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RESEARCH ARTICLE

ATTENUATION OF ANTIOXIDANT DELIVERY BY MEDICINAL FORMULATIONS OF *EMBLICA OFFICINALIS* ENHANCED THROUGH NANOTECHNOLOGY APPROACHES: A REVIEW

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ABSTRACT

Emblica officinalis (amla), a cornerstone of traditional medicine, is widely recognized for its potent antioxidant profile, encompassing polyphenols, flavonoids, tannins, gallic acid, and ellagic acid. These bioactive compounds confer multiple health benefits, including hepatoprotection, cardio protection, anti-inflammatory, and anti-aging effects. However, conventional formulations often suffer from**attenuated bioavailability,** poor solubility, rapid metabolic degradation, and instability of phytoconstituents, which limit their therapeutic efficacy. This review systematically examines the challenges associated with traditional medicinal formulations of Emblica officinalis and highlights the advances offered by **nanotechnology-based delivery systems.** Key nanocarrier approaches—including nanoparticles, liposomes, Nanoemulsions, and polymeric matrices—are discussed in relation to their ability to enhance solubility, stability, targeted delivery, and sustained release of amla-derived antioxidants. The narrative integrates pharmacological evidence, formulation strategies, and mechanistic insights to provide a comprehensive understanding of how nano formulation can overcome conventional limitations. Furthermore, the review outlines current gaps, safety considerations, and future research directions for translating nano-enhanced amla formulations into clinical and nutraceutical applications. By bridging traditional herbal medicine with modern nanotechnological innovation, this review underscores the relevance of advanced delivery strategies in maximizing the therapeutic potential of Emblica officinalis, thereby offering a valuable framework for researchers, formulators, and healthcare practitioners.

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INTRODUCTION

Reactive oxygen species (ROS) are highly reactive molecules that can damage cellular lipids, proteins, and DNA, contributing to the development of chronic disorders such as cardiovascular disease, diabetes, neurodegenerative conditions, and inflammation. When the body's natural antioxidant defenses are unable to neutralize these ROS efficiently, a state known as oxidative stress arises (Lobo *et al*., 2010) . Maintaining an adequate antioxidant balance is therefore crucial for preventing cellular damage and associated pathologies. *Emblica officinalis* (amla), a widely used medicinal plant, is notable for its high levels of bioactive constituents including vitamin C (ascorbic acid), polyphenols, flavonoids, and tannins. These compounds are known to counteract oxidative stress by scavenging free radicals, chelating metal ions, and modulating endogenous antioxidant enzymes (Gul *et al*., 2022a). Despite its strong antioxidant potential, the therapeutic effectiveness of amla is often hindered by the poorstability, rapid metabolism, and limited bioavailability of its active compounds. Conventional formulations such as powders, capsules, or simple extracts may fail to deliver sufficient concentrations of these bioactive to target tissues. To address these challenges, nanotechnology-based delivery systems have emerged as promising tools for enhancing the delivery and efficacy of antioxidants. Formulations such as nanoparticles, microspheres, liposomes, and nanoemulsions can protect bioactive compounds from degradation, improve solubility, enable controlled or sustained release, and enhance absorption at target site (Baranauskaite *et al*., 2024)(Ortasöz *et al*., 2025a). By combining traditional knowledge of *E. officinalis* with modern nano delivery approaches, it is possible to maximize its antioxidant potential and therapeutic benefit in managing oxidative stress-related disorders.

Phytochemistry of *Emblica officinalis:* *Emblica officinalis* (amla) is rich in diverse bioactive compounds that contribute to its potent antioxidant activity. The major phytochemicals include vitamin C (ascorbic acid), polyphenols, flavonoids, tannins, and phenolic acids, which act synergistically to scavenge reactive oxygen species (ROS), chelate metal ions, and modulate antioxidant enzyme activity (Gomez *et al*., 2023)(Gul *et al*., 2022b).

Vitamin C (Ascorbic Acid): Vitamin C is the most abundant water-soluble antioxidant in amla, capable of directly neutralizing ROS and regenerating other antioxidants such as vitamin E. However, it is highly sensitive to heat, light, and pH, which limits its stability and

bioavailability in conventional formulations. Nanotechnology-based delivery systems such as polymeric nanoparticles and liposomes can protect vitamin C, enhance absorption, and provide sustained antioxidant activity in vivo (Fatima *et al*., 2024)(Ortasöz *et al*., 2025b)

Polyphenols and Flavonoids: Polyphenols like gallic acid, ellagic acid, emblicanin A & B, and flavonoids such as quercetin and kaempferol contribute significantly to radical scavenging, metal chelation, and enzyme modulation. Poor solubility and rapid metabolism often reduce their therapeutic efficiency. Encapsulation in nanocarriers or co-formulation with stabilizers can enhance bioavailability, protect bioactive from degradation, and maintain antioxidant activity at target sites (Baranauskaite *et al*., 2024)(Ortasöz *et al*., 2025a).

