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A deep dive into the phytochemical composition of *Murraya koenigii* (curry leaf): Active compounds and their therapeutic implications

Murraya koenigii (köri yaprağı) fitokimyasal bileşimi üzerine derinlemesine bir inceleme: Aktif bileşenler ve terapötik etkileri

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ABSTRACT

Murraya koenigii, commonly known as curry leaf, is native to South Asia and is renowned for its flavor and fragrance in a variety of dishes. Herbal medicines have been used for centuries to treat various illnesses due to their affordability and minimal side effects. In traditional ayurvedic medicine, curry leaf plays a major role. This small deciduous shrub has all the makings of a future industrial product, including nutritional and therapeutic qualities. Research indicates that *Murraya koenigii* has antibacterial, antifungal, and antiprotozoal activities, particularly in its leaves, stems, bark, and oil. The plant's essential oil and extracts have antifungal and antibacterial potentials. Curry leaf may exhibit anticancer effects, potentially attributed to their potent antioxidant properties that help reduce oxidative stress, a known factor in cancer progression. The plant has the potential to be nutritious since it contains fatty acids, minerals, vitamins, carbohydrates and proteins. The whole plant is utilised for its stomachic and tonic qualities. The current study aims to evaluate the global categorisation, origin, morphological characteristics, and traditional uses of curry leaf.

Keywords: *Murraya koenigii*, curry leaf, phytochemical composition, bioactive compounds, antioxidant properties, leaves, extracts, phytoconstituents, therapeutic applications

ÖZET

Yaygın şekilde "köri yaprağı" olarak bilinen *Murraya koenigii*, Güney Asya'ya özgü olup, çeşitli yemeklerdeki lezzeti ve kokusuyla ünlüdür. Bitkisel ilaçlar, uygun maliyetleri ve minimal yan etkilerinden ötürü yüzyıllardır çeşitli hastalıkların tedavisinde kullanılmaktadırlar. Geleneksel ayurveda tıbbında köri yaprağı önemli bir rol oynar. Bu küçük yaprak döken çalı, besleyici ve tedavi edici nitelikler de dahil olmak üzere, geleceğin endüstriyel ürününün tüm özelliklerine sahiptir. Araştırmalar, *Murraya koenigii*'nin özellikle yapraklarında, gövdelerinde, kabuğunda ve yağında antibakteriyel, antifungal ve antiprotozoal aktivitelere sahip olduğunu göstermektedir. Bitkinin uçucu yağı ve ekstreleri, antifungal ve antibakteriyel potansiyellere sahiptir. Köri yaprağı, kanser progresyonunda bilinen bir faktör olan oksidatif stresi azaltmaya yardımcı, güçlü antioksidan özelliklerine potansiyel olarak atfedilen antikanser etkileri sergileyebilir. Bitki, yağ asitleri, mineraller, vitaminler, karbonhidratlar ve proteinler içerdiğinden besleyici olma potansiyeline sahiptir. Bitkinin tamamı stomaşik ve tonik özellikleri için kullanılır. Mevcut çalışmanın amacı köri yaprağının küresel kategorizasyonunu, kökenini, morfolojik özelliklerini ve geleneksel kullanımını değerlendirmektir.

Anahtar kelimeler: *Murraya koenigii*, köri yaprağı, fitokimyasal bileşim, biyoaktif bileşenler, antioksidan özellikler, yapraklar, ekstreler, bitkisel bileşenler, terapötik uygulamalar

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Introduction

The plant curry leaf (*Murraya koenigii*) is a member of the Rutaceae family, which consists of 150 genera and 1,600 species. It is found to be native to South Asia particularly India, Sri Lanka and Bangladesh (Bhusal & Thakur, 2021). The use of *Murraya koenigii* has been documented since the 1st and 4th centuries AD. Tamil and Kannada literature describes *Murraya koenigii* as Kari used as a flavoring agent (Jain et al., 2017). It is considered as one of the essential or fundamental ingredients in South Asian cuisine for its fragrance and aroma (Ghimire & Magar, 2018).

Murraya koenigii (curry leaf) is a common spice and condiment widely used in tropical nations, valued for its ability to retain flavor and other characteristic properties even after drying. The principal components responsible for its distinctive flavor and aroma include pinene, sabinene, caryophyllene, cardinol, and cardinene (Visakh et al., 2023). In addition to its culinary applications, the plant has been traditionally used for its tonic and stomachic properties. It is known to contain a diverse range of bioactive phytochemicals, including lutein, β-carotene, phenolics, essential oils, minerals, proteins, and terpenoids, which contribute to its medicinal and nutritional significance (Datta et al., 2023).

The use of herbal medications for the treatment of a wide range of disorders is advocated due to their cost-effectiveness, efficacy, and limited adverse effects. This section outlines the various applications and benefits of curry leaf. These curry leaf plays a significant role in Indian curries due to their distinctive aroma (Figure 1). It can be used medicinally to cure diabetes, prevent cancer, and treat cardiovascular illnesses (Syaifurrisal et al., 2024). The plant leaves are rich in antioxidants, including lutein, β-carotene, and tocopherol. These compounds exhibit antioxidative and anti-lipid peroxidative properties, protecting the leaves from oxidative damage.

The therapeutic potential of *Murraya koenigii* can be attributed to its rich phytochemical composition, including alkaloids, flavonoids, phenolic compounds, terpenoids, and essential oils. These compounds used a wide spectrum of biological activities such as antioxidant, antimicrobial, anti-inflammatory, antidiabetic, hepatoprotective, and anticancer properties. The plant's unique chemical profile makes it a promising candidate for the development of novel therapeutic agents.

Despite the increasing interest in its medicinal applications, a comprehensive understanding of *Murraya koenigii*'s phytochemical composition and its therapeutic implications remains underexplored. This review aims to delve deeper into the active compounds present in *Murraya koenigii* and elucidate their roles in various biological mechanisms. By synthesizing the latest findings, this study seeks to highlight the plant's potential as a natural source for drug development and to bridge existing gaps in the literature.

The exploration of *Murraya koenigii*'s phytochemistry and pharmacology not only emphasizes its traditional medicinal value but also underscores its potential for addressing contemporary health challenges. This review provides a consolidated perspective for researchers and practitioners, offering insights into the therapeutic applications of curry leaves and paving the way for future studies in phytopharmacology.

Figure 1. Morphology of *Murraya koenigii* leaf

Taxonomic status:

Kingdom:	Plantae
Subkingdom:	Tracheobionta
Superdivision:	Spermatophyta
Division:	Magnoliophyta
Class:	Magnoliopsida
Subclass:	Rosidae
Order:	Sapindales
Family:	Rutaceae
Genus:	Murraya J. Koenig ex L.
Species:	*Murraya koenigii* (L.) Spreng.

