REVIEW ARTICLE

Fenugreek (*Trigonella foenum-graceum L.*): A Comprehensive Review of Phylogenetic Diversity, Metabolomic Profiles, and Pharmacological Applications

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Abstract

One of the classical components of traditional medicine and cuisine, fenugreek (*Trigonella foenum-graecum*) has recently received more attention due to its seeds and leaves, which are highly valued due to their high nutritional value, strong pharmacological ability, and the possibility of reliable substitution into modern applications. The brief cultivation cycle, rising global demand, robust yields, and low production costs have elevated fenugreek's status beyond seed-focused farming, spotlighting its leaves and whole-plant utility. Phylogenetic explorations via molecular markers like random amplified polymorphic DNA, amplified fragment length polymorphism, inter-simple sequence repeat, and simple sequence repeats illuminate its evolutionary heritage, genetic variability, and breeding prospects within the Fabaceae family. Enhanced molecular breeding takes advantage of these findings and produces superior varieties with superior phytochemical composition and agronomical character. As a powerhouse of antioxidants, steroidal saponins, flavonoids, and alkaloids, fenugreek rivals synthetic alternatives in nutraceuticals, offering antidiabetic, anti-inflammatory, and cardio-protective benefits. This review underscores its phylogenetic, nutritional, metabolomic, and pharmacological merits, advocating for variant selection to boost conservation, food security, and sustainable practices, while unlocking potentials in phytoremediation, functional foods, and novel therapeutics.

Key words: Antioxidant, genetic diversity, pharmacology, phylogenomics, secondary metabolites

INTRODUCTION

Fenugreek belongs to the Fabaceae family (*Trigonella foenum-graecum*). The Latin name *Trigonella*, which means little triangle, was given due to its triangular-shaped yellowish-white flowers.[1] It is one of the oldest known medicinal plants, and it was grown in Central Asia since around 4000 BCE.[2] Modern studies regularly use molecular markers to query genetic diversity in the large number of plant and microbial communities.[3] These markers are used in identifying variation within the sequence of the nucleic acids, and hence, they guide breeding strategies of crop improvement and control of inbreeding depression. Similar research on fenugreek has been restricted, but previous research used inter-simple sequence repeat (ISSR), random amplified polymorphic DNA (RAPD), and amplified fragment length polymorphism (AFLP), to demonstrate genetic variation among populations.[4]

Phylogenomics covers a wide range of studies at the interface of evolutionary and molecular biology, where paradigms include not only to understand phylogenetic connections among taxa but also to discover the molecular processes that drive evolution; and also to use interspecies phylogenetic comparisons to infer possible functions of DNA or protein

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sequences.[5] Phylogenomic studies enable us to better understand the genetic diversity and character associations of fenugreek, which are essential for crop development and breeding programs. The medicinal property of fenugreek has been explored in numerous diseases and conditions due to its pharmacological effects, including hypoglycemic, antihyperlipidemic, antihypertensive, antioxidant, anti-inflammatory, immunomodulatory, anticarcinogenic, antipyretic, antiviral, and galactogenic function.[6] Recent experimental research has shown antidiabetic properties of aqueous extract of fenugreek seeds, as well as their galactomannan-rich subfraction, to cause significant amelioration of pancreatic and hepatic damage, and also to reduce the development of diabetic nephropathy in rodents.[7] Recent research also indicates possible functions in appetite control and the regulation of lipid and glucose levels, along with protective benefits for the cardiovascular, gastrointestinal, hepatic, endocrine, and neurocognitive systems. Fenugreek contains various phytochemical compounds such as alkaloids, phenols, saponins and fatty acids. This review emphasizes the genetic diversity and metabolic profile of fenugreek, and it also includes pharmaceutical and nutritional aspects of fenugreek.

BOTANICAL DESCRIPTION AND TAXONOMY

- Kingdom: Plantae
- Division: Magnoliophyta
- Class: Magnoliopsida
- Order: Fabales
- Family: Fabaceae
- Genus: *Trigonella*
- Species: *T. foenum-graecum*.[8]

The plant grows 120–130 cm tall, with erect or prostrate growth and green stems that may turn pinkish due to anthocyanin accumulation. It has trifoliate, oval leaves with smooth margins and flowers that change from yellow in early stages to white at maturity. The pods are brownish with pointed tips, containing rectangular to oval seeds that range from pale brown to golden yellow.[9]

Fenugreek (*T. foenum-graecum*) thrives naturally in uncultivated areas, arid grasslands, and hilly areas that feature undulations in ecological zones of the semi-high rise and highlands. Plant parts and its traditional uses are presented in Table 1. The species is used in the Indian subcontinent as an iconic cool-season crop, and is both irrigated and rainfed farmed. It has been empirically shown that the plant is highly adaptive over a range of soil types, where it grows best with a pH between 5.3 and 8.2. Hot, dry weather conditions are mandatory during the seed maturity and the following harvesting to give the greatest possible yield and also higher quality products.[10,11]

