

Therapeutic and protective valuation of fenugreek (*Trigonella foenum-graecum*)

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Abstract

Fenugreek is a medicinal herb that is primarily found in Asia, the Mediterranean, and Africa, where it served not only as a medicinal plant but also as a spice. The nutritional composition and bioactive compounds present in fenugreek contribute to its numerous health-promoting benefits. Its dried seeds are highly versatile and commonly used as a flavoring ingredient. They are also rich in fiber, protein, fat, minerals, and vitamins, making them a valuable source of nutrition with a well-rounded nutritional composition. Fenugreek seeds are identified as a promising remedy for controlling and preventing diabetes. These seeds contain phytochemicals, such as polyphenols, saponins, and flavonoids, which have the potential to inhibit the digestion and absorption of glucose in the body. Moreover, fenugreek is documented to possess gastroprotective properties, exhibit potential anticancer effects, aid in the treatment of arthritis, demonstrate antimicrobial activities, assist in weight reduction, and potentially regulate hyperthyroidism. As a powerful antioxidant and potential anticancer agent, it improves insulin sensitivity and glucose control for the management of diabetes. Additionally, it has anti-inflammatory benefits, improves immunological functioning, helps to control glycemia, and may regulate cholesterol levels as well as possess antibacterial and immune-boosting qualities. As a result, more research is required to investigate the full potential of fenugreek; these investigations would help to identify potential bioactive components with a particular focus on treating health diseases. This review highlights the morphology, adaptability, nutritional constituents, and the associated functional and medicinal significance of fenugreek.

Keywords: anti-inflammatory; antioxidant; diabetes; fenugreek; nutrients; therapeutic potential

Introduction

Fenugreek, scientifically known as *Trigonella foenum-graecum* (L.) is a remarkable herb with a long history

of culinary and medicinal usage. This versatile plant has gained attention for its diverse health benefits, including its potential in preventing and managing a variety of diet-associated diseases, such as inflammation,

hypertension, cardiovascular issues, diabetes, and cancer (Syed *et al.*, 2020). The incorporation of medicinal herbs such as fenugreek into dietary choices has become increasingly common as these plants offer a safe and nutraceutical-rich approach to promoting well-being without disrupting the body's natural physiology. Furthermore, fenugreek, often utilized as a spice in human food, stands out as one of the most famous plants, well known for its ability to provide valuable functions (Shadab *et al.*, 2024). Different development stages of a fenugreek plant are shown in Figure 1.

In Asia, stems and leaves of fenugreek have a long history of being consumed as vegetables. Fenugreek is an annual plant that undergoes one growth cycle per year and can self-pollinate. Fenugreek belongs to the *Fabaceae* family (also called *Leguminosae*) and is classified under the sub-family *Papilionaceae*. It produces two cotyledons during germination. Species of *Trigonella* are primarily found in Asia (China and India), some parts of Europe, Australia, Africa, and South and North America (Ahmad *et al.*, 2023). Globally, almost 70–97 of different species of fenugreek are cultured. One species is *foenum-graecum*, meaning 'Greek hay', as it has its origin in Greece (Tewari *et al.*, 2024). Fenugreek is considered as one of the most significant medicinal plants because of its rich content of various and essential phytochemicals. The leaves and seeds of fenugreek, known as *methi* in India, are widely utilized for preparing extracts and powders for various medicinal purposes (Verma *et al.*, 2023). Fenugreek is considered as a dietary fiber and other essential nutrient-rich elements necessary for healthy growth and development (Srivastava *et al.*, 2022). Scientists have documented numerous medicinal and pharmacological properties of fenugreek seeds, such as antimicrobial, anticholesterolemic, emollient, febrifuge, carminative,

restorative, laxative, galactagogue, uterine tonic, expectorant, antioxidant, anticarcinogenic, anti-inflammatory, antiviral, demulcent, and hypotensive. The medicinal values of fenugreek have led to the effective utilization of extracts and powders derived from various parts of the plant in both food and pharmaceutical industries (Sun *et al.*, 2021). In this comprehensive review, we examined fenugreek's morphology, adaptability, nutritional components, and its various functional and medicinal attributes. We also delved into its allelopathic potential.