Murraya koenigii is a small, deciduous, aromatic shrub that reaches a height of approximately 6–9 meters and is cultivated at elevations of 1500 meters above sea level. The main stem is dark green to brown colored bark with several dots on it that can be flaked off lengthways to expose the white wood beneath (Sarswat & Yaday, 2023).

The leaves are bipinnately compound, measuring 15–30 cm in length and consisting of 11–25 leathery, glandular leaflets. The flavour of the leaves is slightly fragrant, somewhat acidic, and bitter (Ajay et al., 2011). The inflorescence consists of 60–90 bisexual, funnel-shaped flowers, which emit a fragrant scent, are stalked, complete, and have a diameter of 1.12 cm when fully open. It has 4-5 sepals and 10 straight stamens (Sharma et al., 2024).

The fruiting period begins in mid-July and concludes at the end of August, while the blooming phase starts in mid-April and continues through mid-May. The crop is self-pollinating (3. 2 3, n.d.). Each berry is black in colour and with a glossy surface, measures 1.4 to 1.6 cm in length and 1 to 1.2 cm in diameter, and contains 0.76% of volatile oil that is yellow. The fruits are found in compact clusters, with three to eighty fruits per cluster (Goyal et al., 2020). Suckers are produced by the woody, widely distributed roots.

Propagation methods and chromosomal characteristics

Although seeds are commonly used for propagation, alternative methods such as air layering and root suckers have also been explored. Providing partial shade during germination has been found to enhance seedling establishment. The curry leaf plant has a chromosomal number of 18, confirming its diploid nature (Goel et al., 2020).

Extraction of bioactive compounds

Three bioactive carbazole alkaloids mahanine, mahanimbine, and marrayanol have been successfully extracted from fresh curry leaves using acetone, highlighting their potential pharmacological significance (Dwivedi et al., 2024).

This review is crucial to provide a comprehensive understanding of *Murraya koenigii* (curry leaf), focusing on its phytochemical composition and the active compounds responsible for its therapeutic effects. Despite the growing interest in its medicinal applications, a comprehensive understanding of *Murraya koenigii*'s phytochemical composition and its therapeutic implications remain underexplored. By examining the specific compounds found in *M. koenigii*, such as alkaloids, flavonoids, and terpenoids, this study aims to bridge the gap between traditional knowledge and modern pharmacological evidence. A deeper exploration of these compounds will help clarify their role in treating various health conditions and promote the safe, standardized use of this plant in clinical practice.

1. Application of plant

Murraya koenigii (curry leaf) is widely recognized for its culinary, medicinal, and therapeutic applications. Traditionally, it has been an essential ingredient in South Asian cuisine due to its distinctive aroma and flavor, often used in curries to enhance taste, stimulate appetite, and promote digestion (Balakrishnan et al., 2020). Beyond its culinary uses, the plant holds significant medicinal value, having been used in home remedies for centuries.

The leaves possess wound-healing properties and are locally applied to treat external injuries, burns, and venomous bites. In traditional medicine, they are also used for managing rheumatism. When baked or crisped, curry leaves have been reported to help prevent vomiting (Malode et al., 2021). Additionally, grinding the leaves into a fine powder and mixing them with buttermilk is a well-known remedy for stomach discomfort and acts as a natural laxative when consumed on an empty stomach (Figure 2).

Curry leaf juice, when combined with lime and sugar, serves as a treatment for morning sickness, while the consumption of root juice is believed to relieve renal pain. The stem is traditionally used as a natural teeth-cleansing agent, contributing to gum strength (Chauhan et al., 2017). Furthermore, the plant exhibits anti-astringency properties, and its juice has been used in the treatment of kidney pain (Raghavan, 1957).

Nutritionally, curry leaves are beneficial in addressing calcium and vitamin deficiencies, as well as anemia. The plant has also demonstrated antitumor, hypoglycemic, and anti-hypercholesterolemic properties. Additionally, it has been reported to exhibit anti-inflammatory, antipruritic, and antipyretic effects, making it useful for reducing body temperature (Choo et al., 2020).

In Ayurveda, curry leaves are traditionally used to manage hysteria, rheumatism, hepatitis, cough, and hypertension. A well-known Ayurvedic preparation involves cooking curry leaves with coconut oil until a residue forms, which is then used as a hair tonic to maintain natural hair color and stimulate hair growth (Kundu et al., 2020).

The diverse medicinal and therapeutic applications of *Murraya koenigii* highlight its importance in traditional and modern healthcare practices, warranting further scientific exploration for its pharmacological potential.

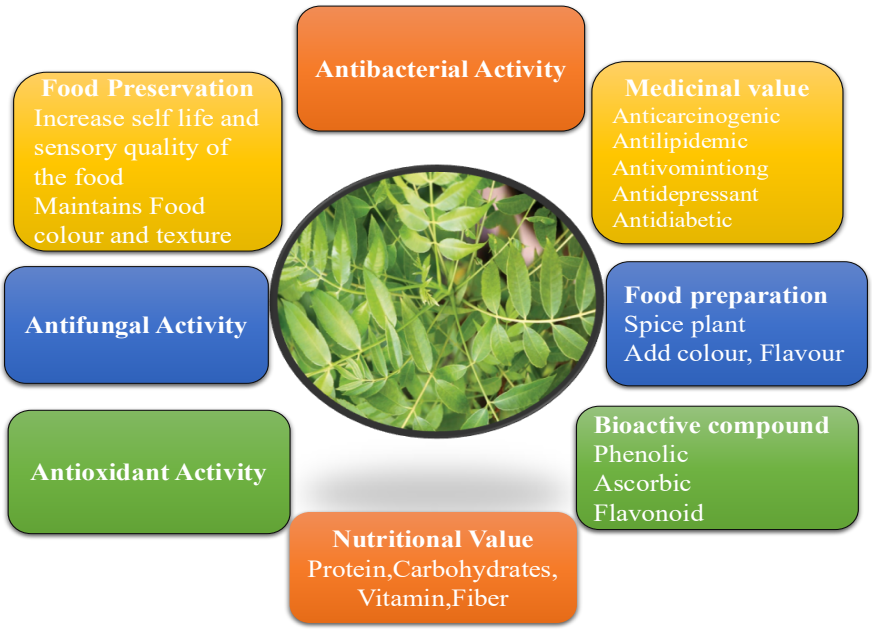


Figure 2. Demonstrating the diverse applications of *Murraya koenigii* (curry leaf)

2. Medicinal uses of *Murraya koenigii*

The plant contains a variety of essential oils, including α-pinene (39.93%), sabinene (13.3%), and trans caryophyllene (9.02%), and has been shown to have antibacterial properties against *Proteus vulgaris*, *Bacillus subtilis*, and *Corynebacterium pyogenes* (Gahtori et al., 2022).

