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HENNA (*LAWSONIA INERMIS* L.): A COMPREHENSIVE REVIEW OF TRADITIONAL MEDICINE, BIOACTIVE CONSTITUENTS AND THERAPEUTIC POTENTIAL

Dhale D. A.*

PG Dept. of Botany, SSVPS's, L.K.Dr.P.R. Ghogrey Science College, Dhule-424005 (MS, India).

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***Corresponding Author: Dhale D. A.**
PG Dept. of Botany, SSVPS's, L.K.Dr.P.R. Ghogrey Science College, Dhule-424005 (MS, India).
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ABSTRACT

Lawsonia inermis L. (Lythraceae), commonly known as henna or mehndi, is an important medicinal and cosmetic plant widely used in traditional systems of medicine, including Ayurveda, Unani, Siddha, and folk healthcare practices across Asia, Africa, and the Middle East. Besides its extensive use as a natural dye for skin, hair, and textiles, the plant possesses significant therapeutic potential owing to its rich phytochemical composition. Major bioactive constituents, including lawsone (2-hydroxy-1,4-naphthoquinone), flavonoids, phenolic acids, coumarins, xanthones, tannins, terpenoids, sterols, and essential oils, are responsible for its diverse biological activities. Traditionally, various plant parts have been used for the treatment of skin diseases, wounds, burns, inflammatory disorders, fever, jaundice, dysentery, microbial infections, and several gynecological ailments. Contemporary pharmacological studies have validated many of these traditional claims by demonstrating antioxidant, antimicrobial, antifungal, antiviral, anti-inflammatory, wound-healing, antidiabetic, hepatoprotective, nephroprotective, anticancer, and immunomodulatory properties through in vitro and in vivo investigations. Recent advances in phytochemical analysis, metabolomics, molecular docking, nanotechnology, and herbal drug standardization have further expanded the pharmaceutical and industrial potential of *L. inermis*. Green synthesis of metallic nanoparticles and the development of novel herbal formulations highlight its emerging applications in medicine, cosmetics, biotechnology, and food preservation. However, challenges related to phytochemical standardization, quality control, clinical validation, safety assessment, and sustainable utilization remain to be addressed. This review comprehensively summarizes the current knowledge on the botany, taxonomy, ethnomedicinal significance, phytochemistry, pharmacological activities, quality control, safety, conservation, and future therapeutic prospects of *Lawsonia inermis*. It also identifies existing research gaps and emphasizes the need for further multidisciplinary investigations to facilitate the development of safe, standardized, and evidence-based plant-derived therapeutics.

KEYWORDS: *Lawsonia inermis*, Henna, Mehndi, Lawsone, Medicinal plant, Ethnomedicine, Phytochemistry, Lythraceae.

1. INTRODUCTION

Medicinal plants have played a pivotal role in human healthcare since antiquity and continue to serve as indispensable sources of therapeutic agents, nutraceuticals, and pharmaceutical lead compounds. The World Health Organization (WHO) estimates that nearly 80% of the global population relies on traditional herbal medicines for primary healthcare, particularly in developing countries where medicinal plants remain readily accessible and culturally accepted (World Health Organization [WHO], 2023). Among these medicinal species, *Lawsonia inermis* L., commonly known as henna or mehndi, occupies a unique position because of its dual importance as a medicinal plant and a natural cosmetic dye.

Lawsonia inermis belongs to the family Lythraceae and is widely cultivated throughout tropical and subtropical regions of Asia, Africa, and the Middle East. The plant has been traditionally employed in Ayurveda, Unani, Siddha, and various indigenous systems of medicine for treating skin diseases, wounds, burns, inflammatory disorders, fever, headache, dysentery, jaundice, urinary disorders, and several gynecological ailments. Besides its medicinal significance, henna has immense socio-cultural value due to its widespread use in body art, hair colouring, textile dyeing, and religious ceremonies across many civilizations (Semwal et al., 2014).

The therapeutic efficacy of *L. inermis* is primarily attributed to its diverse phytochemical composition. The plant contains numerous biologically active constituents including lawsone (2-hydroxy-1,4-naphthoquinone), flavonoids, phenolic acids, coumarins, xanthones, tannins, triterpenoids, sterols, alkaloids, and essential oils. These secondary metabolites exhibit remarkable antioxidant, antimicrobial, anti-inflammatory, wound healing, anticancer, hepatoprotective, nephroprotective, antidiabetic, and immunomodulatory activities, thereby validating many of its traditional medicinal applications (Habbal et al., 2005; Mikhaeil et al., 2004; Sharma et al., 2022).

The uploaded classical literature also highlights the extensive traditional uses of the bark, leaves, flowers, and seeds, along with pharmacognostic characteristics, phytochemistry, pharmacological activities, and toxicological investigations carried out during the twentieth century, thereby providing an important scientific foundation for contemporary research.

During the past decade, considerable scientific progress has been achieved through advanced analytical techniques such as high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS/MS), metabolomics, molecular docking, and nanotechnology-based drug delivery systems. These investigations have broadened the therapeutic scope of *L. inermis* and highlighted its potential applications in pharmaceutical sciences, dermatology, cosmetic industries, food preservation, and biomedical research.

