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Noni (*Morinda citrifolia*) Seed Oil: Phytochemical Composition, Bioactivity, and Emerging Applications in Food and Health

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ABSTRACT

Noni seed oil (NSO) obtained from the seeds of *Morinda citrifolia* is emerging as a valuable yet underexploited ingredient in the nutraceutical and functional food sectors. Rich in polyunsaturated fatty acids—particularly linoleic acid—along with phytosterols, tocopherols, and diverse phenolic compounds, NSO exhibits notable therapeutic activities. This review outlines the botanical characteristics and nutritional importance of noni seeds and evaluates conventional and green extraction techniques, emphasizing their impact on oil quality and bioactive retention. This review also discusses physicochemical stability concerns, especially oxidative degradation and sensory limitations. Encapsulation technologies are highlighted as effective approaches to enhance NSO stability, shelf life, dispersibility, and bioavailability, enabling its incorporation into functional foods, beverages, dairy products, and cosmetic formulations. Valorization of noni seeds as a by-product offers economic and environmental benefits by reducing agro-industrial waste and creating additional market value. However, large-scale processing challenges, regulatory gaps, consumer acceptance, and limited clinical evidence remain major barriers to widespread application. Overall, NSO demonstrates strong potential as a multifunctional food ingredient, warranting further clinical validation and technological optimization for large-scale commercialization.

1 | Introduction

The plant-derived essential oil represents a mixture of bioactive volatile compounds, polyphenols, phytosterols, and phytochemicals serving as a novel ingredient in food, pharmaceutical, and cosmetic industries (Bolouri et al. 2022). Vegetable oils form an important ingredient for a daily human diet as they provide a major source of essential fatty acids and energy and carrier of liposoluble vitamins. These fatty acids help to maintain healthy skin, vision, and immune function; support brain health; and regulate metabolism (Rahim et al. 2023).

Vegetable oils, which are plant-derived oils, are naturally occurring lipids extracted from the oil-bearing seeds of plants.

These were used in food, medicine, fuel, and industrial raw materials in ancient times (Yara-Varón et al. 2017). In the recent years, with the depletion of fossil fuels and the move toward sustainability development, the importance of oilseeds has increased for supplying essential fats and nutrients to the human diet (Tian et al. 2023) while supporting industries, such as cosmetics, pharmaceuticals, detergents, lubricants, polymers, and biofuels. The versatility of these oils and their renewable nature make them crucially important both nutritionally and economically. These oils were derived from various plant parts, such as stems, roots, bark, fruits, leaves, and seeds and were obtained by steam distillation in the olden days. Technology has been improved in extracting and stabilizing this oil from various deteriorations (Sethunga et al. 2022).

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These compounds are obtained by various greener extraction techniques—such as microwave, ultrasound-assisted, and supercritical fluid extraction—and conventional techniques such as Soxhlet extraction, solvent, and shaker extraction—from stems, roots, peels, pomace, leaves and seeds. These components vary with different oil seeds, climate, soil conditions, and harvesting time (Sethunga et al. 2022).

The noni fruit seeds are the main residue from its processing, representing about 2.5% of its weight and containing significant percentages of carbohydrates, proteins, oil, dietary fiber, and ash (Jahurul et al. 2022), as well as bioactive components, such as polyphenols, flavonoids, and carotenoids (Fontes et al. 2023). Another important contribution of noni seeds is the oil that contains the fatty acids lauric, linoleic, oleic, palmitoleic, and stearic acids, which have immunostimulant, anti-inflammatory, anticarcinogenic, or hypotensive activities, as well as extracts that exhibit antimicrobial activity against bacteria and fungi (Almeida et al. 2019). A balanced intake of these acids favors the decrease in blood cholesterol due to an increase in good lipoproteins and lowers bad lipoproteins absorption in the blood.

Oils extracted from plants in food industry play a major role in antioxidant and antimicrobial properties, increasing the shelf life, texture, and flavor of food products. These oils are incorporated into food as functional and nutraceutical foods (Pandey and Sharma 2022). The EC and FDA approved a large number of EOs and their components for use as flavorings and/or preservatives in food products, classifying them as generally recognized as safe (GRAS). Nutraceuticals contain polyunsaturated fatty acid such as omega 3, 6, 9 and tocopherols in extracted oil; it has antioxidant, anti-inflammatory, antimutagenic, antitumor, arthritis, arthrosclerosis, hepatoprotective, and immunomodulatory properties (Schwingshackl and Hoffmann 2021).

Noni (*Morinda citrifolia*) is an evergreen tree of the Rubiaceae family native to Southeast Asia and cultivated in the tropical and subtropical countries such as Polynesia, Vietnam, Malaysia, India, Cambodia, South America, and China. It is called as “mulberry or cheese fruit” in India, and its common name is noni or Nuna (Jahurul et al. 2021). The fruit, leaves, stems and roots have medicinal value. Noni fruit also exhibits a bitter or astringent taste when ripe and a strong rancid smell such as butyric acid (Zhao et al. 2022). The fruit has a shelf-life of 5–7 days at an ambient temperature between 25°C and 30°C and relative humidity between 70% and 75% (D. R. Singh et al. 2007).

Traditionally, noni bark and roots were used as a dye, but medically, all the plant parts, including leaves and fruits, have applications. Noni fruits are traditionally used to treat many diseases, including hypertension, tuberculosis, diabetes, arthritis, and some recent studies show their application in treating cancers (Chan-Blanco et al. 2006). Leaves were used to treat bone fractures and rheumatic pain, and fruits were used for cracking of toes, heart trouble, blood impurities, and stomach pain (M. Y. Wang et al. 2002). The bark is used for asthma and malarial infections, and the stem is used for hernia (Morton 1992).

The industries discarded noni seeds as a waste, but the seeds have many valuable bioactive compounds and remain as underutilized medicinal sources. As per NABCONS study (2022)

oil seeds losses were 2.11 million MT (press release by Press Information Bureau (PIB)). Agro-food industry waste and by-products contain numerous valuable bioactive compounds with nutritional and medicinal properties (S. P. J. Kumar et al. 2017). It can be used as supplements in human and animal diet and as bio fertilizers, biogas, and organic manure, which improves soil fertility and promotes soil health and nutrition (Alam and Islam 2023). Producing functional food products from those seeds would provide a new revenue stream for the noni manufacturer, minimize waste, and offer a more accessible health product (Yadav et al. 2024). In juice and oil industries, peels, pomace, seeds, and seed oil cake are the by-products of food waste. Reutilizing such by-products can yield a variety of valuable components comprising of sugars, pectin, proteins, lipids, polysaccharides, fibers, polyphenols, vitamins, essential minerals, volatiles, and pigments (Fernandez-Lopez et al. 2021). Flavonoids have been reported to exhibit free radical scavenging properties, anti-inflammatory, antiallergic, antiviral, and anticarcinogenic activities. Among different parts of the noni plant, the seed extracts have demonstrated the strongest inhibitory activity, indicating that the seeds contain potent antimicrobial constituents (Dussosoy et al. 2011). Studies show that noni seed oil exhibits broad spectrum antibacterial effects, effectively inhibiting Gram-positive and Gram-negative microorganisms such as *Bacillus subtilis*, *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas diminuta*, *Pseudomonas fluorescens*, and *Proteus morganii* (Noviana et al. 2021). This antimicrobial efficiency is attributed to its rich profile of fatty acids, tocopherols, and phenolic compounds, which disrupt microbial membranes and interfere with cell metabolism. The higher content of total phytosterols in noni-seed oil indicates the possibility of applying NSO as an anti-angiogenic agent for the prevention and treatment of angiogenesis-related diseases. Phytosterols possess a molecular structure closely resembling cholesterol, allowing them to compete for intestinal absorption and thereby reduce serum cholesterol levels (Jones and AbuMweis 2009). Moreover, NSO might be one of the best options for people with high levels of cholesterol and cardiovascular diseases (Potterat and Hamburger 2007). This review therefore places focus on the botanical and nutritional background of the seeds, the extraction techniques of the seed oil, chemical composition, bioactive compounds, the stabilization techniques of extracted oil, applications of oil in foods, regulatory approval, and a gap in clinical validation.