The carbazole alkaloids are found in leaves, fruits, roots and bark of the plant having antidiabetic, anticancer, antibacterial and anti-oxidant properties. The n-hexane seeds extract produces three bioactive carbazole alkaloids namely kurryam (I), koenimbine (II) and koenine (III) and it has been shown that compounds I and II suppress the pooling of rats' enter caused by PGE2 and the diarrhoea caused by castor oil (Vidhya et al., 2020).

Three bioactive carbazole alkaloids mahanine, mahanimbine, and marrayanol have been extracted from fresh leaves using acetone. These compounds exhibit significant antibacterial activity as well as inhibitory effects on topoisomerase I and II (Verma et al., 2022).

Additionally, administration of mahanimbine has been demonstrated to result in a reduction in blood sugar levels in Swiss mice. Extracts of curry leaf have also been shown to reduce the number of cancer cells in mice (Bhandari 2022).

The aqueous extracts of the curry plant have been demonstrated to accelerate the healing of wounds. Alcoholic extracts, specifically the ethanol:water (1:1, v/v) extract of *Murraya koenigii* stem bark, along with the crude root extract of the plant, have been shown to exhibit significant anti-inflammatory properties. Aqueous extracts include tannins and carbazole alkaloids that have hepatoprotective effect. The extract of *Murraya koenigii* alcohol:water (1:1) has been shown to have the best free radical scavenging activities and antioxidant properties (Ghasemzadeh et al., 2014).

2.1. Anti-diabetic property of *Murraya koenigii*

In an animal model, the efficacy of curry leaf in regulating blood sugar levels was investigated. "A noticeable decrease in blood sugar levels was observed". The leaf extract has been reported to lower blood sugar levels (Saini & Reddy, 2015).

This function may be comparable to insulin's effect, which decreases blood sugar levels by either raising the synthesis of insulin by the pancreas or increasing the absorption of glucose by cells due to certain enzymes. This suggests that curry leaf might play a role in managing diabetes.

Evidence-based molecular mechanism

Murraya koenigii exhibits a diverse range of biological activities through its influence on various molecular mechanisms, making it a valuable plant in therapeutic research. The antioxidant activity of *Murraya koenigii* is one of its most notable properties, primarily attributed to its rich content of phenolics and flavonoids, which enhance endogenous antioxidant enzymes like superoxide dismutase (SOD), catalase, and glutathione peroxidase,

thereby mitigating oxidative stress and preventing cellular damage. Additionally, its anti-inflammatory effects are mediated by compounds like mahanimbine, which suppress pro-inflammatory cytokines such as TNF-α and IL-6 through the inhibition of NF-κB signaling (Dwivedi et al., 2024).

The plant also demonstrates significant anticancer activity, with alkaloids such as girinimbine inducing apoptosis in cancer cells via mitochondrial pathways and modulating PI3K/AKT/mTOR signaling to inhibit tumor progression. Furthermore, *Murraya koenigii* exerts neuroprotective effects by reducing oxidative stress in neuronal cells and enhancing acetylcholinesterase activity, offering potential benefits for neurodegenerative conditions like Alzheimer's disease.

Its antimicrobial properties are attributed to its essential oils, which disrupt microbial cell membranes, providing broad-spectrum activity against bacteria and fungi. Moreover, the plant's cardioprotective and hepatoprotective effects are evidenced by its ability to improve lipid profiles, reduce cholesterol, and enhance liver regeneration by counteracting lipid peroxidation. These multifaceted mechanisms highlight *Murraya koenigii* as a promising natural resource for addressing a wide range of metabolic, inflammatory, and oxidative disorders (Mandal et al., 2010).

Regulation of glucose homeostasis

The bioactive alkaloid mahanimbine enhances insulin secretion from pancreatic β-cells, improving glucose uptake in peripheral tissues. Extracts of *Murraya koenigii* modulate key enzymes involved in carbohydrate metabolism, such as α-amylase and α-glucosidase, thereby reducing postprandial hyperglycemia.

Activation of insulin signaling pathways

The plant's polyphenols and flavonoids stimulate PI3K/AKT signaling, which enhances glucose transporter (GLUT4) translocation to the cell membrane, facilitating glucose uptake in muscle and adipose tissues. Downregulation of GSK-3β (Glycogen Synthase Kinase-3β) prevents excessive glycogen breakdown, promoting glucose storage in the liver.

Reduction of oxidative stress and inflammation

Phenolics and flavonoids enhance endogenous antioxidant enzymes, such as superoxide dismutase (SOD), catalase, and glutathione peroxidase, which reduce oxidative damage to pancreatic β-cells. Mahanimbine and girinimbine inhibit the NF-κB pathway, leading to decreased levels of pro-inflammatory cytokines (TNF-α, IL-6), which play a role in insulin resistance (Sachan et al., 2024).

Pancreatic β-cell protection and regeneration

Studies suggest that curry leaf extracts promote β-cell regeneration by reducing lipotoxicity and preventing apoptosis via mitochondrial-dependent pathways. Inhibition of caspase-3 activity reduces β-cell death, thereby preserving insulin secretion capacity.

Lipid metabolism and insulin sensitivity

Curry leaf alkaloids improve lipid profiles by reducing LDL cholesterol and triglycerides while increasing HDL cholesterol, which is crucial for managing insulin resistance in type 2 diabetes. Inhibition of lipid peroxidation in the liver and pancreas further supports metabolic homeostasis.

2.2. Antihyperlipidemic property of *Murraya koenigii*

In animal studies curry leaf significantly reduced the levels of total cholesterol and triglycerides (fat). It has been reported that curry leaf may have a hypolipidemic (lipid-lowering) effect, resulting in a slower breakdown of fat and cholesterol (Dwivedi et al., 2024).

The reduction of cholesterol and low-density lipids (also known as "bad cholesterol") may be facilitated by curry leaf. However, these studies are insufficient to assess the effects of curry leaf on human health. Further study is required to determine the benefit of curry leaf in regulating cholesterol levels in the human body. Consequently, it is advisable to consult a physician before using curry leaf for cholesterol management (Debosree et al., 2012).