Tannins: Hydrolyzable tannins such as emblicanin A & B and punigluconin enhance the radical-scavenging capacity of amla. However, oral absorption is limited in conventional formulations. Nanocarriers, such as liposomes and nanoemulsions, can preserve the stability and bioavailability of tannins, improving systemic antioxidant efficacy (Sharma *et al*., 2024).

Phenolic Acids: Phenolic acids, including gallic and ellagic acids, not only neutralize free radicals but also modulate inflammatory pathways. Their susceptibility to gastrointestinal degradation limits therapeutic efficacy. Nanoencapsulation strategies protect these compounds and allow controlled release, enhancing antioxidant delivery and bioactivity (Yan *et al*., 2022)

Synergistic Phytochemical Interactions: (Gul *et al*., 2022b) The natural combination of vitamin C, polyphenols, flavonoids, and tannins produces synergistic antioxidant effects. Co-encapsulation of multiple bioactives in nanocarriers preserves these interactions, optimizing therapeutic outcomes and ensuring effective delivery in oxidative stress-related conditions.(Kashtiban *et al*., 2024)

Implications for Antioxidant Delivery: Understanding the phytochemistry of *E. officinalis* is crucial for designing effective antioxidant delivery systems. Nanotechnology-based strategies, such as polymeric nanoparticles, liposomes, microspheres, and Nanoemulsion .Integration of phytochemical knowledge with advanced nano delivery approaches enhances the therapeutic potential of amla antioxidants in managing oxidative stress-related disorders.

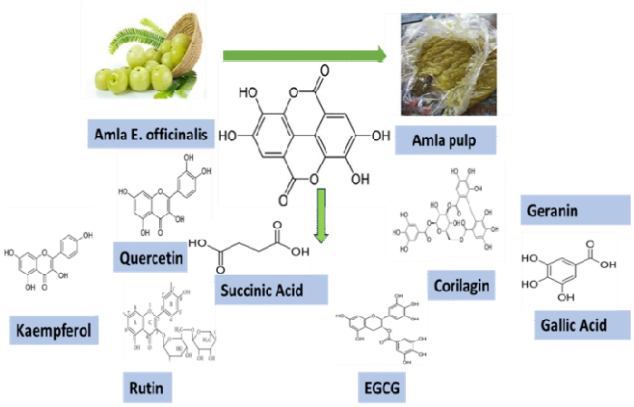

Figure 1. Major antioxidant phytochemical present in *Emblica officinalis* this figure illustrates the major antioxidant phytochemical found in amla including Quercetin, Succinic acid, EGCG, Gallic Acid, Geranin, Rutin, Corilagin.

As summarized in **Table 1**, various nanocarriers have been employed to enhance the antioxidant delivery and stability of *Emblica officinalis*. Phyto-fabricated nanoparticles, including selenium (SeNPs), gold (AuNPs), and silver (AgNPs), synthesized using *E. officinalis* fruit extract, demonstrated significant improvements in free-radical scavenging activity and colloidal stability compared with crude extracts ((Gunti *et al*., 2019),(Wang *et al*., 2021a),(Sharma *et al*., 2024),(Kumari *et al*., 2023b). The extract not only acts as a reducing agent but also provides surface capping, there by stabilizing the nanoparticles. Phytosomal and liposomal formulations, where bioactive polyphenols are complexed with phospholipids, have shown enhanced solubility, membrane permeability, and sustained antioxidant release, increasing both bioavailability and therapeutic retention time (Cao *et al*., 2024),(Ortasöz *et al*., 2025b). Similarly, nanoemulsion-based systems improve dispersibility and solubility of hydrophobic constituents, resulting in higher radical-scavenging efficiency and prolonged antioxidant activity (Kumari *et al*., 2023b).Collectively, these nanotechnology-based approaches bridge traditional herbal therapy with modern delivery systems, enabling controlled antioxidant release, improved stability of labile compounds such as ascorbic acid, and enhanced pharmacological performance of *E. officinalis*(Gandhi *et al*., 2023). These findings underscore the potential of nanoscale formulations in overcoming the limitations of conventional herbal preparations.