Phenology, Morphological Description, and Cultivation

Fenugreek exhibits an erect and aromatic growth habit, resembling a large clover plant. Its stem is cylindrical, measuring approximately 30–60 cm in length and displaying a pinkish hue. Fenugreek roots have a big, finger-like structure. The plant features pinnate, trifoliate leaves with long stalks, consisting of toothed, lanceolate leaflets. The stipules of the leaves are triangular in shape and the leaflets themselves range from obovate to oblanceolate (Singh *et al.*, 2025). It produces white to yellowish-white flowers that emerge in the axils of the plant and are sessile in nature. These flowers are hermaphroditic and primarily pollinated by insects. They are made up of five petals, known as the flag, wing, and keel. The pollen grains are oblong to round in shape, while the flower's ovary is deep green and glaucous (Aasim *et al.*, 2018). The fenugreek flower gives rise to pods that are approximately 15-cm long, brownish to yellowish-brown in color. These pods typically contain 10–20 seeds each. The seeds themselves are small, measuring around 5 mm in length. They have a hard and smooth texture and appear in a dull yellow to brownish-yellow shade (Srinivasan, 2019).

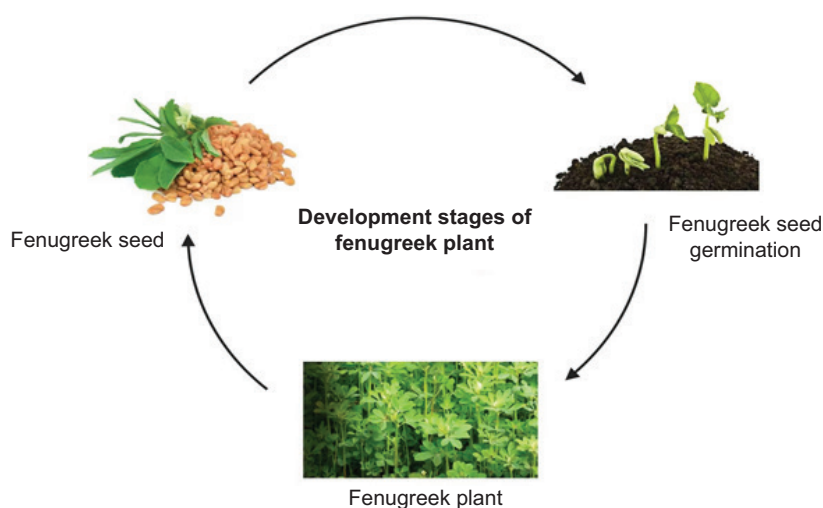


Figure 1. Progression of fenugreek (*Trigonella foenum-graecum*) growth and development: from seeds to mature plants.

Fenugreek typically takes 5–10 days to germinate while the first leaf (trifoliolate) appears 5–8 days after germination. It is considered a fast-growing plant that can thrive in various environments, such as hillsides, dry grasslands, cultivated or uncultivated lands, plains, and field edges. Adequate sunlight is essential for its growth. Fenugreek needs 4–7 months to reach maturity (Nagulapalli Venkata *et al.*, 2017). Fenugreek blooms in midsummer, specifically from June to August, and seeds ripen during late summer (August to September). This plant exhibits drought tolerance and thrives in tropical climates characterized by mild winters and cool summers. However, the development of its leaves and flowers is influenced by variations in temperature.

The place of origin and centralized production of trigonelline is located in the Mediterranean region of Asia and is now widely cultivated in northern and Central Africa, Europe, North America, and Australia. Fenugreek is a global plant with different degrees of cultivation and wild resource distribution because of its strong adaptability. Fenugreek can tolerate an annual precipitation of 3.8–15.3 decimeters (dm) and an annual temperature that fluctuates between 7.8°C and 27.5°C (Coban, 2025).