2 | Botanical and Nutritional Background of Noni Seeds

2.1 | Seed Morphology

Noni (*Morinda citrifolia*) fruit and its seeds are illustrated in Figure 1. Noni seeds exhibit considerable variation in size, with lengths typically between 7.96 and 12.06 mm, whereas their width and thickness generally fall within 3.85–7.15 mm and 1.57–3.36 mm, respectively. A thousand seeds collectively weigh around 31.77 g, indicating that individual seeds average 2025 mg, although this may fluctuate depending on maturity and moisture content. Morphologically, the seeds are oval, oblong, or slightly triangular, transitioning in color from light

brown in the immature stage to dark brown or nearly black upon full ripening (Jahurul et al. 2021). Their surface is hard, smooth, and glossy, giving them a distinctly woody appearance that contributes to durability. Structurally, each seed contains an internal air chamber, which enhances buoyancy and facilitates natural dispersal by water. A single noni fruit—classified as a multiple syncarp—typically encloses 80–100 seeds embedded irregularly within a gelatinous pulp (Nelson 2003). This high seed count and robust morphology play an important role in the plant's ecological adaptation and reproductive success, supporting wide geographic distribution, especially in coastal and island environments.

2.2 | Composition

The seeds of *Morinda citrifolia* (noni) are a rich source of valuable nutrients and bioactive compounds. As presented in Table 1, noni seed demonstrates considerable variation in fat and carbohydrate content, along with notably high dietary fiber levels compared to other oilseeds.

The noni seeds also contain wide variety of bioactive phytochemicals, including β -sitosterol, campesterol, stigmasterol,

ursolic acid, oleanolic acid, and vitamin E (tocopherols), all of which contribute to the oil's antioxidant and functional stability (Jahurul et al. 2021). Minor constituents such as phenolic acids (ferulic, caffeic, and gallic), flavonoids (quercetin, kaempferol), and iridoids such as asperulosidic acid enhance the antioxidant, anti-inflammatory, and antimicrobial potential of the seed.

Furthermore, elemental analysis indicates that noni seeds contain moderate levels of essential minerals—potassium, calcium, magnesium, phosphorus, iron, and zinc—which contribute to their nutritional and functional relevance in food and nutraceutical formulations.

2.3 | Nutrients of Noni Seed

Noni seeds contain a diverse and nutritionally significant composition, making them a valuable by-product of the *Morinda citrifolia* fruit. Table 2 summarizes variations in essential mineral composition among noni and commonly consumed oilseeds. The phytochemical profile of noni seed is equally noteworthy: total polyphenol content ranges from 224.4 to 225.5 mg/100 g in immature and mature seeds, respectively, whereas flavonoids increase with maturity, from 238.8 mg/100 g



FIGURE 1 | Morphology of noni (*Morinda citrifolia*) showing fruit and seeds.

TABLE 1 | Proximate composition of noni and other oil seeds.

Composition	Noni seed	Sunflower seed	Soybean seed	Sesame seed	Moringa seed
Moisture (%)	8.34	5.5	8	4.53	5.95
Ash (%)	3.60	3.49	4.5	4.27	3.38
Protein (%)	7.47	18.72	37.04–42.4	22.41	43.71
Fat (%)	12.49–43.5	37.47	5.90–9.67	41.2	43.6
Carbohydrate (%)	25.83–77.14	6.11	32.8	22	4.36
Dietary fiber (%)	79.04	28.03	24.96–32.63	11	6.5

TABLE 2 | Nutritional composition of noni and other seeds.

Composition (mg/100g)	Noni seed	Sunflower seed	Soybean seed	Sesame seed	Moringa seed
Ca	43.76	78	86.76	1146.25	1.55
Mg	19.76	325	78.68		5.36
Fe	30.07	5.25	2.47	9.45	0.97
Mn	130.52	1.95	86.76		0.60
Na	1.13	9		76.30	0.04

in immature seeds to 257.1 mg/100 g in mature seeds (Jahurul et al. 2021). These bioactive compounds contribute to the strong antioxidant and therapeutic potential attributed to noni seed extracts. Overall, the nutrient density and phytochemical richness of noni seeds highlight their applicability in nutraceutical formulations, dietary Fiber enrichment, and health-promoting food products.

3 | Extraction Techniques for Noni Seed Oil

3.1 | Conventional Method

3.1.1 | Cold Press Extraction

Cold-press extraction is a mechanical method used to obtain oil from seeds without the use of heat or chemical solvents, making it ideal for preserving sensitive bioactive compounds (Bakhshabadi et al. 2025). In this process, cleaned and dried seeds are sometimes lightly crushed and then subjected to gradual mechanical pressure using a screw press or cold-pressing machine. The temperature is carefully maintained below 50°C to prevent thermal degradation of valuable components such as polyunsaturated fatty acids, phenolics, and tocopherols (Kabutey et al. 2023). The released oil is collected, filtered to remove particulates, and stored in dark airtight containers at low temperatures to maintain quality. Although this method is safe, environmentally friendly, and retains the natural flavor, fatty acids, and bioactive of the oil, it generally produces lower yields compared to solvent-based extraction and may be less efficient for seeds with low oil content (Yilmaz and Aydeniz Güneşer 2017).

3.1.2 | Soxhlet Extraction

This technique is based on the principle of continuous extraction of lipids using organic solvents such as hexane, isopropanol, petroleum ether, ethanol, heptane, or chloroform (Choo et al. 2018). In this method, finely ground seed powder is typically placed within a porous thimble or filter paper inside the Soxhlet chamber, whereas the extraction flask contains a measured volume of solvent. The apparatus is heated such that the solvent temperature slightly exceeds its boiling point, causing the vapor to rise, condense in a water-cooled condenser, and percolate through the sample repeatedly. This cyclical process ensures prolonged contact between the solvent and the sample, enhancing lipid recovery. After the desired extraction period—commonly ranging from 4 to 24 hours—the system is cooled, and the solvent is recovered through distillation, leaving behind the extracted oil. Finally, the residual oil-containing flask is dried, cooled, and weighed to determine oil yield (Rashid et al. 2020). Soxhlet extraction, although effective for quantitative oil recovery, is associated with high solvent consumption and longer processing times compared to modern green extraction methods, highlighting the need for optimization and potential alternatives such as ultrasound-assisted or supercritical fluid extraction (L. Wang et al. 2022).

3.1.3 | Solvent Extraction

Solvent extraction is a commonly used method to recover oil from oilseeds, using organic solvents, such as hexane, ethanol, methanol, or isopropanol. This technique generally achieves higher oil yields compared to mechanical or distillation-based methods (Choo et al. 2018; Demirbas 2007). In this process, dried and finely ground plant material is mixed with the selected solvent and allowed to interact for extended periods, often up to 24 h with continuous stirring. The solvent penetrates the seed matrix, dissolving lipophilic components based on their solubility, after which the mixture is filtered, and the solvent is removed by evaporation or distillation to recover the oil. Several factors influence the efficiency and quality of solvent extraction, including the choice of solvent, particle size of the raw material, extraction time, and temperature. A common challenge with solvent extraction is the presence of residual solvent and potential off-odors, which can negatively affect oil stability and sensory quality, necessitating careful solvent recovery and post-processing (L. Wang et al. 2022).

3.2 | Green Technologies for Oil Extraction

Industrial extraction of oil from edible and nonedible seeds typically involves both mechanical followed by chemical solvent extraction methods. Conventionally, hexane has been widely used as the main solvent in commercial operations. However, concerns over environmental pollution, loss of solvents, high operational cost, and limited oil recovery have led to a decline in its use (Schoss and Kočevár Glavač 2024). Industrial and research interest has shifted toward “green extraction” techniques, such as supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), and enzyme-assisted extraction (EAE), which are viewed as safer and more environmentally sustainable alternatives (S. P. J. Kumar et al. 2017).

3.2.1 | Supercritical Fluid Extraction

Supercritical fluid extraction has emerged as a widely adopted modern technique for recovering essential oils, lipophilic compounds, and other volatile constituents from aromatic and medicinal plants. Its growing popularity is largely attributed to its ability to perform highly efficient extraction under low thermal stress, which helps retain heat-sensitive bioactive components and reduces degradation compared with conventional solvent extraction (Reverchon and De Marco 2006). This method enables efficient and rapid extraction under relatively mild temperature conditions, minimizes the need for additional purification and time, and eliminates the use of hazardous organic solvents. Carbon dioxide (CO₂) serves as an excellent solvent for this process because it is nontoxic, nonflammable, easily available, and can be completely removed from the final extract without residue (Afaei et al. 2022). At the supercritical state, CO₂ behaves like both liquid and gas (dense fog). It is pressurized above the critical point 31.1°C and 74 bar (7.4 MPa)

(Callejón et al. 2022). SF demonstrates both liquid and gas in terms of diffusivity and density. Unlike liquids, the density of SFs is highly sensitive to variations in pressure and temperature; even a slight increase in pressure can cause a substantial rise in fluid density, thereby significantly influencing the solvent power of the supercritical fluid. It is then passed over the dried sample under a mild temperature. Additionally, SFE reduces or eliminates the need for organic solvents, minimizes purification steps, and provides extracts of high purity, making it particularly suitable for food, nutraceutical, cosmetic, and pharmaceutical applications (Raventos et al. 2002).