Biochemical Profiling of Amla: Medicinal plants have long served as the backbone of traditional medical systems and continue to hold immense significance for human health. Their bioactive constituents not only support conventional therapies but also provide promising leads for modern drug development. The World Health Organization (WHO) highlights that nearly 80% of the global population still relies on traditional medicine for primary healthcare needs, reflecting its crucial role worldwide (Koshy *et al*., 2015)WHO further encourages researchers to promote the rational and effective use of herbal remedies within national health programs, especially in developing countries, where medicinal plants are regarded as a “local heritage of global value” and often contribute more to health (Hasan *et al*., 2016a) care than synthetic pharmaceutical agents (Petrovska, 2012)*Emblica officinalis* (amla), a highly valued tree in Ayurveda, belongs to the Euphorbiaceae family and is commonly known as Amla or *Phyllanthus Emblica* in botanical literature (Hasan *et al*., 2016b),).

ts distribution spans central and southern India, Sri Lanka, southern China, Pakistan, Bangladesh, Malaysia, the Mascarene Islands, and tropical Southeast Asia. The tree generally reaches 8–18 meters in height, and in India it grows abundantly in tropical forests at elevations up to 4500 feet (Rai *et al*., 2018),(Gantait *et al*., 2021). The botanical characteristics of *E. officinalis*—including its fruits, leaves, seeds, bark, and flowers—are summarized in Table 3 (Hasan *et al*., 2016b)(Rai *et al*., 2018), and each plant part is associated with various therapeutic applications.

Among medicinal plants, *E. officinalis* is one of the most extensively studied species. Reports document a broad spectrum of bioactive compounds such as gallic acid, amino acids, flavone and phenolic glycosides, flavonol glycosides, sesquiterpenoids, nor-sesquiterpenoids, as well as high amounts of fiber, carbohydrates, iron, tannins, alkaloids, and other phenolic constituents. According to (Singh *et al*., n.d.), the nutritional profile of amla fruit surpasses that of many commonly consumed fruits—including apple, lime, grape, and pomegranate—by providing significantly higher levels of minerals, proteins, and amino acids such as glutamic acid, proline, aspartic acid, alanine, cystine, and lysine. Moreover, amla is considered one of the richest natural sources of vitamin C, surpassing most other fruits, as shown in Table 4 (Variya *et al*., 2016a),(Gul *et al*., 2022c).

Phytochemistry of *E. officinalis*: *Emblica officinalis* is a rich source of bioactive constituents, with ascorbic acid being the most abundant compound. The fruit also containsphosphatides, fixed and essential oils, tannins, minerals, vitamins, amino acids, and diverse phenolics (Table 5). Major polyphenols reported include methyl gallate, luteolin, corilagin, isostrictiniin, gallic acid, ellagic acid, chebulagic acid, and chebulinic acid(Variya *et al*., 2016b),(Hein *et al*., 2019). The pulp is particularly rich in tannins, such as phyllaemblicins, chebulagic acid, chebulinic acid, corilagin, ellagic acid**,** and amino acids likeglutamic acid, glycine, histidine, and isoleucine(L. Zhang *et al*., 2003), (Habib-ur-Rehman *et al*., 2007) Other identified compoundsinclude 1,6-di-O-galloyl-D-glucose, 3,6-di-O-galloyl-D-glucose, 3-ethylgallic acid, isostrictiniin, andkaempferol-3-O-(6′-methyl)-rhamnopyranoside(Tewari *et al*., 2019),(Srinivasan *et al*., 2018). Fruit juice contains multiple galloylated mucic acid derivativesandmalic acid gallates(Y. J. Zhang *et al*., 2001), while

Table 1. Nanotechnology-based delivery systems enhancing antioxidant stability and bioavailability of E. officinalis

Delivery System / Nanocarrier	Representative Study (Author, Year)	Material / Method	Key Findings (Antioxidant Delivery & Stability)
Phyto-fabricated Selenium nanoparticles (SeNPs)	(Gunti et al., 2019)	*E. officinalis* fruit extract used for green synthesis of SeNPs	Exhibited strong antioxidant activity and high stability; extract acted as reducing and capping agent.
Gold nanoparticles (AuNPs)	(Wang et al., 2021a)	Biogenic synthesis using *P. Emblica* fruit extract	Displayed enhanced antioxidant and anticancer potential; stabilized by polyphenols in the extract.
Silver nanoparticles (AgNPs)	(Sharma et al., 2024)	Green synthesis using *P. Emblica* extract	Improved free-radical scavenging capacity and colloidal stability compared with crude extract.
Phytosomal formulation	(Cao et al., 2024)	Standardized extract complexed with phospholipids	Enhanced solubility, permeability, and in-vitro antioxidant response.
Liposomal system	(Ortasöz et al., 2025a)	Polyphenols encapsulated in phospholipid liposomes	Sustained antioxidant release and improved transdermal permeability.
Nanoemulsion	(Kumari et al., 2023a)	Oil–water emulsion stabilized with surfactants	Increased dispersibility and antioxidant efficiency of polyphenols.
Comprehensive review of nano formulations	(Gandhi et al., 2023a)	Summary of multiple nanocarrier types	Highlighted advantages of nanoscale delivery for antioxidant stabilization and controlled release.