Nevertheless, issues related to phytochemical standardization, quality control, safety assessment, clinical validation, and sustainable utilization remain inadequately addressed.

Therefore, the present review comprehensively summarizes classical knowledge together with recent scientific advances regarding the taxonomy, botany, geographical distribution, ethnomedicinal importance, phytochemistry, pharmacology, quality control, safety, and future therapeutic prospects of *Lawsonia inermis*, thereby providing an updated resource for researchers, clinicians, pharmacologists, and herbal drug developers.

2. Botanical Description and Taxonomy

Lawsonia inermis L. is the only accepted species of the genus *Lawsonia*, although several botanical synonyms, including *Lawsonia alba* Lam., have historically been reported in taxonomic literature. The accepted scientific name is *Lawsonia inermis* L. according to modern botanical nomenclature (POWO, 2025).

The genus was named in honour of the Scottish physician Isaac Lawson, a close associate of Carl Linnaeus. The species epithet *inermis* means "without thorns," although occasional spine-like branchlets may occur in older plants.

Botanical Description

Lawsonia inermis is a much-branched perennial shrub or small tree, generally attaining a height of 2–8 m depending upon environmental conditions. The plant possesses smooth greyish-brown bark and numerous quadrangular young branches. Mature stems gradually become cylindrical with age.

Leaves are opposite, simple, entire, glabrous, shortly petiolate, elliptic to broadly lanceolate, measuring approximately 2–5 cm in length and 1–2 cm in width. The leaf lamina is leathery with entire margins, acute apex, and distinct pinnate venation. Numerous oil glands and mucilage-containing cells occur within the mesophyll tissues. Classical pharmacognostic investigations have described the leaves as possessing an isobilateral anatomy with ranunculaceous-type stomata, calcium oxalate crystals, oil globules, and mucilage sacs, which serve as important diagnostic features for quality evaluation (Mitra and Kapoor, 1971).

The flowers are small, fragrant, white to cream-coloured or pinkish, borne in large terminal pyramidal panicles. Each flower possesses four crumpled petals, eight stamens, and a superior ovary. Flowering generally occurs from April to September depending upon climatic conditions.

The fruit is a small globose capsule (4–8 mm in diameter) containing numerous angular pyramidal seeds. The seeds possess a hard seed coat and contain fixed oils rich in palmitic, stearic, oleic, linoleic, arachidic, and behenic acids.

The characteristic orange-red dye is produced by the leaves due to the presence of lawsone, a naturally occurring naphthoquinone pigment that binds strongly to keratin proteins present in skin, hair, nails, wool, silk, and leather.

3. Geographical Distribution and Ecology

Lawsonia inermis is indigenous to northern Africa, the Arabian Peninsula, and parts of southwestern Asia. Over centuries, it has become naturalized and extensively cultivated throughout tropical and subtropical regions including India, Pakistan, Bangladesh, Sri Lanka, Nepal, Myanmar, China, Iran, Egypt, Sudan, Morocco, Yemen, Saudi Arabia, Oman, and several Mediterranean countries (POWO, 2025).

India represents one of the largest producers and exporters of henna, with commercial cultivation concentrated in Rajasthan, Gujarat, Madhya Pradesh, Haryana, Punjab, Uttar Pradesh, Tamil Nadu, and parts of Maharashtra.

Rajasthan, particularly the Sojat region of Pali district, is internationally recognized for producing premium-quality henna owing to its favourable climatic and edaphic conditions.

The uploaded source indicates that the species is cultivated throughout India, reflecting its remarkable adaptability to diverse agro-climatic regions.

Ecologically, *L. inermis* thrives under hot arid and semi-arid climates with annual temperatures ranging between 25°C and 45°C. It tolerates prolonged drought, high solar radiation, and low humidity, making it well adapted to xerophytic environments. The species grows optimally in well-drained sandy loam, loamy, or alluvial soils with slightly alkaline to neutral pH (6.5–8.5). Mature plants exhibit remarkable drought tolerance owing to their deep root systems and efficient water-use strategies.

The species prefers annual rainfall between 400 and 1200 mm but can survive under lower precipitation through physiological adaptations. It is commonly cultivated in wastelands, field margins, home gardens, dry scrublands, and agroforestry systems where it contributes to soil conservation and sustainable rural livelihoods.

Pollination is primarily entomophilous, involving bees, butterflies, flies, and other nectar-feeding insects attracted by the fragrant flowers. Seed dispersal occurs mainly through gravity and human cultivation practices.

4. Traditional and Ethnomedicinal Uses

Lawsonia inermis has occupied a prominent place in traditional medicine for more than three millennia. Every part of the plant-including leaves, bark, flowers, seeds, and roots—has been utilized in Ayurveda, Siddha, Unani, Persian medicine, Traditional Arabic medicine, and numerous indigenous healthcare systems.