3.2.2 | Ultrasound Assisted Extraction

Ultrasound-assisted extraction is an emerging green technology that enhances the recovery of bioactive compounds and oils by applying sound waves with frequencies above the human audible range (> 20 kHz). These high-frequency waves generate mechanical vibrations, creating alternating compression and rarefaction cycles within the plant matrix. As these cycles intensify, they induce acoustic cavitation, a process that forms and collapses microbubbles, producing localized high temperature, high pressure, and strong shear forces capable of disrupting cell walls and facilitating the release of intracellular components (Chemat et al. 2017). The extraction efficiency is influenced by parameters, such as the solvent-to-solid ratio (e.g., 1:4 to 1:8 w/v), sonication duration (15–60 min), amplitude, and solvent type, all of which regulate the mass transfer process.

Reduced extraction time improves oil stability. Similarly, UAE may improve the antibacterial properties of the extracted oils (Hernández-Santos et al. 2016). UAE offers several advantages over conventional extraction methods, including faster extraction rates, reduced solvent use, lower operating temperatures, and the improved yields of thermolabile compounds (Chemat et al. 2011).

3.2.3 | Enzyme Assisted Extraction

Enzyme-assisted extraction (EAEP) has emerged as a promising green technology for recovering oils and proteins from a variety of oilseeds. Unlike conventional solvent extraction, EAEP relies primarily on water as the extraction medium and uses specific hydrolytic enzymes to facilitate the release of intracellular nutrients. The structural complexity of plant cell walls—composed predominantly of cellulose, hemicellulose, and pectin—acts as a physical barrier that restricts the diffusion of lipids and proteins stored within cotyledon cells (Rosenthal et al. 1996). By selectively degrading these polysaccharide matrices, enzymes enhance cell wall permeability and facilitate the liberation of embedded biochemical components. Enzymes, such as pectinases, cellulases, and hemicellulases, have been widely evaluated for their ability to weaken and partially solubilize the structural polymers of oilseed cell walls. Pectinases primarily target the middle lamella, increasing tissue disintegration, while cellulases and hemicellulases complement this action by breaking down cellulose microfibrils and associated heteropolysaccharides (Aquino et al. 2019, Sharma et al. 2002).

Although the complete depolymerization of cellulose remains challenging due to its crystalline nature, the synergistic action of multiple carbohydrases significantly improves aqueous extraction efficiency.

The enzymatic treatment significantly improves extraction outcomes: corn oil recovery exceeded 90% using EAEP, and strong cellulase preparations such as Multifect GC and Celluclast yielded approximately 93% and 91% oil recovery, respectively. These results highlight EAEP's potential as a viable alternative to solvent-based methods, offering high efficiency with reduced environmental impact (Moreau et al. 2004).

Conventional oil extraction from edible and nonedible seeds often relies on chemical solvents such as n-hexane because of their high lipid-solubilizing power and ability to deliver very high oil yields (often greater than 95%–98%). However, this method presents several serious drawbacks: it demands substantial energy for heating and solvent recovery, is time-consuming, and uses flammable volatile solvents that pose environmental pollution, health risks, and fire or explosion hazards. Moreover, residual solvent contamination in the final oil can degrade product quality and limit recovery of bioactive component (Dzokom et al. 2025). In contrast, green extraction techniques—including supercritical CO₂ extraction, aqueous/enzyme-assisted extraction, and other nontoxic solvent systems—provide sustainable alternatives. These methods employ nontoxic, nonflammable, and biodegradable solvents or media (water, CO₂, enzymes), significantly reducing environmental impact and operator hazards and offering minimal oxidation, no solvent residues, and better preservation of nutrients and bioactives, thereby making green extraction a more sustainable choice for modern food, nutraceutical, and cosmetic production (R. Martins et al. 2023).

The yield and bioactive compound retention of different extraction methods for noni seed oil are summarized in Table 3.

TABLE 3 | The yield and bioactive substance retention of different extraction methods.

Extraction method	Yield (%)	Bioactive retention (phenolics, tocopherols, phytosterols)
Screw press (cold)	8	Moderate
Soxhlet extraction	10.55	Low
Solvent extraction	12.5	Low–Moderate
Supercritical fluid extraction	20.1	Very high
Ultrasound-Assisted Extraction (UAE)	14	High
Microwave-Assisted Extraction (MAE)	15	Moderate–High
Aqueous Enzymatic Extraction (AEE)	10	Very high

4 | Chemical Composition of Noni Seed Oil

4.1 | Fatty Acids

The chemical composition of noni seed oil reveals a high proportion of unsaturated fatty acids, with polyunsaturated and monounsaturated fatty acids (PUFA + MUFA) accounting for 89.82%, whereas only trace amounts of other fatty acids are present (Jahurul et al. 2022). Fatty acid profiling of dried seeds and crude oil was performed following the AOCS Method Ce 1-62 (AOCS 1998). Fatty acid methyl esters (FAMES) were analyzed using GC-FID (6890N, Agilent, USA) fitted with a BPX70 capillary column (30 m × 0.25 μm × 0.25 mm ID). The chromatographic conditions included an initial hold at 45°C for 5 min, followed by heating to 175°C at 13°C/min, and finally to 215°C at 4°C/min, with respective holding times of 27 and 35 min. The identification of peaks was accomplished by comparison with certified FAME standards (GLC-463, NuChek-Prep), and quantification was based on the area normalization method. The fatty acid composition of noni seed oil is presented in Table 4.

The predominance of PUFAs makes the oil nutritionally valuable (Jahurul et al. 2022). Linoleic acid has demonstrated anticancer potential in vitro and in vivo against skin, breast, colon, stomach, and leukemia cells (Qiu et al. 2024). Both linoleic and oleic acids are also recognized for their moisturizing and skin-repairing benefits and contribute to cardiovascular health by reducing LDL levels, improving lipid profiles, and lowering cholesterol (X. Wang et al. 2024).

4.2 | Phytochemicals

4.2.1 | Sterols

Phytosterols are plant-derived compounds that share a structural similarity with cholesterol and are widely distributed in foods, such as whole grains, nuts, seeds, legumes, and plant oils. Their primary health benefit is their ability to reduce total and LDL-cholesterol by competing with cholesterol for absorption in the intestinal lumen (Othman and Moghadasian 2011). In

addition to lipid-lowering effects, phytosterols demonstrate notable antioxidant, anti-inflammatory, and anticancer properties, contributing to improved cellular protection and enhanced immune function. They also play a supportive role in mitigating metabolic risks, including obesity and type 2 diabetes (Jones and AbuMweis 2009). The phytosterol profile is quantified using gas chromatography–mass spectrometry (GC-MS). Identification is achieved by matching retention times with certified standards, whereas quantification is based on external standard calibration (X. Chen et al. 2023).

The gas chromatography–mass spectrometer (GC-MS) system was used to determine the phytosterol composition. Target substances were identified by comparing their retention times with those of the standards and quantified using the external standard method. Due to these diverse benefits, phytosterols are commonly incorporated into functional foods and supplements designed to enhance heart and metabolic health. The β-sitosterol, campesterol, and stigmasterol contents of the crude NSO are reported to be 431.0, 219.5, and 202.0 mg/100 g, respectively, (West et al. 2008) when compared to sunflower, soyabean, sesame, and olive.

4.2.2 | Tocopherols

NSO contains notable amounts of vitamin E homologs, including α-tocopherol (38.2 mg/100 g), δ-tocopherol (12.2 mg/100 g), and a significantly higher level of γ-tocopherol (335.7 mg/100 g) (Jahurul et al. 2021). Tocopherols, naturally occurring in many vegetable oils, represent the major lipid-soluble components of the vitamin E family and function as potent antioxidants that inhibit oxidative deterioration of polyunsaturated fatty acids through free-radical chain-breaking mechanisms (Nyam et al. 2009).

Beyond their antioxidant function, tocopherols contribute to human health by protecting biomolecules from oxidative stress and may help delay or reduce the risk of chronic diseases, including cardiovascular disorders, cancer, and neurodegenerative conditions such as Alzheimer's disease (B. Chen et al. 2011). Their role in scavenging reactive oxygen species helps preserve cellular integrity and supports physiological defense systems. From a food science perspective, tocopherols also enhance the oxidative stability of oils by preventing rancidity and quality deterioration during storage (Sayago et al. 2007).

4.2.3 | Phenolics

Fruits are widely recognized for their health-promoting properties, largely due to their rich content of phenolic compounds that help counteract oxidative stress and prevent cellular damage caused by free radicals. The total phenolic content in samples is commonly assessed using the Folin–Ciocalteu method (Dominguez-López et al. 2023). TPC for NSO was found to be 48.85 mg GAE/g (Jahurul et al. 2021).