PHYLOGENOMICS OF FENUGREEK

The ten-sectional species of *Trigonella* genus were studied. Seven species of the subgenus Falcatuae were differentiated, and *Cylindrical* and *Foenum-graecum* were used from three species each. The rest of the seven divisions, which included Callicerates, Capitatae, Ellipticae, Erosae, Pectinatae, Samaroideae, and Uncinatae, were only examined using one species. To explore genetic variation within the *Trigonella* genus, 20 species were analyzed using genome size estimation, flow cytometry, and Start Codon Targeted-polymerase chain reaction (PCR) markers. These methods provided a clearer picture of their evolutionary and taxonomic relationships. The study identified three main clusters, with *Thymbra spicata* and *Trigonella corniculata* showing the highest genetic distance and forming separate groups. Overall, the findings confirm that combining molecular markers with genome analysis is a reliable approach for understanding diversity in fenugreek species.[16]

GENETIC DIVERSITY

The genus *Trigonella* is one of the major tribes of the genus Trifoliatae, of the family Fabaceae, or the sub-family Papilionaceae.[17] One of the species of this genus, called fenugreek, is a flowering plant that grows in the form of an annual and has white blooms (autogamous) and is hardly ever visited by insects. Native to eastern Mediterranean ecologies, this plant is planted all over India, Egypt, Ethiopia, Morocco and occasionally in England.[18] It is widely grown in the tropical and subtropical areas in India.[19] One of the relatively rare species of the same family is called blue fenugreek, although it is known as *Trigonella caerulea*.[20] The development of the breeding programs of fenugreek depends on the strong knowledge of the genetic diversity. Scientists use morphological, molecular and biochemical markers of identification. Morphological and biochemical characteristics are prone to environmental and ontogenic effects; however, molecular markers are much less sensitive to these effects, hence a dependable approach to measure genetic diversity.[21] Molecular markers have therefore been able to attain prominence as invaluable resources in the study of populations.[22] The RAPD is another widely used PCR-based markers which is used to determine genetic diversity, phylogenetic relationship, gene tagging and mapping, as well as the identification of hybridization events.[23-25] However, research has been quite limited on populations of fenugreek by the application of ISSR, RAPD and AFLP techniques.[4,26]

A study conducted using 61 Fenugreek accessions utilizing RAPD markers. DNA from young leaves extracted and used 18 random primers for amplification. Polymorphism varied from 33.33% to 100%, with an average of 52.85% for each primer. The genetic similarity among accessions varied from 0.66 to 0.90, indicating moderate to high variability; thus, RAPD markers were effective for assessing genetic diversity

Table 1: Plant parts and its traditional uses

Plant part	Traditional uses	References
Seeds	Used as antidiabetic agent, lactation promoter, treatment of weakness and edema in legs and remedy for burns.	[12]
Leaves	Reduction of menstrual pain and stomach problems; anti-inflammatory paste for eczema and rash treatment.	[12]
Roots	Used as tonic and has antioxidant effects.	[12]
Stem	General medicinal and nutritional support; fodder for livestock; used in various compound formulations in traditional medicine systems.	[13,14]
Sprouts (germinated seeds)	Improved antioxidant and antidiabetic profiles); food use as fresh vegetable; modern functional food application.	[15]