Source: Compiled from recent studies on nanotechnology-based formulations of *Emblica officinalis*(Gunti et al., 2019),(Wang et al., 2021a), (Sharma et al., 2024),(Ortasöz et al., 2025b), (Cao et al., 2024); (Kumari et al., 2023b),(Gandhi et al., 2023a)

Table 2. Taxonomical Classification of *Emblica officinalis*

Taxonomic Rank	Classification
Kingdom	Plantae (Plants)
Subkingdom	Tracheobionta (vascular plants)
Super division	Spermatophyta (seed plants)
Division	Angiospermae (flowering plants)
Class	Magnoliopsida
Subclass	Rosidae
Order	Euphorbiales
Family	Euphorbiaceae
Genus	Emblica
Species	officinalis Gaertn

Source: Table 2 is adapted from (Hasan et al., 2016b) open access article under the Creative Commons Attribution (CC BY) license.

Table 3. Botanical Description of *E. officinalis*

Feature	Description
Habitat	Central and southern India, Pakistan, Bangladesh, Sri Lanka, Malaysia, southern China, the Mascarene Islands, Southeast Asia, and Uzbekistan.
Appearance	Medium sized deciduous tree, 8–18 m height, with thin light gray bark exfoliating in small, thin, irregular flakes.
Used parts	Dried fruits, fresh fruit, seed, leaves, root bark, and flowers.
Leaves	Simple, subsessile, closely set along the branchlets, light green, having the appearance of pinnate leaves.
Fruits	15–20 mm long and 18–25 mm wide, nearly spherical or globular, wider than long with small conic depressions on both apexes. Mesocarp yellow; endocarp yellowish brown when ripe. Globose, pale yellow with six obscure furrows enclosing six trigonous seeds in three 2-seeded crustaceous cocci. Seedlings bear fruits in 7–8 years; budded clones start bearing from the 5th year onward. Fresh fruits light green; ripe fruits light brown; average fruit weight 60–70 g.
Flowers	Greenish yellow, in axillary fascicles, unisexual; males numerous on short slender pedicels; females few, subsessile; ovary 3-celled.
Seeds	Four to six, smooth, dark brown.
Bark	Thick up to 12 mm, shining grayish brown or grayish green.
Flowering and fruiting	February–May and December–January.
Edible part	Mesocarp and endocarp forming the hard stone encaging the seed.

Source Table 3 adapted from (Hasan et al., 2016a), open-access under the Creative commons Attribution (CC BY) license.

Table 4. Nutritional Value of E. officinal

Chemical Components	Amount
Fruits: moisture (%)	81.20
Protein (%)	0.50
Fat (%)	0.10
Mineral matter (%)	0.10
Fiber (%)	3.40
Carbohydrate (%)	14.10
Bulk elements (mg/100 g)	**Net weight**
Calcium (%)	0.05
Phosphorus (%)	0.02
Iron (mg/100 g)	1.20
Vitamin C (mg/100 g)	600
Nicotinic acid (mg/100 g)	0.20

Table 5. Antioxidant Constituents of Emblica officinalis, Limitations in Conventional Delivery, and Nanotechnology-Enabled Enhancements

