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Fennel (*Foeniculum vulgare* Mill.) in modern phytopharmacology: Bioactive compounds, molecular mechanisms and clinical perspectives

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Abstract

Foeniculum vulgare Mill., commonly known as fennel, is a widely recognized medicinal and aromatic plant with significant phytopharmacological importance. This review comprehensively explores the phytochemical composition, pharmacological activities, molecular mechanisms, clinical relevance and emerging applications of fennel in modern healthcare. Fennel is rich in bioactive compounds, including phenylpropanoids such as trans-anethole, flavonoids, phenolic acids, coumarins and essential oils, which collectively contribute to its diverse therapeutic properties. Extensive pharmacological studies have demonstrated that fennel exhibits a broad spectrum of biological activities, including antioxidant, anti-inflammatory, antimicrobial, anticancer, antidiabetic, neuroprotective, cardioprotective and hepatoprotective effects. These activities are mediated through multiple molecular mechanisms, such as inhibition of inflammatory signaling pathways (*e.g.*, NF-κB), activation of antioxidant defense systems (*e.g.*, Nrf2/ARE pathway), regulation of apoptosis and cell proliferation (PI3K/Akt and MAPK pathways), enzyme inhibition and modulation of gene expression.

Despite its promising pharmacological profile, the clinical application of fennel is limited by challenges related to bioavailability, rapid metabolism and variability in phytochemical composition. Recent advancements in drug delivery systems, including nanoformulations and encapsulation techniques, have shown potential in enhancing the stability, bioavailability and therapeutic efficacy of fennel-derived compounds. Clinical studies have provided evidence supporting its effectiveness in managing digestive disorders, dysmenorrhea and infant colic; however, large-scale, well-designed clinical trials are still required for broader validation. Furthermore, fennel has gained attention in the development of nutraceuticals, functional foods and phytopharmaceutical products, highlighting its role in preventive healthcare. Emerging approaches such as phytonanotechnology, metabolomics and green nanoparticle synthesis are expanding its applications and improving its therapeutic potential. *F. vulgare* represents a promising natural resource with multifaceted pharmacological activities and significant potential for integration into modern medicine. Future research should focus on standardization, molecular validation and clinical translation to fully harness its therapeutic and industrial applications.

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