Owing to its adaptability to a range of climatic and growth conditions, fenugreek farming is spread globally (Roba and Mohammad, 2024). The fenugreek crop is confronted with numerous biological agents, for example, bacteria, fungi plus insects, and nonbiological ailments, such as, stagnant water, salinity, submergence, and micronutrient deficiency (Yadav and Ghasolia, 2022). The genotype, climate, environment, farming practices, usage of fertilizers, irrigation, and techniques for processing seeds into regional specialties have an impact on the output and quality of fenugreek (Nimbrana *et al.*, 2024). The fenugreek crop has an indefinite growth pattern; however, transmuted populace produced by chemical and physical transmuting agents have been stated to be effective in producing crops with fast and definite growing patterns

(Basu *et al.*, 2019; Zandi *et al.*, 2017). Ecological factors of fenugreek growth are shown in Table 1.

Fenugreek Nutrients and Phytochemicals

Fenugreek contains a diverse range of nutrients and bioactive compounds that play a vital role in enhancing the functionality of biological systems and promoting overall health (Table 2). The macro and micronutrients in plants play a vital role in facilitating enzymatic activities, which ultimately influence their growth, yield, and quality (Arti, 2014). Each 100 g of fenugreek (leaves) contains approximately 86% moisture, 4.4% protein, 1% fat, 1% fiber, and notable amount of calcium (395 mg), phosphorus (51 mg), magnesium (67 mg), sodium (76 mg), potassium (31 mg), iron (16.5 mg), selenium (167 mg), copper (260 mg), chlorine (165 mg), thiamine (40 mg), nicotinic acid (800 mg), riboflavin (310 mg), carotene (2.3 mg), and vitamin C (52 mg). Additionally, traces of vitamin K are also present (Aher *et al.*, 2016). Fenugreek seeds possess aromatic qualities and are recognized for their carminative and galactagogue properties. They have a mild bitter taste and exhibit antibacterial effects. These seeds are consumed either raw or cooked, providing versatility in their culinary applications. The seeds (biologically endosperm) are the most valuable component of the plant. They possess a fibrous texture and have a sticky, gummy nature. The major constituents of fenugreek seeds are carbohydrates, proteins, lipids (unsaturated acids, such as 4-hydroxy isoleucine, trigonelline, galactomannans, polyunsaturated fatty acids, linolenic acid, oleic acid, and linoleic acid), flavonoids, vitamins, fibers, alkaloids, saponins, steroidal saponins, minerals, and nitrogen compounds (volatile and nonvolatile constituents) (Farhat *et al.*, 2024). Fenugreek seeds have 25% fiber, 23–26% protein, 58% carbohydrates, and 0.9% fat (Wani and Kumar, 2018). In polyphenolic compounds, flavonoids are the principal component of the fenugreek crop, specifically apigenin 6,8-di-C-glucoside,

Table 1. Ecological factors that influence the growth of fenugreek.

Factors	Significant reports/findings	References
Climate	<ul style="list-style-type: none"> The plant can thrive in a Moderate environment with cool summers and mild winters Low to moderate rainfall It exhibits moderate-sensitivity to forest and moderate resistance to drought It can tolerate frost temperature between 10–15°C 	Mehrafarin <i>et al.</i> , 2011
Altitude	<ul style="list-style-type: none"> It Can grow at altitudes up to 1,300–1,400 m above sea level 	Basu <i>et al.</i> , 2016; Kumar <i>et al.</i> , 2013
Soil	<ul style="list-style-type: none"> Loamy and mild alkaline soils are ideal for growth but, in some cases, where the acidity is quite high, application of lime is required Moist and heavy soils restrict its growth The ideal pH range for optimal growth is 8–8.5 	Irum <i>et al.</i> , 2024

Table 2. Nutritional profile of fenugreek (*Trigonella foenum-graecum*).