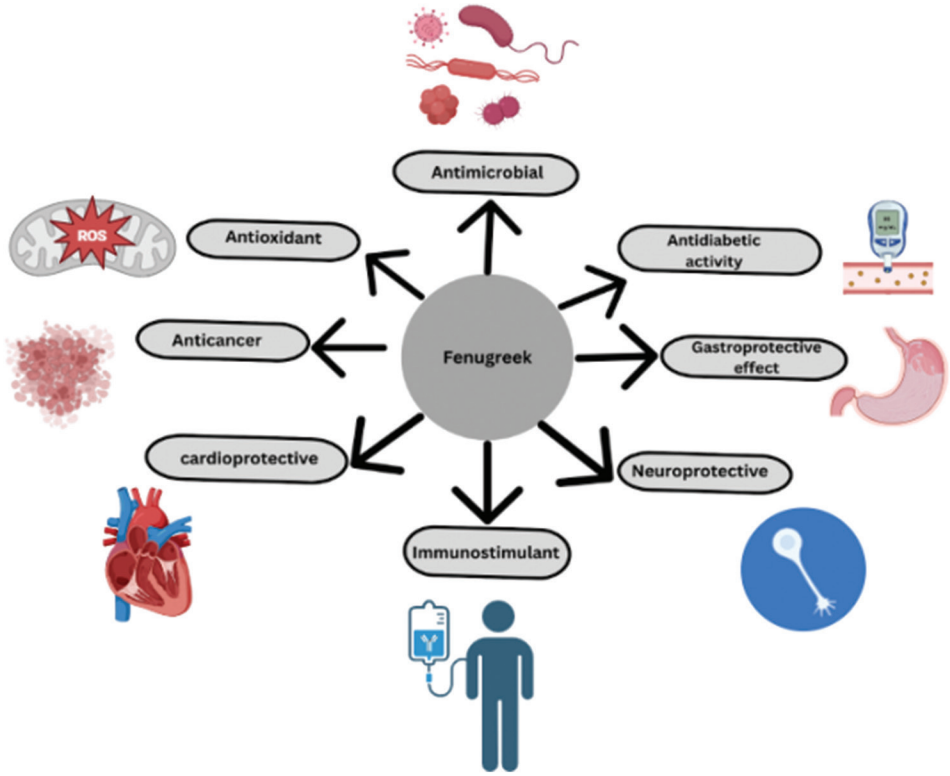


Figure 1: Pharmacological activity of fenugreek

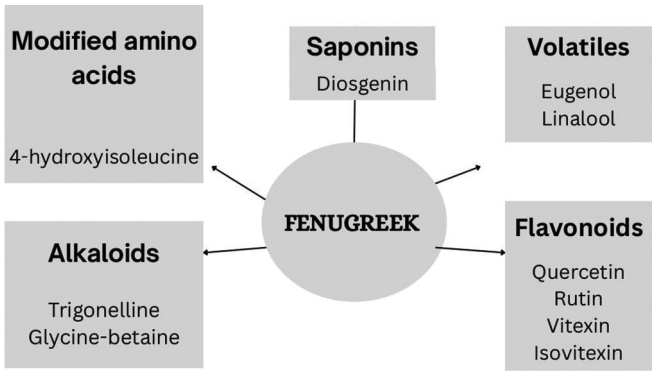
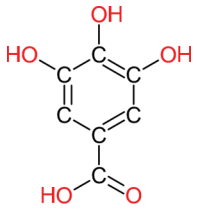
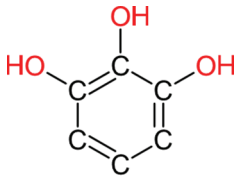
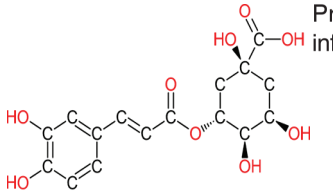
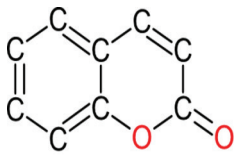
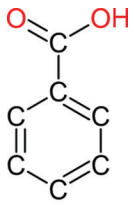


Figure 2: Secondary metabolites in fenugreek

and facilitating fenugreek breeding.[24] Another research on five fenugreek varieties using RAPD and AFLP markers and concluded that both are valuable for genetic diversity, and concluded that AFLP is more reliable for genetic fingerprinting. In addition, AFLP marker technique is used to determine genetic variation, as well as to design variety markers in plants. This technique is reliable when combined with a separation system that is able to resolve DNA fragments size of 50–550 base pairs at single-base-pair resolution.[27]

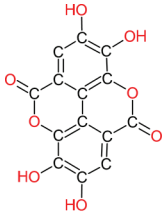
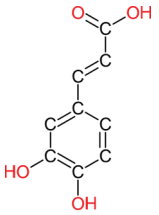
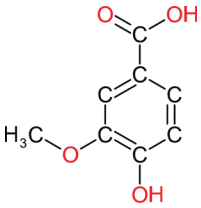
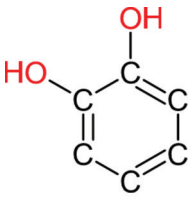
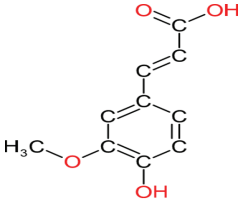
Simple sequence repeats (SSRs) are effective PCR-based markers for detecting high genetic variability. A study at Jawaharlal Nehru Krishi Vishwa Vidyalaya analyzed 27 fenugreek genotypes and grouped them into eight clusters, confirming SSRs as valuable tools for genetic diversity assessment and breeding programs.[21] Metabolomics linked fenugreek biomarkers and its pharmacological benefits are shown in Table 5.