Phytochemical analyses of noni seeds reveal several important flavonoids. Caffeic acid is the predominant compound

TABLE 4 | Fatty acid profile of noni seeds.

Fatty acid profile (%)	Noni seed
Linoleic acid C18:2	71.74
Caprylic C8:0	1.44
Linolenic acid C18:3	0.16
Oleic acid C 18:1	12.36
Eicosenoic acid C20:1	0.11
Palmitic acid C16:0	9.87
Stearic acid C18:0	4.36
Myristic acid C 14:0	0.03
SFA	14.93
MUFA	17.45
PUFA	72.37

(496 µg/100 g), followed by vanillin (36 µg/100 g) and vanillic acid (21 µg/100 g). Other constituents include rutin (18 µg/100 g), kaempferide (5 µg/100 g), artemillin C, and quercetin (3 µg/100 g each), as well as kaempferol (2 µg/100 g). These compounds are associated with multiple bioactivities. For instance, caffeic acid exhibits anticancer, anti-inflammatory, antioxidant, and antiviral properties (Yazar et al. 2025). Kaempferide content in noni seed oil warrants more detailed HPLC-based investigation, as its concentration can decrease or degrade during extraction and processing steps.

5 | Bioactive Properties and Health Potential

Noni seed oil is abundant in unsaturated fatty acids, such as linoleic acid; phytosterols such as β -sitosterol and stigmasterol; tocopherols (vitamin E variants); carotenoids; polyphenols; and other antioxidant compounds. These constituents contribute to its potent antioxidant, anti-inflammatory, antibacterial, anti-fungal, and anticancer activities (Jahurul et al. 2021). Linoleic acid is particularly notable for its anti-inflammatory and skin barrier benefits, whereas tocopherols act as powerful antioxidants protecting cells from oxidative damage. Phytosterols contribute to cardiovascular health by helping to regulate cholesterol levels.

5.1 | Anti-Inflammatory and Antioxidant Activities

Noni seed oil (NSO) exhibits strong anti-inflammatory potential primarily through the dual suppression of cyclooxygenase-2 (COX-2) and 5-lipoxygenase (5-LOX), which are the key enzymes involved in eicosanoid-mediated inflammatory pathways (Cui et al. 2025). Research studies indicate that NSO significantly reduces pro-inflammatory mediator production, contributing to noticeable improvements in both skin and systemic inflammatory conditions (Palu et al. 2012). Its potent antioxidant activity is largely attributed to the presence of phenolic and aromatic compounds, such as scopoletin, kaempferide, vanillin, eugenol, 4-hydroxycinnamic acid, 1,2,4-benzenetriol, and trace amounts of resveratrol and curcumin derivatives, along with tocopherols (Jahurul et al. 2021, Hou et al. 2025). Together, these phytochemicals effectively neutralize reactive oxygen species (ROS) and reduce oxidative stress, a major factor linked to aging and chronic degenerative diseases.

Scopoletin, a coumarin derivative widely reported in noni-based products, contributes prominently to NSO's free radical-scavenging properties and inflammatory regulation (Hou et al. 2025). Beyond its antioxidant activity, scopoletin is associated with improved blood circulation, analgesic effects, and immune support, further enhancing the therapeutic profile of the oil. Supercritical CO₂ extraction is probably the best method because it preserves delicate bioactives such as scopoletin in mild oxygen-free conditions, and ultra sound-assisted extraction achieves better yield of polyphenols (Hou et al. 2025). Kaempferide—a methylated flavonol unusually abundant in NSO compared to other plant oils—shows strong antioxidant and anti-inflammatory effects through suppression

of proinflammatory enzymes and protection against oxidative DNA damage (Cui et al. 2025; Hou et al. 2025). Its lipophilic character promotes efficient incorporation into oil-based systems, improving stability and bioavailability. Additionally, NSO contains notable levels of α - and γ -tocopherols, which protect polyunsaturated fatty acids from lipid peroxidation, stabilize cellular membranes, and support skin repair processes (Jahurul et al. 2021).

5.2 | Skin Health Benefits

Topical application of noni seed oil (NSO) has been shown to enhance skin health through multiple complementary actions. Research studies indicate that NSO helps reduce comedonal lesions and exerts marked anti-inflammatory effects without triggering irritation or comedogenic responses, making it suitable even for sensitive skin types (Palu et al. 2012). Its rich composition of unsaturated fatty acids reinforces the skin's barrier integrity, improves moisture retention, and supports epidermal repair processes (Jahurul et al. 2021).

The oil also demonstrates antimicrobial activity, contributing to the reduction of skin-associated pathogens and the improvement of overall skin clarity (Hou et al. 2025). Bioactive tocopherols in NSO promote skin elasticity and aid in tissue regeneration, whereas its diverse phenolic compounds help mitigate inflammation, reduce hyperpigmentation, and protect against premature aging by counteracting oxidative stress (Cui et al. 2025; Hou et al. 2025). Due to its lipophilic characteristics, NSO penetrates effectively into the stratum corneum (outermost layer of epidermis), enhancing hydration and strengthening the skin barrier. Collectively, these attributes position NSO as a valuable functional ingredient for cosmetic and dermatological formulations.

5.3 | Cardioprotective Potential

The cardioprotective potential of noni seed oil is primarily linked to its content of phytosterols—especially β -sitosterol—as well as unsaturated fatty acids such as linoleic and oleic acids and a range of antioxidant compounds including tocopherols and polyphenols (Jahurul et al. 2021).

β -sitosterol shares a structural resemblance to cholesterol, enabling it to compete with dietary cholesterol for absorption in the intestines, thereby contributing to reductions in circulating LDL cholesterol and improvements in the overall lipid profile, particularly HDL levels (Ras et al. 2014). The polyunsaturated fatty acids present in the oil play a complementary role by supporting healthy lipid metabolism, promoting β -oxidation, reducing hepatic lipogenesis, and helping regulate blood pressure (Richard et al. 2009). Additionally, antioxidants such as tocopherols and phenolic compounds mitigate oxidative stress and vascular inflammation, protecting the cardiovascular system against endothelial damage and the progression of atherosclerosis (Saremi and Arora 2010). Collectively, these bioactive components act synergistically to reduce cardiovascular risk and support overall heart health.

5.4 | Hepatoprotective Effects

Noni seed oil (NSO) demonstrates notable hepatoprotective activity, largely due to its rich profile of antioxidant and anti-inflammatory phytochemicals, particularly scopoletin and related coumarin derivatives. These phenolic constituents are known to downregulate major pro-inflammatory mediators—including NF- κ B, TNF- α , IL-6, and COX-2—thereby reducing hepatocyte swelling, inflammatory cell infiltration, and tissue degeneration during liver injury (Rakotondrabe et al. 2023). In addition to suppressing inflammation, polyphenols in NSO help counteract oxidative stress by scavenging reactive oxygen species (ROS) and minimizing lipid peroxidation of hepatocyte membranes, a key event in chemical or toxin-induced hepatic damage. Scopoletin and other antioxidant molecules further contribute to the liver's defense mechanisms by enhancing endogenous enzymatic systems such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), as well as by promoting glutathione (GSH) synthesis—an essential component of cellular detoxification pathways (Rakotondrabe et al. 2023; Li et al. 2015). Together, these synergistic effects help maintain hepatic integrity and protect against oxidative, inflammatory, and toxic insults.

5.5 | Antidiabetic Potential

Noni seed oil (NSO) contains a diverse range of bioactive molecules—including scopoletin, flavonoids, and other polyphenols—that contribute to its antidiabetic potential (Jahurul et al. 2021). These compounds are known to activate AMP-activated protein kinase (AMPK), a central metabolic regulator that enhances glucose uptake in skeletal muscle and adipose tissue, thereby improving peripheral insulin sensitivity (Hardie et al. 2012). Noni seed oil (NSO) contains a diverse range of bioactive molecules—including scopoletin, flavonoids, and other polyphenols—that contribute to its antidiabetic potential (Jahurul et al. 2021). These compounds are known to activate AMP-activated protein kinase (AMPK), a central metabolic regulator that enhances glucose uptake in skeletal muscle and adipose tissue, thereby improving peripheral insulin sensitivity (Hardie et al. 2012). Polyphenolic constituents also promote the expression of GLUT4 and stimulate its translocation from intracellular storage vesicles to the plasma membrane in insulin-responsive tissues, which is essential for efficient insulin-mediated glucose transport (Huang and Czech 2007). Through this dual regulation—upregulating GLUT4 gene expression and facilitating membrane localization—phenolics help increase cellular glucose utilization.