Plant parts	Components	Net amount (%)	References
Leaves	Mucilage	86.10	Mandal and DebMandal, 2016
	Fat	000.9	
	Carbohydrates	6.000	
	Proteins	4.400	
	Fiber	1.001	
	Minerals	1.005	
Seeds	Proteins	22.00	Snehata and Payal, 2012
	Mucilage	28.00	
	Dietary fibers	50.00	
	Linoleic acid	42.50	
	Palmitic acid	10.50	
Seed oil	Neutral lipids	93.20	Ahmad et al., 2016
	Triacylglycerols	84.80	
Seed	Alkaloids	35.00	Athira et al., 2023
Seed	Saponin	4.800	Del Hierro et al., 2021
Seed	Flavonoids	10.00	Muridhar and Goswami, 2012
Seed	Diosgenin	0.2–0.9	Mohammadi et al., 2020

apigenin-6-C-glucosyl-8-C-galactoside, 6-cgalactosyl-8-C-arabinoside, essentially helpful in reducing blood sugar levels in living organisms. Certain well-known flavones that are present in fenugreek plants are vitexin, quercetin, orientine, luteolin, and epigenin (Banerjee and Bose, 2024). Some studies found that isovitexin and rhaponticin are the chief components in fenugreek seed (Kia et al., 2018). Phosphorus is also present in fenugreek seeds and is apportioned into various types such as phosphoproteins, nucleic acid phosphorus, inorganic phosphorus, phospholipids, and phytates. The process of germination increases the seed's nutrition, such as ascorbic acid, sugar, amino acids, and proteins (Niknam et al., 2021).

Nutritional and Health Impacts of Fenugreek

The fenugreek crop has a vast worldwide demand among related functional foods, nutraceuticals as well as pharmaceuticals (Table 3). Fenugreek is a chemical crop, famous for its vast espousal in industrial areas. Presently, it is utilized using an emulsifying agent, gum, and food stabilizer because of its high content of gum, protein, fiber, other volatile contents, and chemical ingredients. The emulsifying property and excellent moisture retention capacity of fenugreek gum demonstrate an intriguing potential for its incorporation into cosmetic products (Asati et al., 2019). Furthermore, fenugreek gum finds

diverse applications in many food products: it contributes to the softness and dough properties of Iranian flatbread (*sangak*), acts as a fat substitute and enhances firmness in chiffon cakes, and serves as a texture enhancer, promoting good expansion and a low glycemic index in extruded snacks (Dhull et al., 2022). Fenugreek protein is more soluble at alkaline pH (Hassan et al., 2020). Historically, fenugreek seeds were used to facilitate childbirth and enhance lactation. Presently, these are utilized as a traditional remedy for a range of ailments. Women have traditionally consumed fenugreek seeds to alleviate menstrual pain and alleviate stomach issues. Additionally, these seeds are used for treating indigestion, flatulence, and promoting liver health (Kumar et al., 2021; Olaiya and Soetan, 2014). Clinical trials in humans have shown that fenugreek seeds improve various metabolic symptoms associated with diabetes mellitus. These seeds are demonstrated to effectively reduce blood sugar levels and enhance insulin sensitivity (Elsaadany et al., 2022). The antioxidant activity of fenugreek seeds is facilitated by the presence of flavonoids and polyphenols (Srivastava et al., 2022). Additionally, fenugreek exhibits protective effects against oxidation caused by hydrogen peroxide. It helps to prevent erythrocyte hemolysis and lipid peroxidation (Lamsaadi et al., 2023; Mbarki et al., 2017).

A rich amount of steroid diosgenin, used as a supplement in the pharmacological industry, is present in fenugreek seeds. Seeds often contain anti-nutritional components, such as saponins, phytic acid, tannic acid, and alkaloids. Phytic acid possesses antioxidant and anticancer properties as well as the ability to reduce cholesterol levels. Tannins exhibit antibacterial and antiviral characteristics and mitigate inflammation. Saponins contribute in lowering cholesterol and improving blood sugar regulation. Notably, phytic acid, an antinutrient, forms complexes with certain minerals in the gut, rendering them unavailable for absorption by the body. This compound also impedes the digestion of proteins, starch, and fat. Furthermore, when tannic acid is present in significant quantity, it can act as an anti-nutrient by forming insoluble complexes with divalent ions in the gastrointestinal tract, thus reducing their bioavailability (Chaudhuri et al., 2025). Defatted seeds, on the other hand, are free of these substances and are consumed by fatty people (Chaudhary et al., 2018). In alloxanic diabetic mice, biomarkers of oxidative stress are reduced by using fenugreek seed powder as a supplement (Jahan et al., 2024).