Evidence-based molecular mechanism

The antihyperlipidemic property of *Murraya koenigii* is well-documented, with evidence highlighting its ability to regulate lipid metabolism and improve lipid profiles. Key bioactive compounds such as mahanimbine, carbazole alkaloids, and flavonoids contribute to its lipid-lowering effects by modulating molecular pathways. One primary mechanism involves the inhibition of 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase, a rate-limiting enzyme in cholesterol biosynthesis, which reduces plasma cholesterol levels. Additionally, *Murraya koenigii* enhances the activity of lipoprotein lipase, facilitating the hydrolysis of triglycerides into free fatty acids for energy utilization, thereby lowering triglyceride levels.

Studies have shown that *Murraya koenigii* improves the high-density lipoprotein (HDL) to low-density lipoprotein (LDL) ratio by increasing HDL levels while reducing LDL and very-low-density lipoprotein (VLDL) concentrations. Its antioxidant properties also play a critical role in mitigating lipid peroxidation, preventing oxidative damage to lipids, and reducing atherogenic risk. Animal models fed with a

high-fat diet supplemented with *Murraya koenigii* extract demonstrated significant reductions in total cholesterol, triglycerides, and LDL cholesterol, along with improved liver function and reduced lipid accumulation in hepatic tissues.

These findings suggest that *Murraya koenigii* exerts its antihyperlipidemic effects through a combination of enzymatic regulation, antioxidant activity, and advanced lipid transport, making it a promising natural remedy for managing hyperlipidemia and associated cardiovascular risks (Debosree et al., 2012).

2.3. Potential uses of *Murraya koenigii* for skin

One potential benefit of curry leaf and its essential oils is that they may have anti-inflammatory properties. When applied to external, superficial wounds including skin eruptions, burns, and bruises, they have been shown to promote wound healing (Darvekar et al., 2011).

Formulations and lotions containing the essential oils of the leaves may be used for skin whitening, brightening, and moisturizing dry or rough skin. Curry leaf oil may also be helpful in treating skin issues including ringworm, athlete's foot, boils, acne, and pimples (Ningappa et al., 2008).

To find out how curry leaf can help maintain skin health, further study is needed. Thus, people who experience dermatological issues should consult a doctor before using any herbal medications made from curry leave.

Evidence-based molecular mechanism

Murraya koenigii holds significant potential in skincare due to its rich phytochemical composition and diverse therapeutic properties. The plant's leaves are a source of bioactive compounds such as alkaloids, flavonoids, phenolics, and essential oils, which contribute to its antioxidant, anti-inflammatory, antimicrobial, and wound-healing activities. These properties make *Murraya koenigii* an excellent candidate for addressing various skin conditions and promoting overall skin health.

The antioxidant properties of *Murraya koenigii* protect the skin from oxidative stress caused by environmental factors such as UV radiation and pollution, reducing premature aging, hyperpigmentation, and wrinkle formation. Its anti-inflammatory effects, mediated by bioactive compounds like mahanimbine, help alleviate skin inflammation and irritation, making it useful for conditions like eczema, psoriasis, and acne. Furthermore, the antimicrobial activity of *Murraya koenigii*'s essential oils inhibits the growth of bacteria and fungi, effectively preventing and treating skin infections, including acne caused by *Propionibacterium acnes*.

Studies have also highlighted the plant's wound-healing properties, where its flavonoids and alkaloids promote collagen synthesis, enhance fibroblast proliferation, and accelerate tissue regeneration. Topical formulations containing *Murraya koenigii* extracts have shown promising results in improving skin hydration, elasticity, and overall appearance. Additionally, the plant's ability to reduce melanin production offers potential applications in skin-whitening and anti-pigmentation treatments (Darvekar et al., 2011).

2.4. Anti-cancer property of *Murraya koenigii*

Girinimbine, a carbazole alkaloid derived from the roots of *Murraya koenigii*, has been observed to stimulate dose-dependent apoptosis in A549 cells, leading to cell death. Moreover, the author speculates that the conventional mitochondrial pathway, which involves the release of cytochrome C and caspase-dependent apoptosis, may be responsible for the girinimbine-induced cell death (Gahlawat et al., 2014).

Furthermore, it was shown that the carbazole alkaloid in the stem has an effect on the growth of the HL-6024 human leukemia cell line and that the koenoline in the root bark exhibits anticancer activities against KB cell culture (Manandhar, 2021).

Hepatoprotective potential of Murraya koenigii

Curry leaf extract was observed to significantly increase the activity of the liver enzyme that plays a role in the oxidation of lipids in the liver. The study also showed that the extract exhibited hepatoprotective properties, which reduced liver damage (Iyer & Devi, 2008).

Evidence-based molecular mechanism

Murraya koenigii exhibits significant anti-cancer potential, attributed to its diverse bioactive compounds, including carbazole alkaloids (e.g., mahanimbine, girinimbine), flavonoids, phenolics, and essential oils. These compounds exert their effects through multiple molecular mechanisms, making the plant a promising candidate for cancer prevention and therapy.

One of the key anti-cancer mechanisms of *Murraya koenigii* is the induction of apoptosis in cancer cells via mitochondrial pathways. Carbazole alkaloids like girinimbine promote the release of cytochrome c from mitochondria, activating caspase cascades that lead to programmed cell death. Additionally, the plant modulates cell proliferation by inhibiting the PI3K/AKT/mTOR signaling pathway, which plays a crucial role in tumor growth and survival (Sachan et al., 2025).

The anti-inflammatory properties of *Murraya koenigii* further enhance its anti-cancer efficacy. By suppressing the nuclear factor kappa B (NF-κB) signaling pathway and reducing the expression of pro-inflammatory cytokines, it helps mitigate chronic inflammation a major contributor to cancer progression. Its antioxidant activity also plays a vital role in neutralizing reactive oxygen species (ROS), which are implicated in DNA damage and carcinogenesis.

Studies on various cancer cell lines, including breast, colon, liver, and lung cancers, have demonstrated the cytotoxic effects of *Murraya koenigii* extracts. These studies highlight its ability to inhibit cell migration, reduce angiogenesis, and suppress metastasis. Furthermore, the plant has shown synergy with conventional chemotherapy agents, enhancing their efficacy while reducing side effects (Gahlawat et al., 2014).

2.5. Industrial uses of *Murraya koenigii*

Essential oils derived from plants can be added to erythema and sun protection lotions. Several industrial products of the curry leaf plant are made with a volatile oil, crystalline glycoside, and murragin derived from the blossoms (Pharmacognosy of Ayurvedic Drugs, 1957). It may also be utilised for aromatherapy in the soap and cosmetic business (Xie et al., 2006).