Additionally, bioactives reported in NSO may help suppress hepatic glucose production by downregulating key gluconeogenic enzymes, such as phosphoenolpyruvate carboxykinase (PEPCK) and glucose-6-phosphatase (G6Pase), along with transcription factors such as FoxO1, ultimately decreasing hepatic glucose output (W. Zhang et al. 2006). Collectively, these mechanisms contribute to improved glycemic control and may help reduce the risk of diabetes-related metabolic complications. Emerging evidence also suggests that noni-derived phenolics may support the management of metabolic disorders—such as hypertension and type 2 diabetes—through attenuation of

oxidative stress and modulation of inflammatory pathways; however, additional clinical studies are required to confirm these effects (Chan-Blanco et al. 2006).

6 | Stability and Challenges in Noni Seed Oil Utilization

The oil extracted from the seeds of *Morinda citrifolia* (NSO), possesses various stability problems and utilization issues mainly attributed to the changes in its chemical composition during processing and the refining stage. Among these, the refining process such as degumming, deacidification, decolorization, and deodorization, was found to largely alter the NSO lipid profile by reducing the key bioactive compounds of tocopherols, phytosterols, and polyphenols. Such degradation influences its antioxidant and anti-inflammatory activities that play a key role in health benefits and industrial applications (Cui et al. 2025).

6.1 | Oxidative Stability

Oxidation is a degradation mechanism that occurs to any vegetable oil. Rancidity, odors, and off-flavors are the results of this intricate chain of events (Matthäus et al. 2010). Similarly, the oxidative stability of a vegetable oil influences its shelf life (Maszewska et al. 2018). Particularly, certain toxic substances, such reactive oxygen species (RCCs) can produce enhanced lipid peroxidation end products during the oxidation process, which may be detrimental to human health (Guillén and Ruiz 2005). Oil oxidation is caused by a variety of factors, such as the amount and composition of polyunsaturated fatty acids, storage conditions, high temperature, light, increased oxygen availability, and the presence of prooxidants such as chlorophylls and metal ions such as Fe³⁺ and Cu²⁺; these are the key parameters (Choe and Min 2006).

The conventional free radical chain mechanism provides an explanation for oil oxidation reactions. Radical reactions on unsaturated fatty acids are the first step in this process (Laguerre et al. 2017). The three stages of these reactions—initiation, propagation, and termination (Haman et al. 2018)—are as follows: initiation, where free radicals form by the removal of a hydrogen atom from fatty acids due to heat, light, or metal catalysts; propagation, where these radicals react with oxygen to create peroxy radicals that perpetuate the chain reaction by attacking other fatty acids, forming hydroperoxides; and termination, where free radicals combine to form stable, nonradical products such as aldehyde and ketones (Echegaray et al. 2022).

A set of regularly monitored parameters is used to evaluate the oxidative stability of an oil. Peroxide value (PV) is an important parameter for measuring primary oxidation products (peroxides and hydroperoxides), p-Anisidine value (p-AV), TOTOX value, and Rancimat/oxidative stability index (OSI) (Gharby, Guillaume, Elibrahimi, et al. 2021). As secondary oxidation products hydroperoxides, peroxides, and conjugated dienes are unstable substances that rapidly transform into ketones and aldehydes (Gharby, Guillaume, Elibrahimi, et al. 2021).

The p-anisidine value is usually utilized to assess the volume of the secondary oxidation products (Gharby, Guillaume, Elibrahimi, et al. 2021). Although compared to the PV, this is a more accurate indicator of oxidative rancidity. Because anisidine determination cannot detect ketones, this parameter is not entirely comparable to the study of p-anisidine (Cong et al. 2020). Similarly, the total oxidation (TOTOX) value provides a more accurate measure of vegetable oil oxidation. PV (primary oxidation products) and the p-anisidine value (secondary oxidation products) are combined in this measure. Because hydroperoxides (peroxides) are unstable and do not provide an accurate indication of an oil's oxidative stability, the total oxidation value is superior to peroxide and p-anisidine values (Tavakoli et al. 2019). Better quality is generally indicated by a TOTOX value of less than ten (Gharby et al. 2016). The stages of the oxidative stability of vegetable oils can also be monitored through other measurements such as the headspace volatiles (smell), free fatty acids (FFA), thiobarbituric acid value (TBA), iodine value (IV), the Rancimat test, and the Schaal oven test. NSO produced in Sabah had a PV of 10.60 meq/g. The Prevention of Food and Adulteration Act (PFA) states that fresh vegetable oils should have a PV of less than 10 meq/kg. Although it was closer to the value of sunflower oil, the PV of NSO grown in Sabah was significantly higher (10 meq/kg) (Jahurul et al. 2022).

6.2 | Sensory Challenges

Volatile molecules of oil are important indicators of their flavor and quality and essential to quality of oil (He et al. 2021). Aldehydes and ketones serve as an indicator for determining the level of oxidation in fats and oils in addition to giving them aroma (Olmedo et al. 2018). Sensory profiling of NSO, dominated by the prevailing chemical composition regarding volatile compounds and bioactive substances, reveals its complex sensory attributes. NSO usually exhibits a pungent partly disagreeable odor profile due to some of its volatile compounds, namely (E, E)-2,4-decadienal, ethyl caprylate, ethyl hexanoate, hexanal, and hexyl caprylate (M. Wang 2018). These volatile compounds give NSO a strong smell, which can be perceived as fatty, slightly rancid, or with hints of citrus and green notes, depending on the stage of refining. The levels of volatile compounds varied depending on the degree of refinement (Cui et al. 2025). Alcohols initially increased and subsequently declined after refining, whereas most aldehydes continued to increase over time. The oxidative breakdown of polyunsaturated fatty acids may be the cause of the increased concentrations of fatty alcohols, such as 1-hexanol and (R)-(-)-2-pentanol, following degumming and deacidification (Sun et al. 2023). Aldehydes are the major products of lipid oxidation (Olmedo et al. 2018), and their high concentrations indicated that NSO may partially oxidize during the refining process. After deacidification, the content of nonanal, which often corresponds to a green aroma, increased. Lipid hydrolysis products including linoleic acid and α -linolenic acid are known to generate nonanal (Liu et al. 2024).

Its taste profile contains bitterness and pungency, characteristic of oils rich in polyunsaturated fatty acids and phenolic compounds such as scopoletin and kaempferol. Minor phenolic compounds such as kaempferide derivatives may produce subtle

bitterness and mouth-drying astringency (Cui et al. 2025). Refining processes, in particular deodorization, strongly affect the sensory profile by reducing some of these powerful odors and bitterness but also potentially decreasing beneficial phytochemicals and antioxidant properties. The total SFA, MUFA, and PUFA contents of NSO did not change appreciably through the refining process (Cui et al. 2025). The refining process did not significantly change the total fatty acid composition of NSO, in agreement with previous research studies on other vegetable oils (Guo et al. 2023).

6.3 | Safety Considerations and Toxicological Status

Numerous investigations and toxicological evaluations have determined that noni seed oil (NSO) is safe and nontoxic for ingestion and topical application where NSO was found to be noncomedogenic and caused no reactions or irritation, even with repeated exposure (Aguiar et al. 2020). The LD50 of NSO is above 10 mL/kg body weight, which significantly surpasses the threshold for nontoxic status ($LD_{50} \geq 5$ g/kg), indicating minimal acute toxicity risk, according to studies on acute oral toxicity in animal models. There is no possibility of genetic toxicity in NSO or noni juice, according to genotoxicity tests such as DNA damage and Ames's test (West et al. 2011).

Toxicants and antinutrients are naturally occurring substances in grains, plants, and cereals that are crucial to the safety assessment of any foods derived from plants. These antinutrients hindered human nutrient absorption. Phytic acid, oxalic acid, nitrates, nitrites, and aflatoxins B1, B2, G1, and G2 were not detected in the noni seed extract (West et al. 2011).

7 | Food Applications of Noni Seed Oil

7.1 | Direct Use as Edible Oil

Besides its promising nutritional and therapeutic properties, The U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA Panel on Nutrition et al. 2013) have not yet classified noni seed oil as generally recognized as safe (GRAS) or approved it as a novel food, which limits direct application in commercial food systems yet.

Noni seed oil (NSO) has gained increasing interest as a functional edible oil due to its favorable lipid profile and rich bioactive composition. Its high levels of essential fatty acids—particularly linoleic and oleic acids—provide nutritional benefits comparable to commonly consumed plant oils such as sunflower oils, while also offering additional antioxidant protection through phenolics and flavonoids (Jahurul et al. 2022). The oil demonstrates good oxidative stability, making it suitable for culinary uses such as frying and salad preparations, and for use as an edible oil especially for people with cardiovascular disease (West et al. 2008). In food systems, NSO's mild flavor and light color contribute to its potential as a specialty oil that can enhance the nutritional quality of dressings, marinades, and functional health foods, and it can also be used as an

antimicrobial agent in food packaging (Noviana et al. 2021). Additionally, NSO's stability and compatibility with other oils enable its use in blended formulations to improve the functional properties of conventional edible oils.