Table 2: Phytochemical constituents of fenugreek

Phytochemical group	Bioactive compounds	Molecular composition	Molecular mass	Chemical structure	Bioactive properties	References
Phenolic acids	Gallic acid	$C_7H_6O_5$	170.12 g/mol	 164.072	It has high antioxidant activity that protects cells against oxidative stresses and helps to prevent and treat oxidative stress related diseases such as cancer, diabetes mellitus and heart diseases	[12]
	Pyrogallol	$C_6H_6O_3$	126.11g/mol	 120.063	Possess antioxidant and anti-inflammatory activity	[28]
	Chlorogenic acid	$C_{16}H_{18}O_9$	354.31g/mol	 336.167	Promotes regulation of glucose metabolism and reducing inflammation, and protects against chronic diseases	[29]
	Coumarin	$C_9H_6O_2$	146.14g/mol	 140.097	Their bioactivity range is wide, including antioxidant, anti-inflammatory, antimicrobial, Neuroprotective, and antidiabetic effects making them valuable in combating oxidative stress and chronic diseases	[12]
	Benzoic acid	$C_7H_6O_2$	122.12 g/mol	 116.075	It has antioxidant and antimicrobial properties, and protects against several diseases	[28]

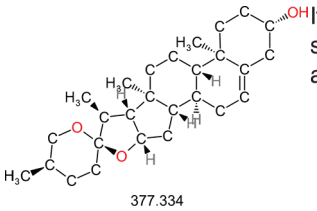
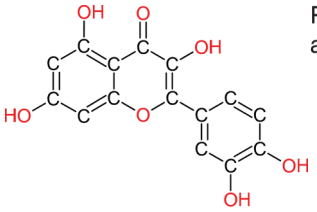
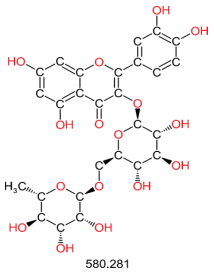
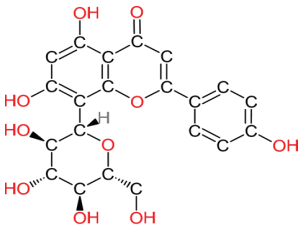
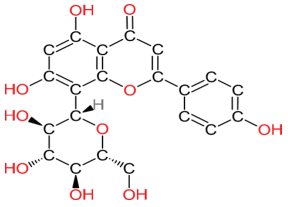
(contd...)

Table 2: *(Continued)*

Phytochemical group	Bioactive compounds	Molecular composition	Molecular mass	Chemical structure	Bioactive properties	References
	Ellagic acid	$C_{14}H_6O_8$	302.19 g/mol	 296.146	Possess nephroprotective effects, and it reduces tissue injury	[30]
	Trans-Caffeic acid	$C_9H_8O_4$	180.6 g/mol	 172.095	Plays a role in acetyl cholinesterase inhibitory activity, which helps in Alzheimer's disease control	[31]
	Vanillic acid	$C_8H_8O_4$	168.15 g/mol	 160.084	Has antioxidant activity and helps to mitigate oxidative stress-related damage	[32]
	Catechol	$C_6H_6O_2$	110.11 g/mol	 104.064	Possess antibacterial and antioxidant compound, prevents microbial diseases	[33]
	Ferulic acid	$C_{10}H_{10}O_4$	194.18 g/mol	 184.106	It has anti-inflammatory, antidiabetic and neuroprotective, cardio protective activities, helps in controlling metabolic diseases	[34]

(contd...)

Table 2: *(Continued)*

Phytochemical group	Bioactive compounds	Molecular composition	Molecular mass	Chemical structure	Bioactive properties	References
Saponins	Diosgenin	$C_{27}H_{42}O_3$	414.6 g/mol	 377.334	It helps in diabetes management by enhancing insulin secretion, promoting β-cell regeneration, and has anticancer property	[35,36]
Flavonoids	Quercetin	$C_{15}H_{10}O_7$	302.23 g/mol	 292.158	Regulates blood glucose level, and to lower cholesterol, and inhibits cancer cell migration and apoptosis	[37,38]
	Rutin	$C_{27}H_{30}O_{16}$	610.5 g/mol	 580.281	It has antioxidant, anti-inflammatory, and vasoprotective activity, protects against cardiovascular and metabolic diseases	[39]
	Vitexin	$C_{21}H_{20}O_1$	432.4 g/mol	 413.229	In cosmetics, vitexin has antioxidant effect and reduces inflammation, and prevent wrinkle formation, and it also possesses antidiabetic and anticancer properties	[6,40]
	Isovitexin	$C_{21}H_{20}O_{10}$	432.4 g/mol	 413.229	Isovitexin-rich fenugreek extracts has properties like collagen synthesis, enhances skin hydration, and helps to prevent wrinkle formation in skin	[41,42]

(contd...)