According to Ayurvedic literature, the plant possesses Tikta (bitter) and Kashaya (astringent) taste, Laghu (light) and Ruksha (dry) properties, Sheeta Veerya (cooling potency), and Katu Vipaka (pungent post-digestive effect).

Traditionally, it is prescribed for the management of Kapha and Pitta disorders, skin diseases, wounds, fever, burning sensation, jaundice, urinary disorders, blood disorders, pruritus, and inflammatory conditions.

The leaves constitute the most therapeutically valuable part of the plant. Fresh leaf paste is externally applied to burns, wounds, ulcers, eczema, psoriasis, fungal infections, cracked heels, boils, and inflammatory skin disorders. Leaf decoctions are administered as astringents and are traditionally recommended for diarrhoea, dysentery, menorrhagia, leucorrhoea, and urinary ailments. Tribal communities in India have also employed leaf preparations to relieve headache, muscle pain, and fever (Raj & Patel, 1978).

The bark is regarded as an alterative and is traditionally used in jaundice, splenomegaly, skin diseases, and urinary calculi. Flowers possess refrigerant and mild sedative properties and have been employed to alleviate headache, induce sleep, and reduce body heat. Seeds contain fatty oils and have occasionally been incorporated into traditional formulations for dermatological disorders (Jain & Tarafder, 1970).

Beyond medicinal applications, henna has exceptional cultural importance throughout Asia, Africa, and the Middle East. The leaves are processed into a fine powder used for decorating hands and feet during weddings, religious ceremonies, and cultural festivals. Natural lawsone pigment is extensively employed for colouring hair, nails, wool, silk, leather, and textiles. Because of its cooling effect, fresh henna paste is traditionally applied to palms and soles during summer months to reduce heat stress and provide symptomatic relief from burning sensations.

Recent ethnopharmacological investigations continue to validate many traditional applications by demonstrating significant antimicrobial, antioxidant, anti-inflammatory, wound-healing, and dermatoprotective properties, thereby supporting the integration of *L. inermis* into evidence-based herbal medicine (Semwal et al., 2014; Sharma et al., 2022).

5. Phytochemical Profile

Lawsonia inermis L. possesses a remarkably diverse phytochemical composition that contributes to its extensive pharmacological activities. Different plant parts, including leaves, bark, flowers, seeds, and roots, contain numerous classes of primary and secondary metabolites such as naphthoquinones, flavonoids, phenolic compounds, coumarins, xanthones, triterpenoids, sterols, tannins, alkaloids, glycosides, essential oils, carbohydrates, proteins, amino acids, and fatty acids (Semwal et al., 2014).

The principal bioactive constituent of *L. inermis* is lawsone (2-hydroxy-1,4-naphthoquinone), a natural orange-red pigment responsible for the characteristic staining property of henna. Lawsone exhibits broad-spectrum biological activities including antioxidant, antibacterial, antifungal, antiviral, anti-inflammatory, wound healing, and anticancer effects (Habbal et al., 2005; Singh et al., 2023). Classical phytochemical investigations first identified lawsone from the leaves, while subsequent studies characterized numerous additional secondary metabolites.

The whole plant on ethanolic extraction yielded, a new coumarin named lacoumarin, shown to be 5-allyloxy-7-hydroxycoumarin (Bhardwaj et al., 1976), three new laxanthones viz., laxanthone I, II and III which were characterized as 1, 3-dihydroxy-6, 7-dimethoxy xanthone; 1-hydroxy-3, 6-diacetoxy-7-methoxy xanthone (Bhardwaj et al., 1977) and 1-hydroxy-3, 7-dimethoxy-6-acetoxy xanthone respectively (Bhadwaj et al., 1978). The structures of laxanthones, were finally confirmed by synthetic studies (Bhardwaj et al., 1979 a, b, c).

Recent phytochemical investigations using High-Performance Liquid Chromatography (HPLC), Gas Chromatography-Mass Spectrometry (GC-MS), Liquid Chromatography-Mass Spectrometry (LC-MS/MS), Nuclear Magnetic Resonance (NMR), and metabolomic approaches have expanded the chemical profile of *L. inermis*. Major phytochemical groups include:

a) **Naphthoquinones:** Lawsone, methylene-3-furan-1,2-naphthoquinone
b) **Flavonoids:** Luteolin, apigenin, quercetin, kaempferol, rutin
c) **Phenolic acids:** Gallic acid, caffeic acid, chlorogenic acid, ferulic acid
d) **Coumarins:** Lacoumarin
e) **Xanthones:** Laxanthone I, II and III
f) **Triterpenoids:** Lupeol, hennadiol, betulin, betulinic acid
g) **Sterols:** β-Sitosterol, stigmasterol
h) **Tannins:** Hydrolysable and condensed tannins
i) **Essential oils:** Eugenol, linalool, α-terpineol, caryophyllene and other volatile terpenes
j) **Fatty acids:** Palmitic, stearic, oleic, linoleic, arachidic and behenic acids in seeds (Chakraborty et al., 1982; Semwal et al., 2014).