7.2 | Incorporation in Bakery, Dairy, Beverages

The application of NSO in food systems is limited because of its unpleasant odor, which is sour and similar to that of butyric acid. This problem can make it hard for consumers to accept it. So direct application of crude NSO into foods without processing can affect sensory properties of food. To overcome these sensory constraints, processing such as deodorization, blending with neutral-flavored oils, and encapsulation techniques can be used. Deodorization can reduce some of the unwanted volatile compounds that cause this odor, but it leads to the loss of heat-sensitive and volatile bioactive compounds, such as phenolics and aroma-active compounds. This poses a significant trade-off between enhancing sensory quality and maintaining functional properties.

Special techniques such as microencapsulation, nanoemulsions, and solid lipid nanoparticles can be an effective solution to mask an undesirable odor and protect the heat-sensitive bioactives from degradation. These techniques enhance oxidative stability, improve dispersibility, and maintain the nutritional integrity of NSO, thereby facilitating its incorporation into diverse food systems. Consequently, the successful application of NSO in food products depends on achieving an optimal balance between sensory acceptability and bioactive retention, with encapsulation emerging as a promising strategy to bridge this gap.

In bakery products, NSO can be used as a partial fat replacer in cookies, breads, and pastries, where its unsaturated fatty acids contribute to improved softness, enhanced moisture retention, and extended shelf life through antioxidant action. Its bioactive constituents may also help reduce oxidative rancidity in baked goods compared to conventional oils.

In dairy-based formulations, NSO can be incorporated into yogurts, ice-creams, and cheese spreads as an omega-rich supplement. Its emulsifying and antioxidant properties aid in maintaining lipid stability, preventing flavor deterioration, and enriching dairy products with health-promoting compounds such as phytosterols and polyphenols (Jahurul et al. 2022).

In beverages, NSO can be delivered through nano emulsions or microencapsulation systems to enhance dispersion, stability, and bioavailability. Such delivery systems enable its incorporation into functional drinks, fruit beverages, and nutraceutical shots without compromising clarity or mouthfeel. Collectively, these applications highlight NSO's potential as a versatile functional oil in modern food product development.

7.3 | Functional Food Development Opportunities

Noni seed oil (NSO) presents significant opportunities for functional food development due to its rich composition of

polyunsaturated fatty acids, phytosterols, tocopherols, and phenolic compounds. The favorable fatty acid profile and high oxidative stability, NSO can be incorporated into functional bread spreads, salad dressings, and fortified edible oils designed to support heart-healthy diets.

Its phytosterol, polyphenol, and high protein content supports development of metabolic-health functional foods—such as protein bars, beverages, or gummies formulated to improve lipid profile, reduce oxidative stress, and enhance insulin sensitivity (Jahurul et al. 2022).

NSO can also be used in microencapsulated or nano emulsion formats to increase bioavailability and mask flavor, enabling its incorporation into functional dairy, snack foods, and nutraceutical beverages (Prakasha et al. 2025). Additionally, NSO's antimicrobial and anti-inflammatory properties allow its inclusion in immune-support functional products and clean-label formulations. NSO's bioactive composition and compatibility with modern delivery technologies make it a promising ingredient for next-generation functional foods targeting wellness, metabolic health, and antioxidant support.

8 | Encapsulation and Delivery Strategies

Noni seed oil is characterized by a high linoleic acid content, which increases its susceptibility to lipid oxidation and associated stability challenges. Encapsulation techniques, including nano emulsions and solid lipid nanoparticles, may therefore offer effective strategies to enhance its oxidative stability. However, due to the limited availability of NSO-specific studies, these approaches are currently discussed as potential strategies based on its physicochemical properties, particularly their high polyunsaturated fatty acid content. Overall, encapsulation represents a promising approach to improve stability, sensory acceptability, and functional performance of NSO, although further experimental validation is required.

8.1 | Microencapsulation

Microencapsulation serves as an effective way to address various limitations associated with the application of essential oils. This application is significantly influenced by the high volatility and chemically unstable nature of essential oils (Estevinho et al. 2013). Microencapsulation is the technique of protecting small solid, liquid, or gaseous particles through a coating system (1–1000 nm) (M. N. Singh et al. 2010). The encapsulated material is called the core, and the material that forms the outer layer of the particle is the wall, or the encapsulating agent (Gonçalves et al. 2016). Besides, oils are susceptible to degradation by interactions with other chemical components and exposure to various elements, such as light, temperature, and oxygen, and they can be encapsulated to achieve controlled release (Bakry et al. 2016). Essential oils can be “trapped” in microcapsules in central region coated with thick wall material and in microsphere oils are dispersed in a wall material which provides excellent protection against various factors. The encapsulation technique, in which tiny particles are encapsulated in solid carriers to

enhance their protection, has the potential to minimize evaporation, facilitate handling, and control the release of essential oils during storage and application (I. M. Martins et al. 2014). Microencapsulation is a technique that transforms the state of essential oils into powder (solid particle) without changing its properties. In microencapsulation, the first step usually involves emulsifying or dispersing the essential oils in an aqueous solution of a wall material that also acts as an emulsifier and then dried (spray drying) under specific conditions (Mohammed et al. 2020). The encapsulation efficiency and stability of material depend on the selection of wall material and encapsulation technique (Carbonell-Capella et al. 2014). There are various physical techniques, such as spray drying, lyophilization, extrusion, emulsification, and the chemical techniques include coacervation, molecular inclusion and ionic gelation. Polysaccharides from various sources (plant, and marine extracts), lipids, and proteins are the materials used to encapsulate active components (Choudhury et al. 2021). The most used are gum Arabic, chitosan, and cyclodextrins (Zabot et al. 2022). However, some more natural substances, which include whey and soy proteins, gelatin, and starch, are of greater significance as coating materials because they represent the “GREEN” trend in various industries (pharmaceutical, cosmetic, and food industry).

Bioavailability of encapsulated material is the proportion of nutrient or bioactive compounds that can be available for metabolic and physical processes by the human body, which includes GI digestion and absorption into the bloodstream.

Microencapsulated fish oil is bioequivalent to standard encapsulated fish oil when consumed at equal doses; the increase in plasma EPA and DHA is comparable in both forms. Microencapsulation additionally improves stability and sensory properties, making it suitable for food fortification without compromising omega-3 absorption (Barrow et al. 2008).

8.2 | Nano Emulsions

Nano emulsions of plant-based oils is an advanced technique that improve bioavailability through decreasing droplet sizes to the nanoscale (often 10–270 nm), improving the solubility and the absorption of hydrophobic bioactives and increasing stability against volatility, oxidation, and environmental stress (Jamir et al. 2023). Properties such as stability, rheology, appearance, color, and texture in nano emulsion systems (NEs) are determined by the particle (droplet) size distribution as well as the nature of the essential oil and its relative chemical composition (Tadros et al. 2004). The goal is to achieve minimum droplet size and maximum stability with good potential. As a result of their low solubility and high sensory qualities (odor), they have limited use in the food sector (Donsi 2018). High energy methods are most suited for food-related nano emulsions preparation. The coarse oil in water emulsions were formed by mixing the components using a high-speed mixer or stirrer. Next, the emulsions are subjected to disruptive forces to reduce the droplet diameter to 200–500 nm (Espitia et al. 2019). High-pressure homogenization (HPH) and ultrasonication (US) dominate fabrication, reducing droplet sizes to 100–150 nm while minimizing PUFA loss.

Ostwald ripening takes place when the dispersed phase solubility in larger droplets (small curvature) is lower than in small droplets (large curvature), causing droplet development due to the formation of a concentration gradient (Thompson et al. 2018). Nano emulsions containing essential oils that are particularly vulnerable to Ostwald ripening due to high oil phase solubility in the aqueous phase despite their largely hydrophobic property (Ryu et al. 2018). Nano emulsions with thyme oil and low quantities of fish oil (< 75%) showed rapid droplet development during or shortly after homogenization. The reason for this was that the relatively high water-solubility of thyme oil produced rapid droplet development because of Ostwald ripening (Walker et al. 2017). In O/W nano emulsions with retinol, long-term stability may demonstrate a more substantial association with chemical stability rather than physical stability (Park et al. 2019).