Source	Major Antioxidant Compounds	Pharmaceutical / Biological Role	Limitations in Conventional Delivery	Nanotechnology-Based Enhancement
Fruit	Gallic acid	Strong antioxidant, anti-inflammatory	Poor stability, rapid metabolism	Nano-lipid carriers improve stability and sustained release
Fruit	Ellagic acid	Potent free-radical scavenger, anticancer	Low aqueous solubility; low bioavailability	Nanoemulsions enhance solubility and absorption
Fruit	Emblicanin A & B	Major hydrolysable tannins; strong antioxidant	Degraded quickly in GI tract	Polymer nanoparticles protect from degradation
Fruit	Corilagin & Geraniin	Antioxidant, hepatoprotective	Limited intestinal permeability	Chitosan-based nanoparticles improve permeability
Fruit	Myricetin & Kaempferol	Antioxidant, anti-inflammatory	Poor water solubility	Solid lipid nanoparticles enhance solubility and oral delivery
Fruit	Quercetin & Rutin	Antioxidant, neuroprotective	Very low bioavailability	Nanocapsules improve systemic circulation time
Fruit	Polyphenols (total)	Anti-aging, anti-inflammatory	Oxidation-sensitive	Nanoencapsulation prevents oxidation
Fruit	Tannins	GI protective, antioxidant	Molecular instability	Nano-dispersions provide stability
Fruit	Vitamin C (ascorbic acid)	Primary antioxidant of Amla	Highly unstable, oxidizes rapidly	Nano-gel and nano-hydrogels enhance stability
Fruit	Flavonoids	Antidiabetic, antioxidant	Low solubility	Nanoemulsions and liposomal delivery improve uptake

Source: Table 5 is adapted with permission (Copyright © 2016 Elsevier Ltd., Amsterdam, the Netherlands) from Variya et al. [5].

additional isolatesincludephyllaemblicin A–D, Phyllaemblic acids, and two phenolic glycosides . Leaves contain gallic acid, methyl gallate, 1,2,3,4,6-penta-O-galloylglucoseand newly reportedacylated flavanone glycosides**,** along withphyllanemblinins A–F(Y.-J. Zhang *et al*., 2000),(Baliga *et al*., 2013). Branches and leaves also possesstrihydroxysitosteroland**,**5,6,7-acetoxysitosterol(Qi *et al*., 2013),(Nambiar *et al*., 2015a). Both pulp and seeds show high phenolic and tannin content, including coumaric acid, myricetin, caffeic acid, gallicacid**,**andquercetin (Nambiar *et al*., 2015b). Among these**,** gallic acid, myricetin**,** kaempferol, emblicanin A and B, chebulagic acid, ellagic acid, pedunculagin, and corilaginare considered the major compounds responsible for lipid-lowering activity. Additional reports cite the presence of punigluconin, pedunculagin, emblicanin A/B(Bansal *et al*., 2015) , fatty acids (linolenic, oleic, stearic, palmitic, myristic), organic acids (citric acid), sugars (glucose, fructose, myo-inositol, galacturonic acid), and other isolates such as amlaicacid, arginine, aspartic acid, astragallin, and β-carotene**.**

Pharmacological Activities of Amla: Due to its extensive medicinal and pharmaceutical relevance, nearly every part of *Emblica officinalis* provides therapeutic benefits According to (Krishnaveni & Mirunalini, 2010) *E. officinalis exhibits a wide range of biological activities, including antioxidant, antimicrobial, anti-inflammatory, anticancer, antiulcer, antidiabetic, memory-enhancing, cardioprotective, neuroprotective, antidiarrheal, renoprotective, and immunomodulatory properties, as illustrated in Figure 1. Furthermore, the major phytoconstituents identified in the species contribute significantly to these activities and show notable anti-hyperlipidemic potential, as summarized in table 5* (F. F. Priya & Islam, 2019),(*Emblica officinalis Geart.*, n.d.). In addition, amla has been reported to exert beneficial effects on hyperlipidemia, osteoporosis, and reactive oxygen species (ROS), which play a major role in promoting oxidative stress and subsequent cellular damage

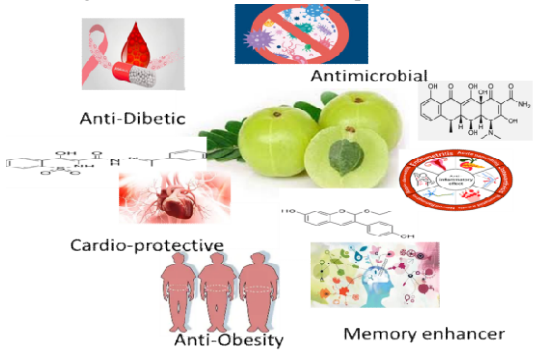

Figure2. Different pharmaceutical activities of E. officinal

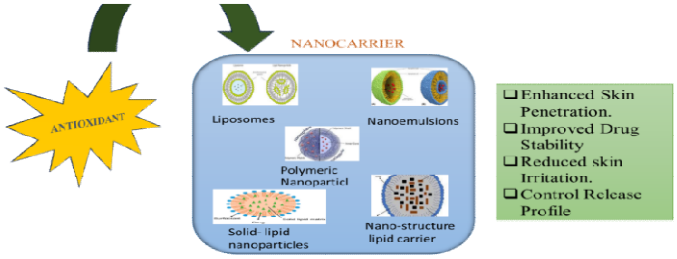

Figure 3. Nanocarrier-Enhanced Antioxidant Delivery System for *Emblica officinalis*This diagram illustrates how nanocarriers—such as polymeric nanoparticles, liposomes, Nanoemulsions, and solid-lipid nanoparticles—enhance the delivery of antioxidant phytochemicals present in *Emblica officinalis*. Nanocarriers protect unstable compounds (like vitamin C, polyphenols, tannins) from degradation, improve solubility and permeability, prolong circulation, and provide sustained or targeted release, thereby significantly increasing overall antioxidant bioavailability and therapeutic efficacy