The leaves are particularly rich in phenolic compounds and flavonoids that contribute significantly to free-radical scavenging capacity. Environmental conditions, geographical origin, harvesting season, soil characteristics, and extraction methods considerably influence the phytochemical composition and biological efficacy of the plant (Sharma et al., 2022).

Modern metabolomic studies have further identified numerous previously unreported metabolites that may serve as potential biomarkers for authentication and quality control of commercial henna preparations. Consequently, advanced chromatographic fingerprinting has become an important tool for standardizing herbal formulations prepared from *L. inermis*.

6. Pharmacological Activities

The diverse phytochemical constituents of *Lawsonia inermis* confer a broad spectrum of pharmacological activities that have been validated through in vitro, in vivo, and computational studies. Traditional medicinal applications reported in Ayurveda and indigenous healthcare systems have increasingly gained scientific support through experimental pharmacology. The uploaded literature documents antibacterial, antifungal, anti-inflammatory, antitubercular, antihyaluronidase, nematicidal, and antifertility activities, while contemporary research has further demonstrated antioxidant, hepatoprotective, nephroprotective, anticancer, antidiabetic, antiviral, immunomodulatory, and wound healing properties.

Among these pharmacological activities, antioxidant, antimicrobial, anti-inflammatory, wound-healing, and dermatoprotective properties are the most extensively investigated. Several studies have demonstrated that crude extracts and isolated compounds from *L. inermis* exert their biological effects through modulation of oxidative stress, inhibition of inflammatory mediators, suppression of microbial growth, enhancement of collagen synthesis, and regulation of immune responses (Semwal et al., 2014; Sharma et al., 2022).

Recent molecular docking and network pharmacology studies have suggested that lawsone and several flavonoids exhibit strong binding affinity towards inflammatory enzymes, microbial proteins, and oxidative stress-related molecular targets, indicating their potential for future drug development.

Furthermore, nano-formulations synthesized using *L. inermis* extracts have shown enhanced antimicrobial efficacy, improved bioavailability, controlled drug release, and reduced toxicity compared to conventional herbal preparations, opening new avenues for pharmaceutical applications.

6.1 Antioxidant Properties

Oxidative stress plays a central role in the pathogenesis of numerous chronic diseases including diabetes mellitus, cardiovascular disorders, neurodegenerative diseases, inflammatory conditions, and cancer. The antioxidant potential of *Lawsonia inermis* is primarily attributed to its abundance of phenolic compounds, flavonoids, tannins, coumarins, xanthones, and the naphthoquinone derivative lawsone (Mikhaeil et al., 2004).

Numerous experimental studies have demonstrated strong free-radical scavenging activity of leaf extracts using DPPH, ABTS, FRAP, ORAC, nitric oxide scavenging, hydroxyl radical scavenging, and lipid peroxidation inhibition assays.

Ethanolic and methanolic extracts generally exhibit higher antioxidant activity owing to their greater phenolic content (Semwal et al., 2014).

The antioxidant mechanisms involve:

a) Neutralization of reactive oxygen species (ROS)
b) Inhibition of lipid peroxidation
c) Enhancement of endogenous antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx)
d) Reduction of oxidative DNA damage
e) Chelation of transition metal ions

Recent studies have also demonstrated that nano-formulated henna extracts possess enhanced antioxidant efficacy due to increased surface area and improved cellular uptake (Singh et al., 2023).

These antioxidant properties contribute significantly to the wound healing, anti-inflammatory, hepatoprotective, nephroprotective, and anticancer activities of the plant.

6.2 Antimicrobial Activities

The antimicrobial activity of *Lawsonia inermis* has been extensively investigated against numerous pathogenic microorganisms. Classical investigations demonstrated antibacterial activity of leaf extracts against *Staphylococcus aureus*, *Streptococcus pyogenes*, *Escherichia coli*, *Salmonella typhi*, *Bacillus subtilis*, *Shigella dysenteriae*, and *Vibrio cholerae*. (Bhatnagar et al., 1961 b; Jain & Pathak, 1970; Bhakuni et al., 1971; Pandey et al., 1982)

Subsequent investigations have confirmed broad-spectrum antibacterial activity against multidrug-resistant Gram-positive and Gram-negative bacteria including Methicillin-resistant *Staphylococcus aureus* (MRSA), *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, and *Enterococcus faecalis* (Habbal et al., 2005).

The antimicrobial mechanisms include:

a) Disruption of bacterial cell membranes
b) Inhibition of protein synthesis
c) DNA damage
d) Suppression of biofilm formation
e) Interference with quorum sensing
f) Generation of oxidative stress within microbial cells

Lawsone, flavonoids, tannins, and phenolic acids are considered the major contributors to antibacterial activity. Synergistic interactions among these phytochemicals further enhance antimicrobial efficacy.

Recent investigations have also explored the incorporation of henna extracts into wound dressings, hydrogels, biodegradable films, food packaging materials, and antimicrobial coatings to prevent bacterial contamination and biofilm development.