Table 2: *(Continued)*

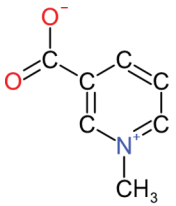
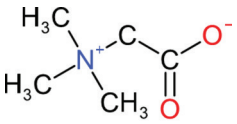
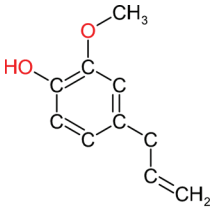
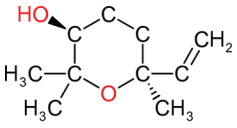
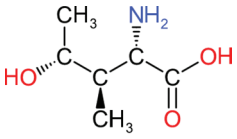
Phytochemical group	Bioactive compounds	Molecular composition	Molecular mass	Chemical structure	Bioactive properties	References
Alkaloids	Trigonelline	$C_7H_7NO_2$	137.14 g/mol	 130.082	It improves glucose and lipid metabolism, and widely used in cosmetic industry and has wide therapeutic potential	[29]
	Glycine-betaine	$C_5H_{11}NO_2$	117.15 g/mol	 106.06	It promotes plant growth, antioxidant activity, and stress tolerance in plants and has anticarcinogen property	[43]
Volatiles	Eugenol	$C_{10}H_{12}O_2$	164.2 g/mol	 152.108	It protects against bacterial and fungal infection and used in skincare and oral care products	[44]
	Linalool	$C_{10}H_{18}O$	154.25 g/mol	 152.108	It is known for its fragrance and used in perfumery industry and also has therapeutic values	[45]
Modified amino acids	4-Hydroxy isoleucine	$C_6H_{13}NO_3$	147.17 g/mol	 134.07	Unique amino acid exhibits antihyperlipidemic and antihyperglycemic effects used in diabetics management.	[46]

Table 3: Chemical characterization of fenugreek essential oils from leaves and fruits across distinct origins

Country	Compound	Content	Plant part used	Detection method	References
India	Cubenol	38.17	Seeds	GC-MS	[47]
	Gamma-non-alactone	3.69			
	Dodecanoic acid	2.4			
	Hexahydrothymol	1.5			
	Ledene oxide	1.05			
	Palmitic acid	0.90			
Bulgaria	Phytol	1.14	Seeds	GC-MS	[47]
	Menthol	0.94			
	Lauric acid	0.97			
	Palmitic acid	2.56			
	γ-n-Amylbutyrolactone	1.78			
	Cuminol	2.66			
	Cubinol	28.8			
	n-Docosane	11			
	Benzoic acid	3.1			
	Palmitic acid	2.75			
Sudan	Oleic acid	9.09	seeds	GC-MS	[48]
	o-Cymol	27.69			
	p-Mentha-1,4-diene	23.92			
	Dioctyl butylphosphonate	8.72			
Saudi Arabia	9Octadecenamide (Z)	17.14			
	Stearic acid	13.51			
	Carvene	36.46			
	Clionasterol	10.95			
Bangladesh	14 compounds identified	Varies	Seeds	GC-MS	[49]
Morocco	Methyl palmitate	Major			[50]

GC-MS: Gas chromatography-mass spectrometry

GENOME-WIDE ASSOCIATION STUDIES

Genome-wide association studies (GWAS) have become a powerful approach for identifying trait-linked loci in fenugreek due to its predominantly self-pollinating nature. In 112 Egyptian genotypes, double digest restriction-site associated DNA sequencing generated 153,881 single nucleotide polymorphisms (SNPs), with significant markers associated with seed length, width, and seed color. RNA-seq–based analyses identified over 3,800 SNPs related to abiotic stress response and diosgenin (DIO) biosynthesis. Recent studies on Indian and North African germplasm are further applying SNP-based GWAS to map loci controlling yield, flowering time, and key biochemical traits.[51-53]

PHYTOCHEMICAL SCREENING OF ESSENTIAL OIL FROM FENUGREEK

Fenugreek dried seeds find extensive use in food and beverage industries as a flavoring additive as well as in both traditional and modern medicine. To reveal the chemical composition, the phytochemical screening of the methanolic extracts of the seeds was conducted by using standard phytochemical detection procedures with the addition of gas chromatography-mass spectrometry (GC-MS) analysis. These researches established the existence of carotenoids, polyphenols, alkaloids, fatty acids, essential oils, proteins with essential amino acids, and significant amounts of iron, ascorbate (vitamin C), and folate. Moreover, GC-MS profiling was effective in determining a wide range of compounds that were in the seed extract.[54] The Phytochemical constituents of fenugreek are presented in Table 2.