Nano emulsification increases the bioavailability of plant-derived oils by increasing digestion, absorption, and transport within the gastrointestinal tract (Yakoubi et al. 2021). They give a significantly higher surface area for pancreatic lipase activity, resulting in a quicker breakdown of triglycerides into absorbable fatty acids and monoglycerides. This fast digestion facilitates the efficient integration of lipids into mixed micelles, which are required for intestinal absorption and systemic distribution (Salvia-Trujillo et al. 2016). Nano emulsions of chia and flaxseed oils had significantly better bio accessibility of α -linolenic acid (ALA) during vitro digestion, indicating increased absorption capacity. Their small droplet size also improves interaction with intestinal epithelial cells and may aid lymphatic transport, bypass first-pass metabolism, and raise plasma omega-3 concentrations. Flaxseed oil nano emulsions in yogurt fortification preserve ALA stability and enhance uptake without sensory alterations (Almasi et al. 2021). Overall, nano emulsions are a more efficient delivery route for plant-based polyunsaturated fatty acids, resulting in higher physiological effectiveness than traditional oil forms.

8.3 | Liposomes

Liposomes serve as effective carriers for essential oils (EOs), enhancing their solubility, stability, and sustained release for therapeutic applications. These microspherical vesicles contain an aqueous layer in the center, are formed from phospholipids such as lecithin and cholesterol, and encapsulate hydrophobic EO components within their lipid bilayer, protecting them from environmental degradation (Hammoud et al. 2019). This approach addresses EO limitations such as volatility and poor bioavailability, making them suitable for antimicrobial, antifungal, and antioxidant uses. Common techniques include ethanol injection, thin-film hydration, freeze-thaw, sonication, and extrusion, each influencing liposome size and EO loading (Gomez and Hosseini 2020). Encapsulation efficiency (EE%) varies depending on oil polarity, vesicle size, phospholipid composition, and preparation technique.

The major challenge associated with liposomal systems is their limited chemical and physical stability. Chemically, phospholipids are prone to degradation through oxidative reactions or hydrolysis (Grit and Crommelin 1993). This instability can be minimized by incorporating antioxidants, reducing exposure to

light, or preparing the liposomes under inert gases such as nitrogen or argon to limit oxygen contact (Vemuri et al. 1995). Liposome stability is also influenced by factors such as particle size, phospholipid composition, surface charge, and the method used for their fabrication. Incorporating cholesterol (Chol) into the lipid bilayer enhances liposome rigidity, decreases membrane fluidity, and reduces the likelihood of vesicle aggregation. This modification also lowers membrane permeability, thereby limiting premature leakage of the encapsulated compound (Nakhaei et al. 2021). To prolong shelf life, liposomes are often converted into a dry powder by freeze-drying (lyophilization). During this process, cryoprotectants such as sucrose, glucose, or trehalose are added to safeguard the vesicles and prevent loss of the encapsulated material (Akbarzadeh et al. 2013).

9 | Industrial and Sustainability Aspects

9.1 | Valorization of Noni Seed as By-Product Utilization

A large amount of noni seeds was discarded as waste from noni juice industry and remains an underutilized medicinal source; they contain protein, dietary fibers, bioactives and polyunsaturated fatty acids.

Valorization of noni (*Morinda citrifolia*) seeds explored their use as a source of noni seed protein concentrate (NSPC) obtained through alkaline extraction and isoelectric precipitation. The NSPC showed high protein content (about 74%), good solubility, and desirable functional properties such as emulsifying, gel formation, and foaming ability. Structural analysis revealed a well-defined globular protein structure with thermal stability and low aggregation tendency. The findings highlight the potential of noni seed proteins as functional food ingredients, promoting sustainable utilization of noni fruit by-products (Hernández Ramírez et al. 2023).

The seed oil extracted from noni shows high in linoleic and oleic unsaturated fatty acids which are beneficial to cardiovascular diseases, rich in phenolics and phytosterols, has anti-inflammatory, antioxidant, antimicrobial, wound healing, infection control, and moisturizing properties (Jahurul et al. 2022). Noni seed oil parameters similar to sunflower oil show nontoxic (West et al. 2008), as a new source of edible vegetable oil.

Following oil extraction, defatted seed meals can be converted into animal feed, soil amendment, or a substrate for novel bioproducts. The integration of biorefinery concepts maximizes material and energy recovery (Vasileiou et al. 2023).

Noni seed oil (NSO) is utilized in cosmetics for its skin-nourishing properties, owing to its high content of important fatty acids such as linoleic acid, which aid in skin health and moisture retention. NSO is noncomedogenic and has been demonstrated to have potential anti-inflammatory qualities by inhibiting both COX-2 and 5-LOX enzymes, indicating that it could be used to treat skin disorders such as acne. NSO is therefore used in skin healing,

antiaging, and moisturizing compositions for combating dryness and irritation (Palu et al. 2012). Valorization helps mitigate environmental impacts by reducing agro-industrial waste, promoting circular economy practices.

9.2 | Scale-Up Challenge

The main problems in valorizing noni seeds are economic feasibility, processing efficiency, supply consistency and quality control (Carbonell-Capella et al. 2014). Producing noni seed oil (NSO) on a large scale is extremely expensive because the cost of collecting seeds from juice production lines complicates continuous industrial processing, and the transportation, storage, and pre-processing (drying, cleaning) of seeds add to operational complexity. Seeds must be collected after fruit processing and thoroughly cleaned from pulp residues, and properly dried to prevent spoilage and loss of yield and quality. These logistics costs may erode the economic advantage from valorization.

It is challenging to maintain consistent quality due to variable seed composition caused by climatic and geographic conditions, and the oil is highly prone to oxidation, requiring stabilization techniques such as microencapsulation or liposomes or nano emulsions (I. M. Martins et al. 2014, Corrêa-Filho et al. 2022, Hernández Ramírez et al. 2023) to maintain critical quality attributes. Analyses of refined NSO showed changes in lipid composition: refining processes such as degumming, deacidification, and deodorization significantly altered the levels of phytosterols, phenolic compounds, tocopherols, and volatile compounds in the oil—which may reduce its bioactivity or functional value (Cui et al. 2025).

In order to ensure the production of high quality oil, laboratory methods such as Soxhlet extraction, ultrasound-assisted extraction and small batch pressing need to be compared with industrial methods such as continuous screw pressing, large scale solvent extraction or supercritical carbon dioxide processing. Scaling SC-CO₂ extraction to commercial volumes poses economic and technical challenges. High-pressure equipment, energy costs, CO₂ recycling systems, and maintenance overhead increase capital and operational expenditures. Green extraction and processing techniques (e.g., SC-CO₂, ultrasound-assisted extraction, and enzymatic treatments) are often suggested to minimize the environmental footprint and solvent waste, but such technologies may not yet be standardized for noni seeds, and techno-economic analyses (TEA) and life-cycle assessments (LCA) remain limited (Nozari and Kander 2025). Furthermore, scaling up extraction and processing processes requires investment in technological improvement to maximize yield and preserve bioactive compound integrity.

Although seed oil appears nutritionally attractive (rich in linoleic acid, unsaturated fatty acids; non-toxic), market acceptance, consumer awareness, regulatory approval, and demand from food/cosmetic/nutraceutical sectors will strongly determine economic returns. Additionally, refining to meet food-grade specifications may degrade beneficial compounds (antioxidants

and phenolics), reducing the perceived added value (Palu et al. 2012).

9.3 | Economic and Environmental Benefits

The increasing global demand for sustainable food systems has intensified interest in the valorization of agricultural by-products. Within the noni fruit (*Morinda citrifolia* L.) industry, the seeds typically remain underutilized despite constituting a significant proportion of the fruit mass. Historically considered waste, noni seeds are now recognized as a promising resource for high-value applications, particularly in the production of noni seed oil, protein concentrates, dietary fibers, and bioactive-rich extracts. The shift from discarding seeds to integrating them into processing chains presents considerable economic and environmental advantages, contributing to circular-economy models and reducing production costs.

Economically, valorizing noni seeds transforms an otherwise discarded material into marketable ingredients. The cold-pressed or solvent-extracted noni seed oil, rich in linoleic acid, oleic acid, phytosterols, tocopherols, and unique compounds such as damnacanthal and scopoletin, commands premium prices in cosmetic, nutraceutical, and functional food markets (Jahurul et al. 2022). Companies benefit from creating an additional revenue stream without expanding cultivation areas or significantly increasing input costs. Because noni fruit processing companies already handle the raw material for juice or puree production, collecting and processing the seeds requires minor adjustments to existing facilities. This reduces overhead expenses and allows the industry to maximize the economic value derived from each kilogram of fruit (Tavakoli et al. 2019).