Curry leaf include beta carotene, folic acid, riboflavin, calcium, and zinc, these compounds are beneficial to dental health and can be used to make mouthwashes. Curry leaf oil, which is translucent, clear, and yellow, is commonly exported from India. The extract derived from the seeds of the plant can be utilized in the preparation of in skin lightening and rough skin improving creams. *Murraya koenigii* (curry leaf) is increasingly utilized in skin-lightening formulations due to its rich content of flavonoids, phenolics, and vitamin C, which help reduce hyperpigmentation and promote an even skin tone. Its antioxidant properties protect against oxidative stress, while bioactive alkaloids like mahanimbine aid in regulating melanin synthesis. Extracts from the leaves are incorporated into face creams, serums, and herbal masks to brighten the skin naturally. Additionally, curry leaf essential oil is blended with other botanicals for enhanced skin-rejuvenating effects, making it a valuable ingredient in the cosmetic industry. Petroleum ether and acetone extracts from the leaves can be used to prepare larvicide against (Handral et al., 2012).

Food industry

1. Flavoring agent: The leaves are widely used in the food industry as a natural flavor enhancer in spice blends, ready-to-eat meals, and processed foods.

2. Essential oil extraction: Curry leaf essential oil, rich in bioactive compounds such as α-pinene, β-pinene, and caryophyllene, is used for food preservation and flavoring.

3. Nutraceuticals: Extracts from the leaves and seeds are incorporated into functional foods and dietary supplements due to their antioxidant and anti-diabetic properties.

Pharmaceutical industry

1. Drug development: Bioactive alkaloids like mahanimbine and girinimbine present in *Murraya koenigii* exhibit anti-inflammatory, anti-diabetic, and anti-cancer properties, making them valuable for pharmaceutical formulations.

2. Ayurvedic and herbal medicines: The plant is a key ingredient in herbal formulations for treating digestive disorders, diabetes, and neurological conditions.

3. Antimicrobial agents: Extracts are used in developing antimicrobial coatings and natural preservatives in pharmaceutical products.

Cosmetic and personal care industry

1. Hair care products: Due to its rich antioxidant and antimicrobial properties, curry leaf extracts are incorporated into shampoos, hair oils, and hair growth serums.

2. Skincare: The antibacterial and anti-aging properties of curry leaf extracts make them useful in face creams, anti-acne treatments, and natural skin toners.

3. Aromatherapy: Curry leaf essential oil is used in aromatherapy products due to its calming and stress-relieving effects.

Agriculture and pesticide industry

1. Biopesticides: The plant contains natural insecticidal compounds that can be used to develop eco-friendly pesticides.

2. Animal feed supplement: The high protein and mineral content in dried curry leaves make them a potential ingredient in animal feed to enhance nutrition.

3. Soil enhancer: Decomposed curry leaves enrich the soil with organic matter, improving soil fertility.

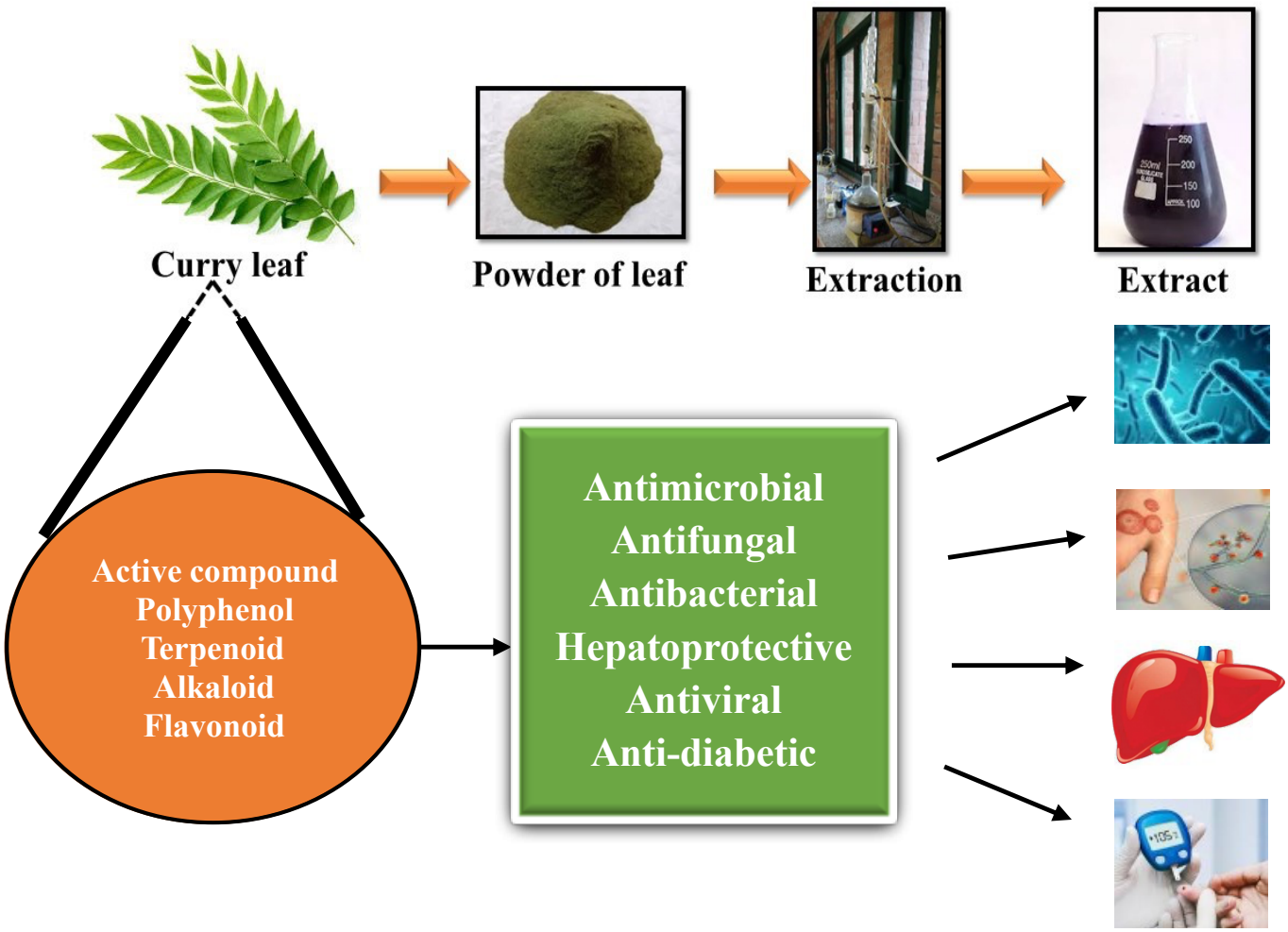


Figure 3. Extraction workflow of *Murraya koenigii* (curry leaf)

Perfumery and fragrance industry

Essential oils: Curry leaf essential oil is used in the production of perfumes, deodorants, and incense sticks due to its unique aroma.