Trigonella hamosa (branched fenugreek) was investigated using a hydro-methanolic extract, which underwent detailed phytochemical profiling and multiple *in vitro* bioactivity assays, including antioxidant, antidiabetic, antimicrobial, antiviral, and thrombolytic tests. GC-MS analysis identified 22 bioactive compounds. Subsequent molecular docking studies showed promising binding interactions with the α-amylase enzyme, highlighting its potential for future drug

development.[55] The nutraceutical property of fenugreek are shown in Table 4.

Phytochemical screening of fenugreek gum

Fenugreek gum is a natural polysaccharide containing a broad spectrum of secondary metabolites with methanol and aqueous extracts show the richest qualitative phytochemical profile. Preliminary phytochemical screening to detect major groups of compounds such as steroids, fats and oils, alkaloids, proteins, saponins, tannins, phenolic compounds, flavonoids, and carbohydrates. The Chemical characterization of fenugreek essential oils from leaves and fruits across distinct origins shown in Table 3. The results showed that methanol and aqueous extracts contain rich phytoconstituents, indicating that polar solvents are more efficient for extracting bioactive components from fenugreek gum. High-performance thin-layer chromatography also used to determine retention factor values and peak areas of components in different extracts, confirming that fenugreek gum is chemically diverse and has potential applications in pharmaceuticals, nutrition, and other industries due to the combined presence of nutritionally valuable and pharmacologically active compounds.[56]

Table 4: Nutraceutical property

Component used	Beneficial effects
Seeds	Good for heart[57]
	Reduce the risk of constipation[58]
	Digestive effect[57]
	Immunomodulatory effect[59,60]
	Reduces blood sugar levels[61]
	Anti-inflammatory[62]
	Hepatoprotective [63]
	Anti-obesity[64]
	Wound healing[65]
	Muscle performance enhancement[65]
	For decreasing blood pressure[58]
	Shields cells from oxidation[65]
	Hypocholesterolemic[66]
Seeds and leaves	Helps decrease hypertension[58]
	Shields cells from oxidation[65]
	Anticancer[58,64]
Leaves	Galactagogue[67]

PHARMACOLOGICAL ACTIVITY

Antidiabetic potential

Biochemical profile of fenugreek consists of a number of bioactive compounds that have significant place in the control of metabolism-related disorders. Secondary metabolites in fenugreek are shown in Figure 2. It is also important to note that a water-soluble dietary fiber (SDF) extracted using fenugreek seeds grown in Canada has shown a strong capability of reducing the level of blood glucose. The demonstration of the effect of the galactomannan fraction of fenugreek in inhibiting the intestinal uptake of glucose significantly was demonstrated in controlled *in vitro* studies using lean and obese rodent models, hence substantiating the role of fenugreek in glycemic regulation.[68] The subsequent studies on the antidiabetic effects of SDF extracted using fenugreek clarified that the compound prominently improves the homeostasis of glucose, basically by slowing the processes of carbohydrate digestion and absorption.[69] A 10-day clinical intervention assessed the effects of the fenugreek seed powder supplementation in patients having the Type 1 diabetes diagnosis. Findings revealed that feeding on fenugreek resulted in a significant 54% reduction of 24 h urinary glucose excretion, which was an effective way of regulating hyperglycemia among this group of patients.[70] These observations demonstrate the feasibility of use of fenugreek as supplementary therapeutic agent in the treatment of diabetes. In the framework of the Egyptian traditional medicine, fenugreek is held in high regard due to its strong hypoglycemic effects. A study conducted *in vitro* also revealed that has shown the dose-dependent suppressions of α-amylase activity by fenugreek extract.[71]

Table 5: Metabolomics-linked fenugreek biomarkers and its pharmacological benefits

Metabolite	Linked diseases	Metabolomics approach	Model used for the study	References
Trigonelline	Type 2 diabetes, glucose homeostasis	Targeted LC/UPLC–MS/MS quantification in fenugreek extracts and germinating seeds.	*In vivo* (rats), *in vitro*; quantitative in extracts	[90]
4Hydroxyisoleucine	Insulin secretion, insulin resistance, metabolic syndrome	UPLC–MS/MS targeted metabolite method from fenugreek extract.	*In vivo* (rats), *in vitro*; targeted quantification	[90]
Diosgenin	Dyslipidemia, cancer linked disease	Quantified with UPLC–MS/MS	*In vivo* (animal models), networktype analyses	[91]

LC: Liquid chromatography, UPLC-MS/MS: Ultra-performance liquid chromatography-tandem mass spectrometry