6.3 Antifungal and Antiviral Activities

Lawsonia inermis exhibits potent antifungal activity against numerous human and plant pathogenic fungi. Early investigations demonstrated inhibitory activity against *Candida albicans*, *Cryptococcus neoformans*, *Trichophyton* *mentagrophytes*, *Microsporum canis*, *Aspergillus niger*, *Helminthosporium* spp., *Ustilago tritici*, and *Diplodia natalensis*.

Lawsone has been identified as one of the principal antifungal compounds, acting through:

a) Inhibition of fungal cell wall synthesis
b) Alteration of membrane permeability
c) Suppression of mitochondrial respiration
d) Inhibition of nitrate reductase and peroxidase enzymes
e) Prevention of spore germination

These findings support the traditional use of henna leaves in the treatment of fungal skin infections such as dermatophytosis, ringworm, athlete's foot, and candidiasis.

In recent years, antiviral research has received considerable attention. In vitro and molecular docking studies have suggested that lawsone, flavonoids, and related phenolic compounds possess inhibitory activity against several RNA and DNA viruses by interfering with viral proteases, polymerases, and host-cell entry mechanisms. Preliminary computational studies have also indicated potential inhibitory interactions against SARS-CoV-2 main protease (Mpro), influenza virus neuraminidase, herpes simplex virus (HSV), hepatitis viruses, and dengue virus proteins. However, these findings require further experimental validation and well-designed clinical investigations before therapeutic recommendations can be made (Sharma et al., 2022; Singh et al., 2023).

Overall, the antifungal and emerging antiviral properties of *L. inermis* highlight its potential as a promising source of natural antimicrobial agents for pharmaceutical, veterinary, agricultural, and cosmetic applications.

6.4 Anti-inflammatory Activity

Inflammation is a complex physiological response to tissue injury and microbial invasion; however, persistent inflammation contributes to the development of chronic disorders such as arthritis, cardiovascular diseases, diabetes, neurodegenerative disorders, and cancer. *Lawsonia inermis* has long been employed in traditional medicine for the treatment of inflammatory conditions, burns, ulcers, skin diseases, and painful swellings. Contemporary pharmacological investigations have validated these traditional claims through both in vitro and in vivo studies (Semwal et al., 2014).

The anti-inflammatory activity of *L. inermis* is primarily attributed to the synergistic effects of lawsone, flavonoids, phenolic acids, tannins, coumarins, and triterpenoids. These phytochemicals inhibit several inflammatory mediators, including cyclooxygenase (COX-2), lipoxygenase (LOX), inducible nitric oxide synthase (iNOS), tumor necrosis factor-alpha (TNF-α), interleukin-1β (IL-1β), interleukin-6 (IL-6), prostaglandin E_2 (PGE_2), and nuclear factor-kappa B (NF-κB), thereby reducing inflammatory responses (Sharma et al., 2022).

Classical experimental studies demonstrated significant anti-inflammatory activity of alcoholic leaf extracts in carrageenan-induced paw edema, granuloma pouch, and cotton pellet granuloma models, with efficacy comparable to hydrocortisone under experimental conditions. Furthermore, the extracts exhibited antihyaluronidase activity, suggesting their role in reducing tissue inflammation and vascular permeability.

Recent investigations have also reported that nano-formulations prepared from *L. inermis* extracts exhibit enhanced anti-inflammatory efficacy owing to improved bioavailability and controlled release of bioactive compounds.

Molecular docking studies further indicate strong interactions of lawsone and flavonoids with inflammatory signaling proteins, supporting their potential as lead compounds for the development of novel anti-inflammatory agents (Singh et al., 2023).

6.5 Wound Healing Potential

Among the numerous therapeutic properties of *Lawsonia inermis*, wound healing remains one of the most extensively documented traditional applications. Fresh leaf paste has been widely used for centuries to treat cuts, burns, ulcers, boils, eczema, diabetic wounds, cracked heels, and various dermatological disorders. Traditional healers attribute these effects to the cooling, antimicrobial, and anti-inflammatory properties of the plant.

Experimental studies have confirmed that topical application of *L. inermis* extracts significantly accelerates wound contraction, collagen synthesis, fibroblast proliferation, epithelialization, angiogenesis, and extracellular matrix remodeling. The wound-healing activity is largely mediated through antioxidant protection, suppression of microbial colonization, modulation of inflammatory cytokines, and stimulation of growth factors such as vascular endothelial growth factor (VEGF) and transforming growth factor-beta (TGF-β) (Semwal et al., 2014).

Lawsone, flavonoids, and tannins play complementary roles by scavenging reactive oxygen species, preventing lipid peroxidation, enhancing fibroblast migration, and increasing hydroxyproline content, thereby improving collagen maturation and tensile strength of healing tissues. In addition, the broad-spectrum antibacterial and antifungal activities of *L. inermis* reduce the risk of secondary wound infections, facilitating faster tissue regeneration.

Recent pharmaceutical research has incorporated henna extracts into hydrogels, nanofibers, wound dressings, biodegradable films, and polymeric scaffolds, which have demonstrated improved wound healing outcomes in experimental animal models. These innovative formulations indicate promising clinical applications in chronic wounds, burns, diabetic ulcers, and postoperative wound management (Sharma et al., 2022).