Textile and dye industry

Natural dye source: Extracts from the leaves and bark contain tannins and flavonoids, which can be used for natural fabric dyeing.

Biotechnology and research applications

1. Nanotechnology: Curry leaf extract has been explored for green synthesis of nanoparticles, particularly silver and gold nanoparticles, used in medicine and material sciences.

2. Bioactive compound isolation: The plant serves as a rich source of alkaloids, flavonoids, and phenolics for biochemical research and drug discovery (Dwivedi et al., 2025).

3. Extraction techniques and phytochemical characterization of *Murraya koenigii*

In India and other tropical nations, *Murraya koenigii* (Rutaceae), also known as “curry leaf” in Hindi, is a commonly used as condiment and spice. Extraction of phytochemicals from the plant has yielded a variety of compounds, including acridine alkaloid, bioactive coumarins, and carbazole alkaloid, which are particularly abundant in the leaves. Additionally, phytochemicals such as koenimbin, iso-mahanimbin, and girinimbine have been identified (Chowdhury et al., 2008) (Figure 3).

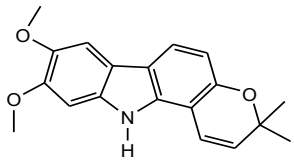
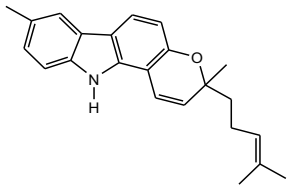
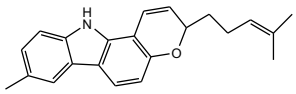
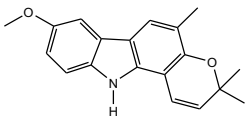
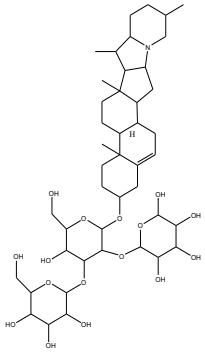
Besides, cyclomahanimbin, tetrahydromahanmbine, murrayastine, and murrayalin have reportedly been found in the leaves. Numerous phytochemicals in *M. koenigii* (curry leaf) are associated with a range of beneficial properties, including anti-diabetic, stimulant, anti-dysentery (Yankuzo et al., 2011), antioxidant, lipid-lowering (Manna et al., 2008), anti-nociceptive, anti-aging, anti-cancer, hepatoprotective, antifungal, and antibacterial activities (Jachak et al., 2024).

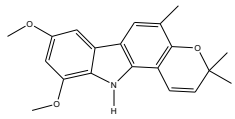
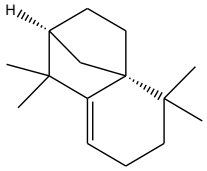
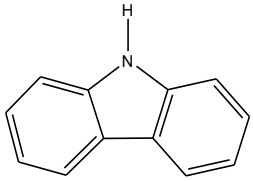
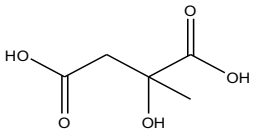
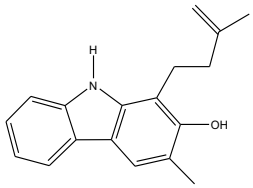
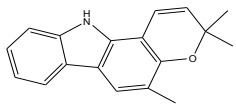
4. Chemical constituents of curry leaf

4.1. Alkaloids

Alkaloids are organic compounds that include one or more nitrogen atoms in a heterocyclic ring. Defining them is challenging because, from a chemical, biochemical, or physiological perspectives, they do not consist of a consistent arrangement of substances (Table 1). There may not be a single, universal definition for alkaloids, despite the fact that they are all nitrogen-containing substances (Singh et al., 2023).

Table 1. Structural representation of alkaloid phytoconstituents in *Murraya koenigii*

Chemical constituents	Plant parts	Pharmacological activities	Mechanisms	Structures	References
Koenigicine	Leaves	Neuroprotective	Decreasing glycemic level		(El-Shiekh et al., 2024)
Mahanimbicine	Leaves	Antiamnesic	Protect against the neurodegenerative diseases		(Guo et al., 2022)
Isomahanimbine	Leaves and roots	Anti-analgesic	Anti-nociceptive effects		(Zou et al., 2023)
Koenimbine	Leaves and roots	Antidiabetic, antiamnesic	Decreases oxidative stress by acting on paraoxonase 1 activity or protect against the neurodegenerative diseases		(Kureel et al., 2017)
Solanine	Leaves, seeds, and fruits	Cytotoxicity, effect on dental caries antioxidant, antimicrobial, antidiabetic, and hyperlipidemic	Inhibition of cavity formation or oxidative stress inducer		(Lawal et al., 2008)

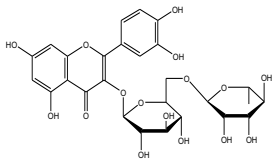
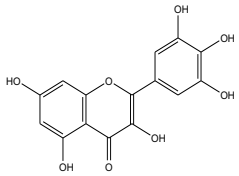
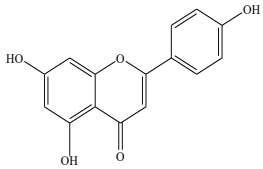
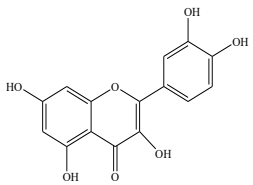
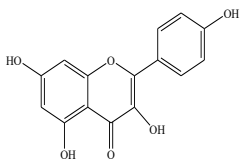
Mukonicine	Leaves	Antioxidant	Increases the GSH Content in the liver and reduction in hepatic malondialdehyde in kidney		(Samanta et al., 2018)
Isolongifolene	Leaves	Antioxidant, neuroprotective	Increases the GSH content in the liver and reduction in hepatic malondialdehyde in kidney or decreasing glycemic levels		(Singh et al., 2014)
Carbazole	Stems		Liver and reduction in hepatic malondialdehyde in kidney		(Rao et al., 2011)
Malic Acid	Stem bark	Antioxidant	Increases the GSH content in the liver and reduction in hepatic malondialdehyde in kidney		(Nigam, 2023)
Mukoenine A	Roots and stem bark	Antidiarrheal	Prostaglandin E2-induced enter pooling and reduction in gastrointestinal motility		(Das et al., 2023)
Girinimbine	Roots, stem bark, and seed	Anti-tumour, antitrichomonal	Act against *Trichomonas gallinae*		(Al Harbi et al., 2016)

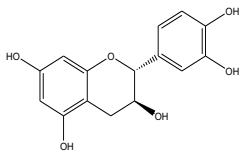
4.2. Flavonoids

Flavonoids are are secondary metabolites that are phenolic and are produced by plants as a defensive mechanism. They are responsible for the production of aromatic compounds and the pigmentation of fruits and plants.