Establishing small-scale seed collection and oil extraction units generates local employment and supports rural livelihoods. Farmers and cooperatives gain additional income by supplying seeds, especially during the off-season of other crops. Encouraging decentralized processing also stimulates local entrepreneurship, contributing to poverty reduction and community-level economic resilience.

From an environmental perspective, fruit processing industries generate large amounts of solid waste, and improper disposal of seeds may lead to microbial growth, foul odor, and attract pests (Meduri et al. 2025). Using seeds as raw materials for oil extraction or protein powders minimizes waste generation and mitigates environmental pollution also contributes to lowering the carbon footprint. This approach aligns with the principles of sustainable waste management and supports national goals for reducing landfill loads (sustainable development goals) and greenhouse gas emissions.

Where extraction facilities employ solvent recycling or green technologies (cold pressing, supercritical CO₂, or enzymatic extractions), solvent emissions and effluent loads can be minimized, further improving environmental outcomes (Nozari and Kander 2025).

10 | Future Perspectives and Research Gaps

10.1 | Unexplored Bioactivities

Although the current literature identifies antioxidant, anti-inflammatory, and antimicrobial properties of noni seed oil (Jahurul et al. 2022), several biological activities remain poorly characterized. The presence of unique phytochemicals—such as lignans, phytosterols, flavonoids, scopoletin, and damnacanthal—are known in other seed oils to exert diverse pharmacological effects (Fatin et al. 2020)—suggests potential roles in neuroprotection, metabolic regulation, hepatoprotection, dermal regeneration, and gut microbiota modulation (Ghanbari-Gohari et al. 2025), although these activities have not been thoroughly evaluated in noni seed oil.

One critical unexplored area is neuroprotection. Compounds such as scopoletin and damnacanthal, found in various parts of the noni plant, have demonstrated antioxidant and neuro-modulatory activities in other models, suggesting potential neuroprotective properties that merit further assessment. Similarly, the rich sterol and tocopherol content indicates possible cardioprotective and cholesterol-lowering effects, like sterol-rich oils such as sesame or rice bran oil. However, experimental verification—especially using in vivo models—is absent. Antifungal properties and potential uses as a plant resistance bio stimulant, involving inhibition of fungal protein synthesis via molecular interactions of oil compounds (Dias et al. 2024). However, most of these effects are only hypothesized based on the chemistry of the oil or isolated plant components. Systematic in vitro, in vivo are needed to map bioactivity pathways, identify molecular targets, and establish dose-response relationships. This represents a major research gap, as noni seed oil is still in its early stage of functional characterization.

10.2 | Synergy With Other Bioactives

Synergistic interactions between nutrients, particularly between phenolics, sterols, and polyunsaturated fatty acids, are well-established in functional food science. However, the synergy potential of noni seed oil remains largely unstudied, despite its complex composition that includes tocopherols, flavonoids, sterols, and essential fatty acids.

Noni seed oil contains unsaturated fatty acids, tocopherols, plant sterols, and phenolics (Jahurul et al. 2022), all of which have potential to interact synergistically with bioactive from other natural ingredients. Combinations with omega-3 oils, polyphenol-rich extracts (green tea, rosemary, turmeric), or probiotics could enhance antioxidant, anti-inflammatory, and cardiometabolic effects (Jacob and Kalangi 2021).

Incorporating noni seed oil into multi-ingredient functional foods offers substantial promise. Similarly, pairing it with polyphenol-rich plant extracts—such as green tea catechins, curcumin, rosemary diterpenes, or anthocyanins—could

improve oxidative stability and amplify antioxidant efficiency (Shahidi and Ambigaipalan 2018).

Furthermore, synergy between lipid-based carriers and bioactive phenolics can significantly influence bioavailability. Noni seed oil, when integrated into delivery platforms such as liposomes, nano emulsions, and micro encapsulated particles, may provide superior retention and release of sensitive compounds (Mohammed et al. 2020; Jamir et al. 2023). These systems can also improve the stability of other co-delivered nutraceuticals, creating opportunities for next-generation functional formulations.

Another unexplored domain is the interaction of noni seed oil with probiotics and prebiotics, which could yield enhanced effects on gut health, immunity, and metabolic function. Such combinations are being widely explored in nutraceutical design, and noni seed oil provides an excellent lipid matrix for such innovations. Future research should focus on synergistic formulation testing, and modeling of multi-component interactions to understand how noni seed oil can enhance or be enhanced by other bioactive.

10.3 | Need for Clinical Validation

Despite promising in vitro and in vivo findings, clinical validation of noni seed oil remains one of the most significant research gaps. Most available studies have been conducted on noni fruit juice or leaf extracts, while direct human evidence for noni seed oil is almost nonexistent. Noni seed oil (NSO) from *Morinda citrifolia* has limited clinical validation, primarily through small-scale human topical safety and efficacy trials rather than large randomized controlled trials or systemic studies (Palu et al. 2012).

NSO demonstrated concentration-dependent inhibition of COX-2 (84%–85%) and 5-LOX (40%–49%) enzymes, suggesting anti-inflammatory potential for skin conditions such as acne, although not clinically tested beyond safety. These findings support cosmetic use.

There is a translational gap between laboratory studies and human effects. In vitro antioxidant or enzyme-modulating activity does not automatically translate to physiological effects in humans. Human metabolism, absorption, and biotransformation of these compounds can differ significantly, and bioavailability of noni seed oil constituents has not yet been clinically quantified.

Clinical trials required to measure how much of the bioactive fraction (e.g., phytosterols, lignans, and coumarins) reaches systemic circulation after oral consumption. Without these data, it is impossible to determine effective dosage, safety thresholds, or long-term metabolic effects. A small number of rodent studies suggests safety at moderate doses, but these results cannot be generalized to humans (West et al. 2008).

To be recognized in nutraceutical markets, noni seed oil requires human RCTs (randomized controlled trials), such as anti-

inflammatory effects in healthy adults and lipid-lowering potential in heart patients etc., clinical validation is essential for commercial labeling, product positioning, and consumer acceptance.

10.4 | Regulatory Aspects for Food/Nutraceutical Markets

Regulatory bodies such as the U.S. Food and Drug Administration (FDA, 2022), European Food Safety Authority (EFSA, 2013 & 2018), and Codex Alimentarius Commission (FAO/WHO, 2022) have not yet classified noni seed oil as a GRAS (generally recognized as safe) substance or as an approved novel food ingredient. Only some noni fruit products—primarily juice and puree—have received approval in some regions, creating a regulatory gap for the seed oil. For regulatory approval, noni seed oil requires standardized compositional specifications (fatty acid profile and sterols, phenolics), toxicity and allergenicity assessments, oxidative stability and shelf-life studies, clear extraction and processing guidelines, and the establishment of maximum daily intake limits and labeling guidelines for health claims.

Regulators also increasingly emphasize sustainability, traceability, and environmental impact, especially for products derived from agricultural by-products. Because noni seeds are typically discarded during juice processing, developing sustainable seed-oil recovery processes could facilitate regulatory acceptance and improve global marketability.

Safety profiles from animal genotoxicity and antioxidant tests support NSO as nontoxic for potential food use, but clinical data gaps necessitate toxicological dossiers for approval (West et al. 2008).

11 | Conclusion

Noni seed oil has emerged as a promising yet underutilized resource within the nutraceutical sector, owing to its rich profile of bioactive lipids, phenolics, phytosterols, and antioxidants. Advances in extraction technologies have significantly improved oil yield, purity, and preservation of thermolabile compounds. Developments in encapsulation, especially nano emulsions and liposomal systems, have further strengthened the potential of noni seed oil by improving its stability, solubility, and controlled release, thereby enhancing its bioavailability in food, cosmetic, and therapeutic applications. Despite these advancements, scientific validation of noni seed oil remains incomplete. From an industrial perspective, valorization of noni seed by-products offers substantial economic and environmental benefits, supporting circular bioeconomy models and reducing agro-waste. However, challenges such as standardized extraction protocols, regulatory compliance, long-term safety assessments, and scale-up feasibility must be addressed before the oil can be fully integrated into mainstream functional food and nutraceutical markets. Overall, noni seed oil holds considerable potential as a multifunctional nutraceutical ingredient. Continued research in

clinical validation, advanced delivery systems, synergistic bio-activities, and sustainable large-scale processing will be essential to translate laboratory findings into commercially viable and scientifically substantiated applications.

Author Contributions

Sumidha Palanisamy: conceptualization, writing – original draft. **Kanimozhi Viswanathan:** writing – review and editing, supervision. **Pavithra Radhakrishnan:** conceptualization, writing – original draft. **Sonali Lini:** conceptualization, writing – original draft. **Sukumar Muthusamy:** writing – review and editing, supervision.

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The authors declare no conflicts of interest.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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