6.6 Anticancer Potential

Natural products remain one of the most important sources of anticancer drug discovery. In recent years, *Lawsonia inermis* has attracted considerable scientific interest owing to the cytotoxic and antiproliferative activities exhibited by its bioactive constituents.

Several phytochemicals, including lawsone, flavonoids, xanthones, coumarins, and triterpenoids, have demonstrated selective cytotoxicity against a variety of human cancer cell lines such as breast (MCF-7), cervical (HeLa), liver (HepG2), colon (HT-29), lung (A549), and leukemia cells. These compounds induce apoptosis through mitochondrial dysfunction, activation of caspases, DNA fragmentation, cell cycle arrest, and inhibition of angiogenesis (Semwal et al., 2014).

Mechanistic studies have shown that henna-derived compounds suppress oxidative stress, inhibit NF-κB signaling, regulate mitogen-activated protein kinase (MAPK) pathways, and modulate the expression of apoptosis-related proteins including Bax, Bcl-2, p53, and caspase-3. Such molecular events collectively contribute to reduced tumor cell proliferation and enhanced programmed cell death (Sharma et al., 2022).

Recent computational investigations using molecular docking and network pharmacology have identified several *L. inermis* phytochemicals as potential inhibitors of cancer-associated molecular targets. Green-synthesized metallic nanoparticles prepared using henna extracts have also demonstrated enhanced anticancer efficacy due to improved cellular uptake and targeted cytotoxicity.

Although the available in vitro and preclinical evidence is encouraging, well-designed animal studies and randomized clinical trials are still required to establish the safety, efficacy, and therapeutic potential of *L. inermis* as an anticancer agent.

6.7 Antidiabetic Activity

Diabetes mellitus is one of the fastest-growing metabolic disorders worldwide, characterized by persistent hyperglycemia resulting from impaired insulin secretion, insulin resistance, or both. Traditional medicinal systems have long recommended *Lawsonia inermis* for managing diabetes and its associated complications.

Experimental studies have demonstrated significant hypoglycemic activity of leaf extracts in streptozotocin- and alloxan-induced diabetic animal models. Treatment with ethanolic and aqueous extracts resulted in reductions in fasting blood glucose, glycated hemoglobin (HbA1c), serum cholesterol, triglycerides, and low-density lipoprotein (LDL) levels while improving insulin sensitivity and hepatic glycogen content (Sharma et al., 2022).

The antidiabetic effects are attributed to multiple mechanisms, including:

a) Enhancement of pancreatic β-cell function.
b) Increased insulin secretion and peripheral glucose utilization.
c) Inhibition of α-amylase and α-glucosidase enzymes.
d) Reduction of oxidative stress in pancreatic tissues.
e) Improvement of glucose transporter (GLUT4) expression.
f) Modulation of inflammatory cytokines associated with insulin resistance.

Polyphenols, flavonoids, tannins, and lawsone collectively contribute to glycemic regulation by protecting pancreatic β-cells against oxidative damage and improving carbohydrate metabolism. However, the uploaded historical literature reported no significant hypoglycemic activity for one crude whole-plant extract under specific experimental conditions, highlighting the influence of extraction methods, plant parts, and experimental protocols on pharmacological outcomes.

Future clinical investigations are needed to standardize dosage, evaluate long-term safety, and establish evidence-based therapeutic recommendations.

6.8 Hepatoprotective and Nephroprotective Effects

The liver and kidneys are highly susceptible to oxidative stress induced by toxins, drugs, heavy metals, and metabolic disorders. Increasing experimental evidence suggests that *Lawsonia inermis* possesses significant hepatoprotective and nephroprotective activities owing to its rich antioxidant phytochemical composition.

Animal studies have demonstrated that administration of *L. inermis* extracts protects hepatic tissues against chemically induced liver injury caused by carbon tetrachloride, paracetamol, and other hepatotoxic agents. These protective effects are associated with reductions in serum alanine aminotransferase (ALT), aspartate aminotransferase (AST), alkaline phosphatase (ALP), bilirubin, and lipid peroxidation, accompanied by restoration of normal hepatic architecture (Semwal et al., 2014).

Similarly, nephroprotective investigations have shown that henna extracts attenuate renal injury by decreasing serum creatinine, blood urea nitrogen (BUN), and oxidative stress markers while improving renal antioxidant enzyme activities. Histopathological studies have demonstrated reduced tubular necrosis, inflammatory infiltration, and glomerular damage in experimental animal models.

The protective mechanisms include:

a) Scavenging of reactive oxygen species.
b) Enhancement of endogenous antioxidant defense systems (SOD, CAT, GPx).
c) Suppression of inflammatory cytokines.
d) Inhibition of lipid peroxidation.
e) Stabilization of cellular membranes.
f) Prevention of apoptosis in hepatic and renal tissues.

Recent metabolomic and molecular studies further suggest that phenolic compounds and flavonoids from *L. inermis* regulate multiple signaling pathways involved in oxidative stress, inflammation, fibrosis, and programmed cell death, thereby providing comprehensive organ protection (Singh et al., 2023).