Flavonoids are well recognized for having anti-inflammatory, anti-cancer, and antioxidant properties (Table 2). There are several types of flavonoids, including anthocyanins, flavones, flavanols, and flavanones. In colored rice varieties, anthocyanins are the main flavonoid (Mitra et al., 2012).

Table 2. Comprehensive structural representation and characterization of flavonoids present in *Murraya koenigii*

Chemical constituents	Plant parts	Pharmacological activities	Mechanisms	Structures	References
Rutin	Leaves	Antibacterial, anti-inflammatory	Suppressed activity of proinflammatory cytokines by diminishing TNF-α and IL-1β production in microglia		(Uraku et al., 2015)
Myricetin	Leaves	Anti-cancer, antidiabetic	Reduced production of inflammatory cytokines		(Uraku et al., 2015)
Apigenin	Leaves	Anti-cancer, antioxidant, and anti-inflammatory	Induce muscle relaxation and sedation		(Ningappa et al., 2008).
Quercetin	Leaves	Antibacterial	Promote cell apoptosis		(Ningappa et al., 2008).
Kaempferol	Leaves	Antioxidant, anti-inflammatory	Inhibit signalling pathway		(Ningappa et al., 2008).

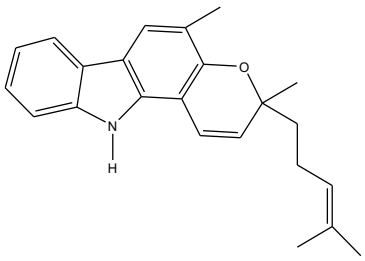
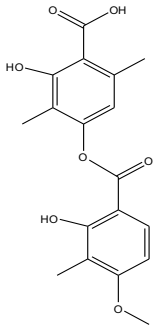
Catechin	Leaves	Vasodilating activity	Inhibit A549 cell by regulating cell cycle arrest		(Uraku et al., 2015)

4.3. Phenolic compounds

Polyphenols consist of phenolic acids, flavonoids, tannins, lignans, and coumarins. Phenols are plant-based antioxidants and the organization of phytochemicals most abundant in entire grains. They exist in various forms, including insoluble, soluble, conjugated, and esterified forms (Sasidharan & Menon, 2011).

The main phenolic acids present in rice are those found in whole grains, namely protocatechuic acid, *p*-coumaric acid, ferulic acid, sinapic acid, and vanillin (Table 3).

Table 3. Structural representation of phenolic compounds in *Murraya koenigii*

Chemical constituents	Plant parts	Pharmacological activities	Structures	References
Mahanimbine	Leaves and bark	Antibacterial, anticancer, apoptotic and anti-invasive potential		(Elumalai et al., 2015)
2-hydroxy-4-methoxy-3,6-dimethylbenzoic acid (Benzoic acid)	Bark			(Joseph & Peter, 1985)

4.4. Terpene compounds

Terpene compounds exist in a wide range of forms and varieties. Their applications are growing in scope as industrial processes continue to progress (Ningappa et al., 2010).

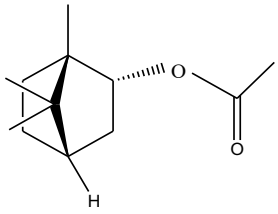
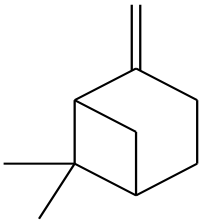
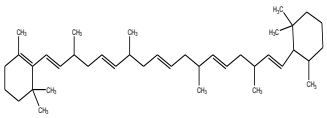
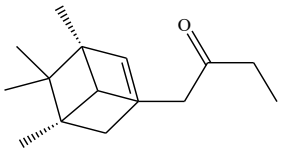
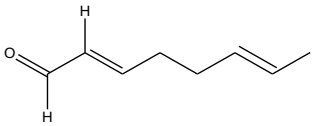
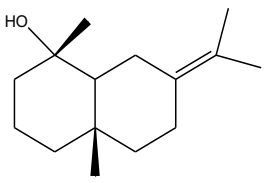
Chinese baijiu is a fermented food and one of the world's six primary distilled liquors. There are several different flavour varieties, the most common of which are twelve (Rastogi et al., 1990).

However, strong flavour varieties, such as those found in Wuliangye and Luzhou Laojiao (sometimes referred to as "Luzhou-flavor liquor") and Maotai and Langjiu (often referred to as "Maotai liquor"), currently dominate the market (Table 4 and Table 5).

Terpenes are primarily used in the pharmaceutical sector as novel anti-cancer medications (Prajapati et al., 2003).

For instance, element, a naturally occurring anti-cancer substance with somewhat harmful side effects, suppresses brain tumours, liver cancer, lung cancer, and nasopharyngeal carcinoma (Rao et al., 2007).

Table 4. Structural representation of terpene phytoconstituents in *Murraya koenigii*

Chemical constituents	Plant parts	Pharmacological activities	Mechanisms	Structures	References
Bornyl Acetate	Leaves, Stems, Roots	Analgesic effect	Inhibits the NF-κB signal pathway		(Khurana et al., 2019)
β-Pinene	Leaves	Antibacterial, antidepressant, cytotoxic, and antimicrobial			(Viswanathan et al., 2020)
Carotene	Leaves	Cancer treatment	Inhibits UV-B carcinogenesis		(Beenakumari et al., 2011)
Chrysanthenyl Acetate	Leaves, Stem	Analgesic effect	Inhibits prostaglandin synthetase		(Khan et al., 1996)
Citral	Leaves, Stems	Antifungal, antibacterial	Inhibited LPS-induced nitric oxide (NO) production		(Igara et al., 2016)
Juniper Camphor	Leaves	Antidiarrheal, anti-inflammatory			(Dasgupta et al., 2003)

