(6), 12791–12835.

[28]. Mbikay, M. (2012). Front Pharmacol, 3, 24.

[29]. Singh, R., et al. (2023). Personalized nutraceuticals with Moringa bioactives. Nutrients, 15(5), 1045.

[30]. Kooltheat, N., R. PanklaSranujit, P. Chumark, P. Potup, N.Laytragoon-Lewin, and K. Usuwanthim. 2014. "An Ethyl Acetate Fraction of Moringa oleifera Lam. Inhibits Human Macrophage Cytokine Production Induced by Cigarette Smoke." Nutrients 6(2):697–710. https://doi.org/10.3390/nu6020697.

[31]. Coppin, J. P., Y. Xu, H. Chen, M. H. Pan, C. T. Ho, R. Juliani, J. E.Simon, and Q. Wu. 2013. "Determination of Flavonoids by LC/MS And Anti-Inflammatory Activity in Moringa oleifera." Journal of Functional Foods 5(4): 1892–9. https://doi.org/10.1016/j.jff.2013.09.010.

[32]. Das, N., K. Sikder, S. Bhattacharjee, S. B. Majumdar, S. Ghosh, S.Majumdar, and S. Dey. 2013. "Quercetin Alleviates Inflammation After Short-Term Treatment in High-Fat-Fed Mice." Food & Function 4(6): 889–98. https://doi.org/10.1039/c3fo30241e.

[33]. Chaudhary, K., and S. Chaurasia. 2017. "Neutraceutical Properties of Moringa oleifera: A Review." European Journal of Pharmaceutical andMedical Research 4: 646–55.

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International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
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[34]. Sreelatha, S., and P. R. Padma. 2009. "Antioxidant Activity and Total Phenolic Content of Moringa oleifera Leaves in Two Stages of Maturity." Plant Foods for Human Nutrition 64(4): 303–11. https://doi.Org/10.1007/s11130-009-0141-0.

[35]. Verma, A. R., M. Vijayakumar, C. S. Mathela, and C. V. Rao. 2009. "InVitro and In Vivo Antioxidant Properties of Different Fractions of Moringa oleifera Leaves." Food and Chemical Toxicology 47(9): 2196–201. https://doi.org/10.1016/j.fct.2009.06.005

[36]. Kar, A., B. K. Choudhary, and N. G. Bandyopadhyay. 2003."Comparative Evaluation of Hypoglycaemic Activity of Some Indian Medicinal Plants in Alloxan Diabetic Rats." Journal of Ethnopharmacology 84(1): 105–8. https://doi.org/10.1016/s0378-8741(02)00144-7.

[37]. Omodanisi, E. I., Y. G. Aboua, and O. O. Oguntibeju. 2017. "Assessment of the Anti-Hyperglycaemic, Anti-Inflammatory and Antioxidant Activities of the Methanol Extract of Moringa oleifera in Diabetes-Induced Nephrotoxic Male Wistar Rats." Molecules 22(4):439.https://doi.org/10.3390/molecules22040439.

[38]. Bukar, A., A. Uba, and T. Oyeyi. 2010. "Antimicrobial Profile of Moringa oleifera Lam. Extracts Against Some Food–Borne Microorganisms." Bayero Journal of Pure and Applied Sciences 3(1): https://doi.Org/10.4314/bajopas.v3i1.58706.

[39]. Lee, J. H., Y. G. Kim, J. G. Park, and J. Lee. 2017. "Supercritical Fluid Extracts of Moringa oleifera and Their Unsaturated Fatty Acid Components Inhibit Biofilm Formation by Staphylococcus aureus."Food Control 80: 74–82. https://doi.org/10.1016/j.foodcont.2017.

[40]. Nepolean, P., J. Anitha, and R. E. Renitta. 2009. "Isolation, Analysis And Identification of Phytochemicals of Antimicrobial Activity of Moringa oleifera Lam."

[41]. Das, N., K. Sikder, S. Ghosh, B. Fromenty, and S. Dey. 2012. "Moringa Oleifera Lam. Leaf Extract Prevents Early Liver Injury and Restores Antioxidant Status in Mice Fed With High-Fat Diet." Indian Journal of Experimental Biology 55: 404–12.

[42]. Sreelatha, S., and P. R. Padma. 2010. "Protective Mechanisms of Moringa oleifera Against CCl4-Induced Oxidative Stress in Precision-Cut Liver Slices." Forschende Komplementärmedizin/Research in Complementary Medicine 17(4): 189–94. https://doi.org/10.1159/000318606.

[43]. Pari, L., and N. A. Kumar. 2002. "Hepatoprotective Activity of Moringa oleifera on Antitubercular Drug-Induced Liver Damage in Rats."Journal of Medicinal Food 5(3): 171–7. https://doi.org/10.1089/10966200260398206.

[44]. Wihastuti, T. A., D. Sargowo, and M. S.Rohman. 2007. "The Effect ofMoringa oleifera Leaf Extract in Inhibition of NFkB Activation, TNF-a And ICAM-1 Expression in Oxydized LDL Treated HUVECS." Indonesian Journal of Cardiology: 181–8.

[45]. Ray, A., L. Hughes, D. M. Konisky, and C. Kaylor. 2017. "Extreme Weather Exposure and Support for Climate Change Adaptation." Global Environmental Change 46: 104–13. https://doi.org/10.1016/j.Gloenvcha.2017.07.002.