Cardio protective property

Fenugreek contains Coumarin, which helps stop platelets from clumping too much, lowering the chance of blood clots that can trigger irregular heartbeats or strokes. Researchers tested fenugreek in rats with chemically induced heart attack-like damage (using isoproterenol) and found that taking it orally really protected the heart. It reduced heart muscle damage, eased oxidative stress, boosted antioxidant enzymes like superoxide dismutase and catalase, and lowered thiobarbituric acid reactive substances (TBARS) level-a sign of less fat damage in the heart.[72] Diabetes often leads to heart complications, including diabetic cardiomyopathy, where heart cells die off due to high sugar, inflammation, and oxidative stress. A study on diabetic rats given streptozotocin showed that fenugreek seed extract improved metabolism, cut down heart cell death (apoptosis), and helped preserve normal heart structure. Most of this protection came from reducing oxidative stress and preventing excessive cell loss in the heart.[73] Overall, these results highlight fenugreek's real potential for supporting heart health-both by preventing clots and shielding the heart in diabetes.

Parkinson's disease

It is the common neurodegenerative disorder that affects people all over the world. Its characterised by symptoms such as slowness of the movement (Bradykinesia) muscle stiffness, postural imbalance and gait problem in latest stages people also experience anxiety and depression.[74] Mostly Parkinson's disease occurs due to the loss of dopamine-producing neurons in the substantia nigra pars compacta (SNC) region of brain.[75] Exact cause for this disease is unknown. Oxidative stress is one of the major factor responsible for neuronal damage. Modern treatment is levodopa and dopamine helps to relieve the symptoms, but it also causes side effects.[76] Hence, natural components with antioxidants and neuro productive properties are exposed. Neuro productive effects against oxidative stress are present in Trigonelline, which is present in fenugreek. Experiment of rat model of disc degeneration induced by six hydroxyl dopamine (60HDA) by a dose of Trigonelline (100 mg/kg) restore the dopamine-producing neuron in the (SNC), and it enhance anti apoptotic activity, indicates it role in controlling Parkinson disease.[77]

Antioxidant

Antioxidants are molecular substances that can inhibit the oxidative phenomenon that causes unstable atoms and thus prevent the damages of cells and tissues caused by oxidation and minimize the occurrence of the human and animal diseases, including cancer, heart diseases and Alzheimer. Different fractions from germinated fenugreek seeds were evaluated for antioxidant activity, with the aqueous fraction showing the highest effect. The strong antioxidant potential is likely due to the presence of flavonoids and polyphenols.[65] The antioxidants are neutralizers of the free radicals, and thus reduce the intensity and occurrence of associated pathologies.[67] Fenugreek has a protective effect on fatty acid breakdown and increases antioxidant defences that are enzyme-based.[78] Different solvents such as methanol, ethanol, hexane, dichloromethane, acetone and ethyl acetate are used in the extraction process of fenugreek seeds, giving the extracts free -radical neutralizing properties.[79]

A comparative study showed that fenugreek contains higher levels of bioflavonoids and polyphenols than coriander, contributing to its stronger antioxidant potential. Antioxidant activity was evaluated using nitro blue tetrazolium and hydrogen peroxide scavenging assays. *Trigonella* species demonstrated the highest superoxide and free radical scavenging ability.[80] Fenugreek contains flavonoids that prevent the accumulation of intracellular reactive oxygen species, and have a protective effect on mitochondrial DNA, protecting it against oxidative damage, therefore, alleviating mitochondrial dysfunction.[81]

Anti-inflammatory activity

Fenugreek is an ancient herb whose medicinal qualities are well established, and most especially its anti-inflammatory effect. Polycystic ovary syndrome is a common endocrine disease among women that triggers the development of metabolic disturbances and chronic low-grade inflammation. The anti-inflammatory effect of fenugreek seed extract was evaluated in an *in vitro* study using protein denaturation tests, membrane stabilization tests and erythrocyte sedimentation rate tests. The extract performed better than celecoxib, which is a common non-steroidal anti-inflammatory medication, in all concentrations.[82] Other findings showed that the aqueous extract alleviated ulcerogenesis.[65] Moreover, in a mouse-based diabetes model, the use of fenugreek reduced the macrophage infiltration into adipose tissue and suppressed the expression of proinflammatory genes in the mRNA.[83]

Obesity

In animal research, obesity is a progressive result of the deposit of excessive body fat, which leads to the development of undesirable health conditions and aggravates other health issues. In a controlled study on 32 male rats, a high-calorie diet successfully induced obesity, leading to adverse metabolic changes. When fenugreek seed powder was administered, key physiological and biochemical parameters gradually returned to near-normal levels. Fenugreek supplementation reduced body fat accumulation and adipose tissue deposition, highlighting its anti-obesity potential. In addition, its aqueous extract improved glucose and lipid metabolism, lowered TBARS levels, and enhanced antioxidant enzyme activity, suggesting protective effects against obesity-related complications.[84,85]