Despite promising experimental evidence, large-scale clinical trials remain limited. Future translational research should focus on standardized herbal formulations, pharmacokinetics, long-term safety evaluation, and clinical efficacy before routine therapeutic use can be recommended.

6.9 Cosmetic and Industrial Applications

Lawsonia inermis L. is globally recognized as one of the most important natural cosmetic plants. For thousands of years, its leaves have been used as a safe, plant-based dye for decorating the skin, colouring hair, nails, and textiles.

Today, increasing consumer preference for herbal and eco-friendly products has renewed scientific and commercial interest in henna-based cosmetic formulations (Semwal et al., 2014).

The principal colouring agent, lawsone (2-hydroxy-1,4-naphthoquinone), readily binds with keratin proteins present in hair, skin, nails, wool, silk, and leather, producing a stable orange-red to reddish-brown colour. Unlike many synthetic dyes, pure henna is biodegradable, renewable, and generally considered environmentally friendly.

Traditionally, henna paste has been applied during weddings, religious ceremonies, and cultural festivals across South Asia, the Middle East, and North Africa. Besides its decorative role, the cooling, antimicrobial, and anti-inflammatory properties of the leaf paste make it useful in treating cracked heels, burns, minor wounds, fungal infections, dandruff, and scalp disorders. The uploaded literature also documents its traditional use for colouring palms, soles, hair, beard, eyebrows, and nails.

Modern cosmetic industries extensively utilize *L. inermis* in the manufacture of:

a) Herbal hair dyes and conditioners
b) Anti-dandruff shampoos
c) Hair oils and scalp tonics
d) Herbal soaps and face packs
e) Skin creams and lotions
f) Natural tattoo preparations
g) Herbal cosmetics and personal care products

In addition to cosmetic applications, henna has considerable industrial significance. Lawsone serves as a natural textile dye for cotton, silk, wool, and leather industries. Owing to its antimicrobial and antioxidant properties, henna extracts are increasingly incorporated into biodegradable food-packaging films, antimicrobial coatings, wound dressings, cosmetic preservatives, and green nanomaterials. Furthermore, recent studies have demonstrated the successful biosynthesis of silver, gold, zinc oxide, and iron oxide nanoparticles using *L. inermis* extracts, highlighting its emerging applications in nanotechnology and biomedical engineering (Sharma et al., 2022; Singh et al., 2023).

7. Quality Control and Standardization

The therapeutic efficacy of herbal medicines depends largely on the quality, authenticity, purity, and consistency of plant materials. Because *Lawsonia inermis* is widely marketed as powdered leaves and herbal formulations, standardization has become essential to ensure product safety and efficacy.

Classical pharmacognostic investigations established several diagnostic characteristics of henna leaves, including isobilateral leaf anatomy, ranunculaceous-type stomata, mucilage sacs, calcium oxalate crystals, oil globules, and fluorescence characteristics under ultraviolet light. A microscopic method based on epidermal mucilage sacs was also developed for detecting adulteration in commercial henna powders.

Modern quality evaluation involves:

a) Botanical authentication using macroscopic and microscopic characteristics.
b) DNA barcoding for species identification.
c) Physicochemical analysis including moisture content, ash values, extractive values, and foreign matter.
d) Quantification of lawsone using HPLC, HPTLC, LC-MS/MS, and GC-MS.
e) Chromatographic fingerprinting for quality assurance.
f) Determination of total phenolic and flavonoid contents.
g) Heavy metal analysis (lead, cadmium, mercury, arsenic).
h) Microbial contamination testing.
i) Pesticide residue analysis.
j) Detection of synthetic dye adulterants such as para-phenylenediamine (PPD).

International regulatory agencies increasingly recommend Good Agricultural and Collection Practices (GACP), Good Manufacturing Practices (GMP), and standardized phytochemical profiling to ensure batch-to-batch consistency of herbal products. Authentication using metabolomic fingerprinting and chemometric analysis has further improved quality assessment of commercial henna formulations.

8. Toxicity and Safety

Lawsonia inermis has been used safely for centuries in traditional medicine and cosmetic applications. Pure henna leaf powder is generally considered safe when used externally in recommended quantities. However, safety concerns arise from adulterated commercial preparations and inappropriate medicinal use.

The uploaded literature indicates that *L. inermis* exhibited relatively low acute toxicity in experimental animals, with an intraperitoneal LD_{50} greater than 1000 mg/kg in mice. Experimental toxicological investigations also reported a low incidence of allergic dermatitis and occasional pollen hypersensitivity in susceptible individuals.

Despite its favourable safety profile, several adverse effects have been reported:

a) Allergic contact dermatitis
b) Skin irritation and erythema
c) Photosensitivity reactions
d) Rare hypersensitivity responses
e) Respiratory allergy due to pollen exposure

The major toxicological concern is "black henna," which contains the synthetic dye para-phenylenediamine (PPD).