Experimental and clinical studies have also reported anti-atherosclerotic properties of seeds (Singh et al., 2022). A study has stated that when fenugreek seeds were supplemented in a diet of dairy goats, it notably lessens the level of serum cholesterol and concentration of triglyceride. Fenugreek seeds increase milk fat concentration, and milk quality characteristics, such as

Table 3. Nutritional/health effects of fenugreek.

Nutritional components/unit	Nutritive value of seeds per 100 g	Nutritive value of leaves per 100 g	Health impact	References
Fiber/g	47.55	4.90	Bind Food toxins, enhances insulin production, safeguard the mucous membrane of the colon and controls glucose absorption	Türker <i>et al.</i> , 2022
Proteins/g	364.00	4.40	Stimulates insulin activity	Tura <i>et al.</i> , 2023
Fat/g	7.500	0.83	Provides strong pain-relieving and appetite-stimulating potential	Heshmat-Gahdarjani <i>et al.</i> , 2020
Carbohydrates/g	42.30	6.00	Improves glucose kinetics, and inflammatory status	Khan <i>et al.</i> , 2018; Malin <i>et al.</i> , 2019
Calcium/mg	1.760	3.95	Supports Bone health, control blood pressure, prevent colon cancer, aid in weight management and reduce the symptoms of premenstrual syndrome	Khorshidian <i>et al.</i> , 2016
Iron/mg	335.0	165.0	Essential for production of red blood cells	Akbari <i>et al.</i> , 2022
Magnesium/mg	1.910	0.670	Helps in managing Hypertension, cardiovascular disease, osteoporosis and diabetes	Gharne and Davodalhosseini, 2015
Copper/mg	1.16	2.60	Contributes significantly to biological (cellular) defenses against oxidative stress	Liu and Miao, 2022
Potassium/mg	891	0.310	Control heart rate and blood pressure by countering sodium effects	Seghatoleslami <i>et al.</i> , 2013
Vitamin C/mg	3.0	1.30	Plays a crucial part in the immunological response, collagen biosynthesis, orthogenesis, detoxification, wound-healing, absorption of iron and prevents blood clot formation	Bishnoi <i>et al.</i> , 2020
Riboflavin/mg	0.366	0.220	Provides anti-inflammatory, antinociceptive, antioxidant, anticancer, and antiaging effects	Suwannasom <i>et al.</i> , 2020; Sheikhlari <i>et al.</i> , 2018

polyunsaturated fatty acid concentration (Akbag *et al.*, 2022). The antioxidant, hepato-protective, hypocholesterolemic, and hypoglycemic effects of fenugreek seeds are well known (Sindhu *et al.*, 2022). Aqueous extract of fenugreek seeds has antibacterial and antifungal properties (Lohvina *et al.*, 2021). Saponins are also found in fenugreek seeds, and decrease gluconeogenic enzyme activity and digestive enzymes in stagnant bowels and boost glycogen levels in the body (Akbari *et al.*, 2022). Owing to their nutraceutical characteristics, fenugreek seeds are recommended and incorporated into our regular diet. Their moderate consumption is considered safe and can offer a wide range of health benefits (Wani and Kumar, 2018).

Therapeutic Properties of Fenugreek

Fenugreek has great medicinal properties because of a wide variety of significant phytochemicals found in it, such as 4-hydroxy isoleucine, galactomannan

fenugreekine, trigonelline, and diosgenin (Kachhwaha *et al.*, 2024). Fenugreek has many health benefits. Fenugreek seeds are beneficial for treating gastric ulcers. Fenugreek is a cleansing herb that helps to detoxify the body, cleanse the lymphatic system, and purify the blood. Fenugreek seeds are thought to be beneficial as a galactagogue that promotes lactation in aphrodisiac and heart disease (Visuvanathan *et al.*, 2022). Globally, fenugreek is used for various purposes; for example, China uses fenugreek seeds for treating kidney problems and cervical cancer. In the Balkans and Middle East, the plant's aerial parts are used for treating abdominal cramps while suffering with diarrhea. In South India, seeds are roasted and used for treating dysentery. As a natural health product, it is used for curing and treating ailments, thus providing health and medical benefits. That's why it is a potential nutraceutical (Tewari *et al.*, 2024). In addition to its traditional uses, fenugreek has many pharmacological properties, such as hypocholesterolemic, anti-inflammatory, antioxidant, anticarcinogenic, antinociceptive, and antidiabetic effects (Figure 2). The figure shows a