Emblica officinalis contains a high concentration of polyphenols, tannins, and various bioactive phytochemicals that help in reducing oxidative stress and cellular injury. The natural antioxidant components of amla contribute significantly to free-radical scavenging, and both methanolic seed and fruit pulp extracts exhibit strong, dose-dependent DPPH radical inhibition activity (Fitriansyah *et al*., 2018), (G. Priya *et al*., 2012). The aqueous extract of the fruit has also shown remarkable ferric-reducing potential, free-radical neutralization, and suppression of reactive oxygen species (ROS) generation (Middha *et al*., 2015). The antimicrobial potential of E. officinalis has been demonstrated using different solvent systems, which revealed notable antifungal activity against Aspergillus species (Satish *et al*., n.d.). Ethanolic and acetone extracts of the fruit were effective against Candida albicans and Fusarium equiseti, while antibacterial activity against Staphylococcus species was confirmed by the zone-of-inhibition method. Tube dilution assays further showed significant reductions in the colony counts of Escherichia coli, Staphylococcus aureus, Klebsiella pneumoniae, and Pasteurella multocida (Saini *et al*., 2022), (*Antiradical Efficiency of 20 Selected Medicinal Plants: Natural Product Research: Vol 26, No 11*, n.d.) Additionally, pentagalloyl glucose, a phytoconstituent of amla, has been identified to possess anti-influenza activity and was evaluated through WST-1, plaque-forming unit, time-of-addition, and hemagglutination inhibition assays (Liu *et al*., 2011). Anti-inflammatory activity has also been reported, where water extracts of E. officinalis reduced paw edema in acute carrageenan-induced inflammation and lowered myeloperoxidase levels, granulomatous tissue mass, and plasma extravasation in chronic inflammation models

in Sprague–Dawley rats (Usharani *et al*., 2019) . Hepatoprotective effects were validated through histopathological evaluation using HepG2 cells against t-butyl hydroperoxide (t-BH) toxicity, and in vivo protection against carbon tetrachloride- and thioacetamide-induced liver damage using a 50% hydroalcoholic fruit extract. Nephroprotective effects were evident from reductions in thiobarbituric acid–reactive substances, serum creatinine, and blood urea nitrogen in aged rats (Malik *et al*., 2016) ,(Purena *et al*., 2018). The aqueous fruit extract also demonstrated antidepressant activity in Swiss albino mice during the forced swim and tail suspension tests, revealing reduced depression-like behavior. Improvements in memory were observed in aged mice in the elevated plus-maze and passive avoidance tests, accompanied by lower serum cholesterol levels and elevated brain cholinesterase activity (Dhingra *et al*., 2012). Immunomodulatory effects were confirmed in albino rats through increased hemagglutination antibody titers, macrophage migration indices, leukocyte counts, lymphocyte distribution, respiratory burst activity, and lymphoid organ mass, indicating stimulation of both humoral and cell-mediated immune responses (Suja *et al*., n.d.). In type II diabetic models, aqueous extracts of E. officinalis significantly lowered blood glucose, triglycerides, and alanine transaminase (ALT) levels in alloxan-induced diabetic rats (Ansari *et al*., 2014). Oral administration of 350 mg/kg extract improved multiple biochemical parameters, including serum glucose, glycosylated hemoglobin, insulin, cholesterol, triglycerides, HDL levels, protein, urea, and creatinine (Akhtar *et al*., 2011). Amla's flavonoids and other phytochemicals also contribute to its cholesterol-lowering potential. Clinical findings have shown marked reductions in C-reactive protein (CRP), LDL cholesterol, and total cholesterol (Gopa *et al*., 2012) ,(Variya *et al*., 2018) reported significant hypolipidemic effects of E. officinalis in patients with type-II hyperlipidemia, comparable to simvastatin therapy, with improvements in total cholesterol, LDL, and triglyceride profiles (Husain *et al*., 2019). Polyphenols from E. officinalis also exhibit gastroprotective effects. Bioactive compounds of amla have demonstrated inhibitory action against clarithromycin-resistant Helicobacter pylori strains in vitro (Mehrotra *et al*., 2011). Animal studies further revealed antiulcer potential: in mouse models, E. officinalis extracts decreased gastric secretion, ulcer index, hemorrhagic lesions, and intraluminal bleeding induced by pylorus ligation, indomethacin, necrotizing agents (25% NaCl, 0.2 M NaOH, 80% ethanol), and cold stress. The 500 mg/kg dose showed the most pronounced protection, particularly in indomethacin-induced ulceration (Al-Rehaily *et al*., 2002).