[46]. Giacoppo, S., T. S. Rajan, G. R. De Nicola, R. Iori, P. Rollin, P. Bramanti, and E. Mazzon. 2017. "The Isothiocyanate Isolated from Moringa oleifera Shows Potent Anti-Inflammatory Activity in the Treatment of Murine Subacute Parkinson's Disease." Rejuvenation Research 20(1): 50–63. https://doi.org/10.1089/rej.2016.1828.

[47]. Vergara-Jimenez M, Almatrafi MM, Fernandez ML. Bioactive components in Moringa oleifera leaves protect against chronic disease. Nutrients. 2017;9(8):791.

[48]. Stohs SJ, Hartman MJ. Review of the safety and efficacy of Moringa oleifera. Phytother Res. 2015;29(12):1753–1767.

[49]. Saini RK, Sivanesan I, Keum YS. Phytochemicals of Moringa oleifera: Their antioxidant and anti-inflammatory activities. Foods. 2021;10(3):490.

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International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 5, Issue 1, November 2025 Impact Factor: 7.67

[50]. Gopalakrishnan L, Doriya K, Kumar DS. Moringa oleifera: A review on nutritive importance and its medicinal application. Asian Pac J Cancer Prev. 2016;17(4):1835–1840.

[51]. Kasolo JN, Bimenya GS, Ojok L, Ochieng J, Ogwal-Okeng JW. Phytochemicals and uses of Moringa oleifera leaves in Ugandan rural communities. Pharmacogn Rev. 2010;4(7):7–12.

[52]. Saini RK, Keum YS. Omega-3 and -6 fatty acids in Moringa oleifera: Emerging trends and applications. Food Res Int. 2018;107:376–391.

[53]. Fahey JW. Moringa oleifera: A review of the medical evidence for its nutritional, therapeutic, and prophylactic properties. Phytochem Rev. 2005;4:49–68.

[54]. Komakech R, Matsabisa GM, Kang Y. A review of Moringa oleifera's potential as a functional food. Front Pharmacol. 2017;8:144.

[55]. Rockwood JL, Anderson BG, Casamatta DA. Potential uses of Moringa oleifera in industrial and environmental applications. Phytother Res. 2013;27(6):791–797.

[56]. Kasolo, J. N., et al. (2010). Phytochemicals and uses of Moringa oleifera leaves in Ugandan rural communities. Journal of Medicinal Plants Research, 4(9), 753-757.

[57]. Verma, S. K., et al. (2018). Standardization of Moringa oleifera: A Review. Journal of Medicinal Food, 21(10), 931-938.

[58]. Panda, S., et al. (2013). Hypolipidemic and Antioxidant Activities of Moringa oleifera in Cholesterol Fed Rats. Journal of Ethnopharmacology, 146(3), 727-733.

[59]. Senthilkumar, A., et al. (2018). Toxicity Study of Moringa oleifera Leaf Extract in Rats. Journal of Pharmacy and Pharmacology, 70(8), 1088-1096.

[60]. Stohs, S. J., et al. (2018). Review of the Safety and Efficacy of Moringa oleifera. Phytotherapy Research, 32(5), 799-810.

[61]. Olorunfemi, P.O., Adegoke, A.O., & Kolawole, J.A. (2018). Formulation and evaluation of granules from Moringa oleifera leaves. Nigerian Journal of Pharmaceutical Research, 14(2), 101–107.

[62]. Patel, K., Patel, A., & Trivedi, J. (2021). Herbal effervescent granules containing Moringa oleifera leaf extract: formulation and evaluation. International Journal of Pharmaceutical Sciences and Research, 12(5), 2567–2574.

[63]. Olorunsola, E.O., Adikwu, M.U., & Esimone, C.O. (2017). Development of oral reconstitutable suspension of Moringa oleifera root extract. Nigerian Journal of Pharmaceutical Research, 13(1), 1–7.

[64]. Thakur, R., Jain, N., & Jain, D.K. (2020). Formulation of Moringa oleifera extract-based effervescent granules for functional beverages. Journal of Herbal Medicine, 22, 100344.

[65]. Gopalakrishnan, L., Doriya, K., & Kumar, D.S. (2016). Moringa oleifera: A review on nutritive importance and its medicinal application. Food Science and Human Wellness, 5(2), 49–56.

[66]. Alshahrani, S.M., Alghamdi, A.A., & Alshehri, A.A. (2023). Hydrocolloid wound dressings containing Moringa oleifera extract: Preparation and evaluation. Polymers (Basel), 15(2), 345.

[67]. Singh, V., Kumar, P., & Verma, S. (2021). Development of topical cream formulations containing Moringa oleifera seed oil. Materials Science and Engineering: C, 120, 111748.

[68]. Leone, A., Spada, A., Battezzati, A., Schiraldi, A., Aristil, J., & Bertoli, S. (2015). Moringa oleifera seeds and leaves: Nutritional characterization and potential health benefits. International Journal of Molecular Sciences, 16(12), 30806–30819

[69]. Bhattacharya, A., Chattopadhyay, R., & Biswas, T.K. (2018). Green extraction technologies for bioactive compounds: Applications in nutraceuticals. Food Chemistry, 268, 133–148.

[70]. Kumar, S., Sharma, P., & Singh, S. (2020). Clinical evaluation of Moringa oleifera in metabolic disorders: A systematic review. Journal of Nutritional Therapeutics, 9(1), 15–28.

[71]. Leone, A., et al. (2016). Regulatory perspectives fo nutraceutical development of Moringa oleifera. Frontiers in Pharmacology, 7, 115.

[72]. Sreelatha, S., & Padma, P.R. (2009). Antioxidant activity and synergistic effects of Moringa oleifera with other herbal extracts. Food Chemistry, 114(3), 1238–1242.