Unlike natural henna, PPD-containing products may cause severe allergic dermatitis, blistering, chemical burns, permanent scarring, and, in rare cases, systemic toxicity. Consequently, regulatory agencies strongly discourage the use of adulterated black henna preparations.

Oral administration of high doses of *L. inermis* extracts has not been adequately evaluated in humans. Therefore, prolonged internal use should only be undertaken under qualified medical supervision. Additional toxicological studies, including chronic toxicity, reproductive toxicity, genotoxicity, pharmacokinetics, and herb-drug interaction studies, remain necessary before widespread therapeutic recommendations can be made.

9. Conservation Status and Sustainable Utilization

Unlike many endangered medicinal plants, *Lawsonia inermis* is extensively cultivated and is currently **not considered globally threatened** according to available international botanical databases (POWO, 2025). Nevertheless, sustainable cultivation practices remain important for maintaining high-quality germplasm and conserving genetic diversity.

Commercial cultivation is concentrated in arid and semi-arid regions of India, particularly Rajasthan, Gujarat, Madhya Pradesh, Haryana, and Uttar Pradesh, where the species contributes significantly to rural livelihoods and herbal industries. Increasing global demand for natural dyes and herbal cosmetics has stimulated large-scale cultivation, emphasizing the need for sustainable agricultural practices.

Conservation strategies should include:

a) Collection and conservation of elite germplasm.
b) Establishment of seed banks and field gene banks.
c) Promotion of Good Agricultural and Collection Practices (GACP).
d) Organic cultivation to reduce pesticide contamination.
e) Sustainable harvesting without damaging natural populations.

f) Selection of high-lawsone yielding cultivars.
g) Application of tissue culture and micropropagation for rapid multiplication.
h) Conservation of traditional ethnobotanical knowledge associated with henna cultivation and utilization.

Climate change, prolonged droughts, land-use changes, and indiscriminate harvesting of wild populations in certain regions may influence genetic diversity and phytochemical composition. Therefore, integrating conservation biology with modern breeding programmes will be essential for ensuring sustainable utilization of *L. inermis*.

10. Future Research Perspectives

Although considerable progress has been achieved in understanding the medicinal potential of *Lawsonia inermis*, several important research gaps remain.

Future investigations should focus on:

a) Isolation and structural characterization of novel bioactive metabolites.
b) Multi-omics approaches including genomics, transcriptomics, proteomics, and metabolomics.
c) Elucidation of molecular mechanisms underlying pharmacological activities.
d) Clinical trials evaluating efficacy against dermatological disorders, diabetic wounds, inflammatory diseases, and microbial infections.
e) Pharmacokinetic and bioavailability studies of lawsone and related compounds.
f) Development of standardized herbal formulations and dosage guidelines.
g) Exploration of synergistic interactions between phytochemicals.
h) Nano-formulations for targeted drug delivery.
i) Green synthesis of multifunctional nanoparticles for biomedical applications.
j) Development of authenticated quality control markers using metabolomics.
k) Investigation of antiviral efficacy against emerging viral pathogens.
l) Studies on herb-drug interactions and long-term safety.
m) Breeding programmes for high-yielding, disease-resistant cultivars rich in lawsone.
n) Sustainable cultivation and climate-resilient production systems.

Integrating traditional knowledge with modern pharmaceutical sciences, biotechnology, computational biology, and artificial intelligence-based drug discovery may facilitate the development of novel therapeutic agents derived from *L. inermis*.

11. CONCLUSION

Lawsonia inermis L. is a versatile medicinal and cosmetic plant that has served human civilization for several millennia. Traditionally recognized for its natural dyeing properties, the species has emerged as an important source of biologically active phytochemicals with diverse pharmacological applications. The presence of lawsone, flavonoids, phenolic acids, coumarins, xanthones, triterpenoids, tannins, and other secondary metabolites underlies its antioxidant, antimicrobial, antifungal, antiviral, anti-inflammatory, wound-healing, hepatoprotective, nephroprotective, antidiabetic, and anticancer activities.

Traditional medicinal knowledge has been increasingly validated through modern phytochemical, pharmacological, molecular, and nanotechnological investigations. Advances in chromatographic fingerprinting, metabolomics, molecular docking, and green nanotechnology have expanded the therapeutic and industrial applications of *L. inermis*, particularly in herbal medicine, cosmetics, food preservation, and biomedical sciences. Nevertheless, challenges related to standardization, quality control, clinical validation, safety assessment, and regulatory acceptance continue to limit its wider pharmaceutical utilization.

Future multidisciplinary research integrating ethnobotany, phytochemistry, molecular pharmacology, biotechnology, and clinical medicine is essential to fully exploit the therapeutic potential of *L. inermis*. Well-designed clinical trials, standardized herbal formulations, advanced quality assurance protocols, and sustainable cultivation strategies will facilitate its transition from traditional medicine to evidence-based phytopharmaceutical development. Given its long history of safe traditional use and expanding scientific evidence, *Lawsonia inermis* represents a valuable natural resource with significant potential for the discovery of novel therapeutic agents and environmentally sustainable cosmetic and industrial products.

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