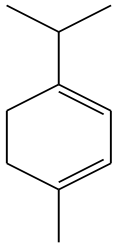
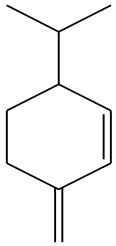
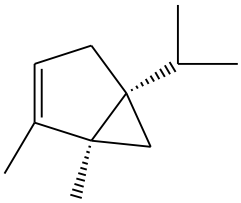
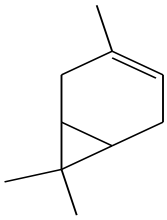
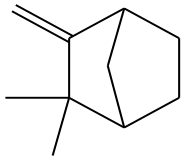
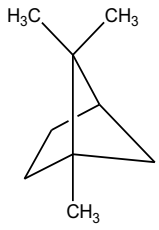
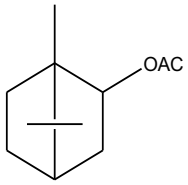
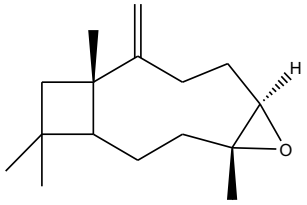
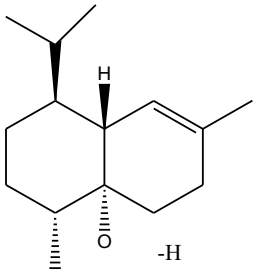
α-Terpinene	Leaves	Antioxidant			(Chelliah et al., 2016)
β-Phellandrene	Leaves	Anti-inflammatory			(Kushwaha et al., 2024)

Table 5. Structural representation of essential oil phytoconstituents in *Murraya koenigii*

Chemical constituents	Plant parts	Pharmacological activities	Structures	References
α-Thujene	Leaves	Anti-ageing		(Rajendran et al., 2014)
3-Carene	Leaves	Antioxidant, antimicrobial		(Raina et al., 2002)
Camphene	Leaves	Anti-cancer		(Rana et al., 2004)

Eucalyptol	Leaves	Anti-cancer		(Wee et al., 2024)
Isobornyl acetate	Leaves	Antimicrobial		(Tripathi et al., 2024)
Beta-caryophyllene oxide	Leaves	Antimicrobial, anti-carcinogenic		(Iqbal et al., 2017)
Cubenol	Leaves	Antioxidant, antimicrobial		(Verma et al., 2023; Chellappandian et al., 2024)

5. Molecular mechanisms and bioactivities of *Murraya koenigii* in therapeutic applications

5.1. Antioxidant

Singlet oxygen (O_2), hydrogen peroxide (H_2O_2), the superoxide anion (O_2•−), and the hydroxyl radical (•OH) are examples of reactive oxygen species (ROS) that are commonly produced as consequences of external stimulation and cellular metabolic activities.

These ROS cause homeostatic abnormalities, which in turn cause oxidative stress, which in turn causes tissue damage and cell death (Nagappan et al., 2011). Biomolecules including lipids, proteins, and nucleic acids can be damaged by ROS at high concentrations (Sharma & Kumar, 2019). Age-related diseases illnesses such as cancer, atherosclerosis, arthritis, and so forth are promoted by unchecked ROS accumulation to grow by unchecked ROS buildup throughout life, even in the presence of antioxidant defense mechanisms such as enzymatic and non-enzymatic antioxidants.

Natural antioxidants derived from plants have been seen as a potentially effective treatment for the avoidance and management of several illnesses, including neurodegenerative (Soundappan et al., 2018).

5.2. Oxidative stress

Free radicals are chemical entities that have one or more unpaired electrons. Reactive oxygen species (ROS) are referred to as "free radicals" in biological systems.

O_2, H_2O_2, and •OH are important ROS (Ramnath er al., 2023). Reactive nitrogen species (RNS), such as peroxynitrite (NO_3^-), NO, and S-nitroso thiols, are known to cause oxidative stress in addition to ROS.

Both ROS and RNS are particularly produced as a component of the cellular defense against invading infections and emerge as intermediates in several metabolic pathways. Additionally, free radicals control a wide range of functions, including as proliferation, glucose metabolism, and cellular growth (El-Shiekh et al., 2024).

5.3. Mitochondrial dysfunction

The main source of high-energy metabolism in cells is the mitochondria, referred to as the powerhouse of the living cell.

Additionally, mitochondria regulate programmed cell death and/or the apoptosis-signaling pathway, scavenge free radicals, and maintain calcium homeostasis (You et al., 2015).

Reduced adenosine triphosphate (ATP) synthesis, elevated reactive oxygen species (ROS) production, compromised calcium buffering, damage to mitochondrial DNA (mtDNA), modified mitochondrial shape, and changes in mitochondrial fission and fusion the consequences of mitochondrial damage include. The ultimate consequence of these processes is cell death.

Presently, the bulk of reactive oxygen species (ROS) are thought to be produced by mitochondrial complexes I and III. This is probably because NADH and dihydroflavine-adenine dinucleotide (FADH2) release electrons into the electron transport chain (ETC) (Hema et al., 2013).

Conclusions

Murraya koenigii (curry leaf) is a valuable plant with diverse bioactive compounds, including alkaloids, flavonoids, phenolics, terpenes, and essential oils. These contribute to its antioxidant, antimicrobial, anti-inflammatory, and antidiabetic properties. Beyond medicinal uses, the plant is applied in culinary, cosmetic, and environmental fields.

Given its value as a natural remedy, curry leaf should be prioritized in the development of new medications. These active compounds have demonstrated potential effects in a variety of health issues, including antioxidant, anti-inflammatory, antibacterial, anti-diabetic, and hepatoprotective properties, making curry leaf a useful plant in both traditional and modern medicine. Its capacity to combat oxidative stress, decrease inflammation, promote metabolic health, and fight infections makes it an important element in natural health formulations.

As research into the particular processes underlying these advantages continues, *Murraya koenigii* may play an even more important role in preventive healthcare and integrative medicine, providing a natural alternative to many synthetic medicines. Further research is anticipated to advance our understanding of its entire therapeutic potential, paving the path for further novel uses in wellness and healthcare. *Murraya koenigii* should be taken into consideration for various clinical and non-clinical research projects in order to thoroughly investigate its pharmacotherapeutics, toxicity, correct standardisation, and clinical trials, all while exploring its many uses.

Because of the potential health benefits of *Murraya koenigii*, future research should also look into its safety to avoid any harmful effects. Understanding its safety, proper use, and how to apply it in treatment is important to make sure it's both effective and safe.

Author contributions

Study conception and design: P.S., A.K., L.K., K.J. Data collection: P.S. and K.J. Analysis and interpretation of results: P.S. and P.S. Drafting of the manuscript: P.S. and P.S. All authors have reviewed the results and approved the final version of the manuscript.

Declaration of interests

The authors declare that there is no conflict of interest.

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