Asthma

Human study

Asthma refers to a chronic respiratory illness. The condition is managed by the use of corticosteroids, and a study investigating the effect of fenugreek seed extract on patients with mild asthma reported that fenugreek acts as a lung tonic and could be used in the management of mild asthma.[86]

Animal model

Mice were used in an experiment to test fenugreek seeds as a treatment of allergic asthma, which in Persian medicine is referred to as Rabi, with the key aim of suppressing the infiltration of Th2 cytokines that cause inflammation by lowering the levels of mRNA expression in bronchoalveolar lavage fluid. The results showed that aqueous seed extract of fenugreek suppressed the mucus hypersecretion, peribranchial and perivascular inflammatory conditions, and hyperplasia of the goblet cells in the lung tissues compared to ovalbumin-sensitized controls, which implies that the extract is the most suitable intervention to treat allergic asthma.[65]

Gastroprotective effects

Animal trails

Fenugreek seed has nutraceutical properties and has been used traditionally to treat gastrointestinal disorders, especially gastric ulceration. The rats were starved (24 h) followed by administration of either aqueous extract (1, 2 or 3 mL/kg), gel fraction (500, 600 and 700 mg/kg) or omeprazole (10 mg/kg^{-1}) through gastric intubation in a controlled experimental design. One hour post-dosing, each animal was given 1.5 mL of HCl-ethanol mixture, which was a mixture of HCl, 150 mM dissolved in 70% v/v ethanol, which was the vehicle of control. The findings revealed that the orally administered fenugreek seed fractions have a profound gastro-protective effect, and the flavonoid and polysaccharide components of the gel fraction have been discovered as the major mediators of this property.[87]

Antimicrobial activity

Fenugreek seeds have inbuilt antibacterial properties. Pharmacological activity of fenugreek are presented in Figure 1. The antibacterial activity of seed extracts was determined against six bacterial isolates consisting of *Pseudomonas aeruginosa*, *Proteus mirabilis*, *Salmonella typhi*, *Escherichia coli*, and Vibrio parahaemolyticus that were collected in different clinical sources, including stool, wound exudate, urine and skin lesions. The largest inhibition zones were observed with *Staphylococcus aureus* and *P. aeruginosa* with a 22 mm and 17 mm against the extract, respectively.[88] Another study matched the antimicrobial efficacy of *T. foenum-graecum* phytoconstituents to that of 0.2% chlorhexidine (CHX). The preparations under study were fenugreek absolute, DIO, and furanone. The evidence demonstrates that fenugreek extract may be a better alternative to CHX in the gingival and periodontal infection management.[89]

Future prospects

The genetic diversity and biochemical composition of *T. foenum-graecum* have been studied using molecular markers, including RAPD, AFLP, ISSR and SSR, and initial phytochemical surveys, as reported, but the combination of state of art multi-omics technologies has not yet been fully developed. The available literature supports the therapeutic use of active constituents of fenugreek (steroidal saponins, flavonoids, alkaloids, and other phytochemicals) in the treatment of diabetes, inflammation, and cardiovascular conditions. However, the cellular signaling pathways, pharmacokinetics and clinical efficacies of these metabolites, in leaves, seeds, and processed products, remain unknown to us and deserve all possible research. Additional investigation is essential to define distinct therapeutic requirements of metabolic syndromes, weight management, and neuroprotection, especially by use of phylogenomics and SNP-based genomic mapping. Therefore, future studies must strive to harmonize the time-tested applications with the current genetic-enhancement and precision-gene-editing technology, including CRISPR-Cas9, and at the same time facilitate the application of sustainable agronomic strategies that would increase the production of health-promoting nutraceuticals in this ancient medicinal herb.

CONCLUSION

This in-depth exploration sheds light on the incredible versatility of fenugreek (*T. foenum-graecum*), underscoring its status as a powerhouse crop packed with nutrients and a valuable medicinal ally, especially in its seeds and leaves. Techniques such as RAPD, AFLP, ISSR, and SSR have revealed impressive genetic variation among different strains and varieties, setting the stage for smarter breeding programs. At the same time, its rich mix of bioactive elements likes steroidal saponins, flavonoids, alkaloids, proteins, fibers, vitamins, and mineral drives a host of health perks, from managing diabetes and reducing inflammation to safeguarding the heart and providing antioxidant support, as shown in early laboratory and animal studies. While fenugreek has long been a staple in traditional healing practices, unlocking its true power will require robust, large-scale human trials to solidify its effectiveness against metabolic disorders and beyond. Moving forward, merging time-honored knowledge with cutting-edge science such as phylogenomics, metabolomics, transcriptomics, SNP-based mapping, and CRISPR gene editing, holds the key to decoding its secrets, paving the path for innovative advances in nutraceuticals, drugs, and tougher, more sustainable crop strains.

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