Nano formulation of *Emblica officinalis* for Enhanced Antioxidant and Therapeutic Applications: Nanomedicine has emerged as a powerful platform that integrates both therapeutic and diagnostic modalities, offering personalized strategies for managing life-threatening diseases such as cancer and diabetes. Nanocarriers serve as efficient and biocompatible systems capable of transporting phytochemicals directly to target tissues while maintaining biodegradability and minimizing toxicity. Their ability to provide site-specific, controlled, and sustained release significantly enhances the pharmacokinetic behaviour and bioavailability of plant-derived compounds. Additionally, nanoparticles improve membrane penetration and help prevent drug efflux through the gastrointestinal mucosa, thereby overcoming limitations associated with conventional herbal formulations (Middha *et al*., 2015). Growing interest in nanotechnology has stimulated the exploration of nano-enabled approaches to enhance the functional performance of phytochemicals. In the case of *Emblica officinalis*, nano formulation has become a prominent research area due to its potential to improve synergistic activity and increase the bioavailability of key antioxidant constituents. For instance, formulated a nanoemulgel incorporating Carbopol 940 with E. officinalis extract, demonstrating enhanced synergistic antimicrobial activity. Silver nanoparticle-based amla formulations have shown effective antiproliferative and cytotoxic responses, as reported by (Rosarin *et al*., 2013) and (Soundarajan *et al*., 2020). Further studies have explored biosynthesized nanocomposites combining silver or graphene oxide with E. officinalis, revealing strong antibacterial and cytotoxic effects. Likewise, documented significant antibacterial and cytotoxic potential of amla-mediated graphene oxide–silver nanocomposites against oral pathogens. Naik *et al*. [100] demonstrated the anticancer and antidiabetic properties of silver- and zinc-oxide-based phytofabricated (Ranjani & Hemalatha, 2022) nanoparticles derived from E. officinalis, supporting their safe and eco-friendly use in pharmaceutical applications. Moreover, green-synthesized magnesium oxide nanoparticles incorporating amla extract exhibited notable photocatalytic degradation of Evans Blue dye and antimicrobial activity, suggesting potential applications in environmental remediation. These findings highlight the capability of nano formulation strategies to overcome the poor absorption and instability associated with polyphenols and other functional constituents of amla, ultimately improving the bioavailability and overall therapeutic performance of the plant's active compounds (Dabulici *et al*., 2020),(Taleuzzaman *et al*., 2021)

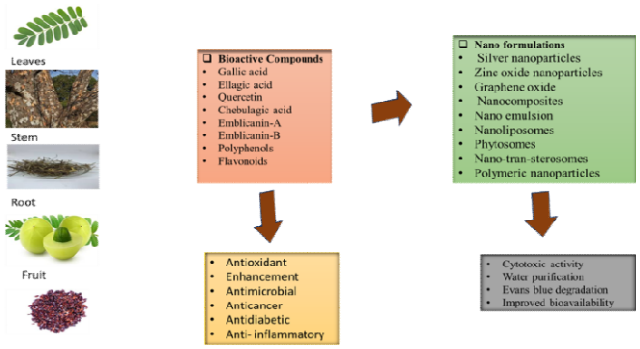

Figure 5. Nano formulation pathway of *Emblica officinalis* and its bioactive compounds

In contrast, several isolated phytoconstituents of *E. officinalis*—including ellagic acid, gallic acid, quercetin, and chebulagic acid—have been formulated into nano-delivery systems to enhance their oral bioavailability, stability, and biocompatibility.(Harakeh *et al*., 2020) reported that nano formulated ellagic acid exhibits significant antidiabetic potential, whereas (Hosny *et al*., 2020)developed sustained-release nanotransferosomes of ellagic acid demonstrating superior antiproliferative activity.Gallic acid, a major active component of amla with wide therapeutic relevance, has also been successfully nano encapsulated to overcome its poor solubility and limited absorption. Using probe sonication and high-pressure homogenization, gallic acid nanoparticles were prepared with glyceryl monooleate (GMO), chitosan, and poloxamer 407, resulting in improved controlled release, particularly targeting the colonic region (Patil & Killedar, 2021). Additionally, dendrimer-based nanodevices coated with gallic acid have been developed to overcome chemoresistance in neuroblastoma cells (Alfei *et al*., 2020). Further, gallic acid– and quercetin-based nano polymers have been synthesized to enhance their pharmacokinetic behavior and bioavailability. Recent studies have increasingly focused on the cosmetic and dermatological applications of gallic-acid nano formulations, reflecting expanding interest in their therapeutic and skin-protective properties (Khan *et al*., 2018).

Limitations of Nano-formulated *Emblica officinalis*

Toxicity / Safety Concerns

- In a study, *Emblica officinalis* fruit extract–coated iron oxide nanoparticles showed increased ROS, DNA damage, and apoptosis in A549 lung cancer cells.(Thoidingjam & Tiku, 2019)
- In a different work, gold nanoparticles made using amla extract induced apoptosis in gastric carcinoma cells via mitochondrial impairment.(Wang *et al*., 2021b)
- In a chitosan-casein nano-delivery system (CS-casein-Amla), cytotoxicity was measured on normal HDF (human dermal fibroblast) cells, and though toxicity was *lower* in nanoparticle form than free amla, there is still measurable effect.(Ramezani *et al*., 2024a)

Formulation / Stability Issues

- In the chitosan-casein system (capping with casein + chitosan), authors report that the freeze-drying step caused stress and led to **particle size enlargement**, showing that processing (lyophilisation) can destabilize the nanoparticles. (Ramezani *et al*., 2024b)
- In liposomal formulation of amla polyphenols, stability is a concern: they had to incorporate the liposomes into a *gel* (Carbopol hydrogel) to improve controlled release and stability. (Baranauskaite *et al*., 2024)

Limited Pharmacokinetics / Biodistribution Data

- I could not find many *in vivo* PK (absorption, distribution, metabolism, excretion) studies specifically for **nano-encapsulated amla phytochemicals**in the literature. (This itself is a limitation: lack of data.)

Quality Control / Standardization

- Because many of these studies use **green synthesis** (plant extract–mediated), the exact composition of the extract (polyphenols, tannins, etc.) can vary. For example, in silver nanoparticle synthesis with amla, the pH and extract concentration strongly affected the synthesis. (Ramesh *et al*., 2015)
- This variability can make reproducibility between batches difficult.

Regulatory / Translational Gap

- Even though not always directly stated, many of these research articles do *not* progress to animal models (or further to human clinical studies) for the nano-formulations: most are in vitro or small-scale synthesis + characterization + basic bio-assays (antibacterial, cytotoxicity). That shows a gap in translation.

Toxicology of the Parent Extract

- The methanolic extract of *E. officinalis* itself has a reported $\mathbf{LD_{50}}$ of ~1125 mg/kg (in mice) in one toxicological study. (Middha *et al*., 2015)
- Thus, even without nano, very high doses are not risk-free, meaning nanoformulation could amplify toxicity concerns if delivered more efficiently / in higher concentration to cells.

CONCLUSION

Emblica officinalis is an exceptionally rich source of natural antioxidants, yet the therapeutic potential of its bioactive compounds is often restricted due to poor stability, rapid degradation, and limited gastrointestinal absorption. This review highlights that conventional formulations fail to deliver optimal levels of key phytoconstituents such as gallic acid, ellagic acid, emblicanin A and B, and other polyphenols, resulting in reduced biological efficacy. Advancements in nanotechnology provide an efficient solution by improving solubility, protecting active compounds from oxidative breakdown, enhancing permeability, and ensuring controlled and targeted release .Evidence from recent studies demonstrates that nano-enabled delivery systems—such as nanoparticles, Nanoemulsions, liposomes, phytosomes, and polymeric nanocarriers—significantly improve antioxidant bioavailability and amplify pharmacological activities including antidiabetic, anticancer, anti-inflammatory, antimicrobial, cardioprotective, and hepatoprotective effects. These findings clearly signify that integrating nanotechnology with amla-based formulations can overcome major delivery challenges and elevate its therapeutic value. However, despite promising experimental outcomes, further research is essential to establish long-term safety, dose optimization, stability parameters, and clinical validation of these nano formulations. With continued scientific advancement and standardized evaluation, *E. officinalis*–based nano delivery systems hold strong potential to emerge as effective, safe, and sustainable therapeutic candidates for combating oxidative stress–related diseases and chronic metabolic disorders.

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