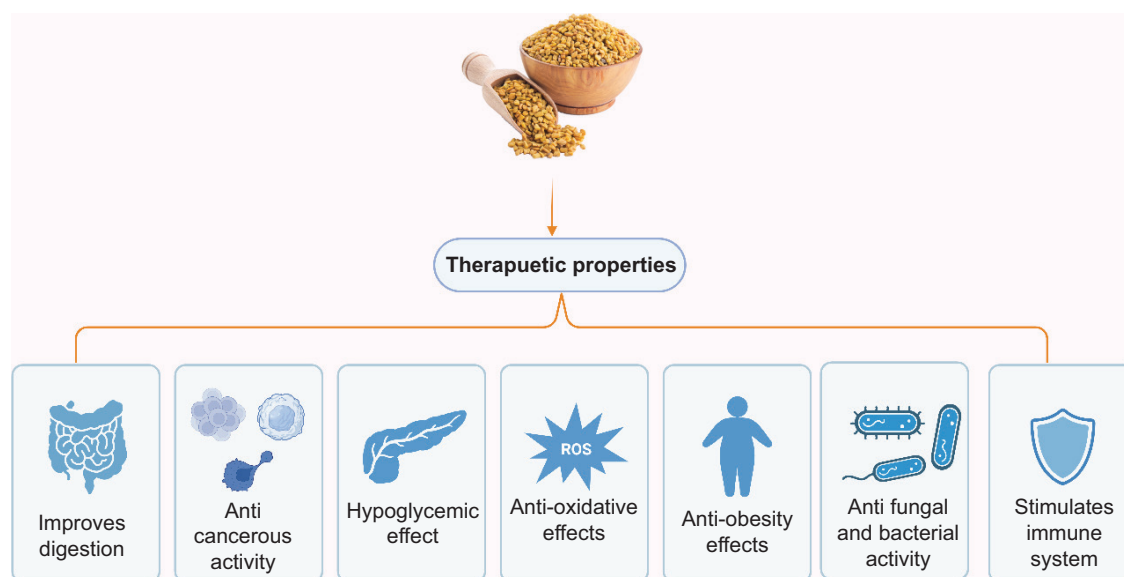


Figure 2. Health and therapeutic potential of fenugreek.

comprehensive visual insight into the numerous benefits of fenugreek, highlighting its potential as a natural remedy for a range of health issues and as a valuable dietary supplement.

Anticancer properties

Fenugreek seeds are widely used to treat high cholesterol and high triglycerides, but they have also recently drawn attention as a potential for treating cancer (El Bairy *et al.*, 2017). Fenugreek seeds exhibit promising anticarcinogenic properties, making them a potential complementary therapy for cancer patients undergoing chemotherapy. Fenugreek extract has shown a protective effect by altering the apoptosis induced by cyclophosphamide and reducing lipid peroxidation caused by free radicals in mice urinary bladder (Kilambi and Shah, 2021). Studies have reported that diosgenin found in fenugreek inhibits cell proliferation and induces apoptosis in the H-29 human colon cancer cell line (Laila *et al.*, 2022). Furthermore, fenugreek has demonstrated hepatoprotective properties, and the polyphenolic extract derived from the seeds identified as a safeguarding agent against liver abnormalities caused by ethanol (Al-Timimi, 2019). In addition, extracts from the entire fenugreek plant have demonstrated cytotoxic effects (*in vitro*) against different human cancer cell lines (CCLs), such as HT29 (a colon cancer cell line) and IMR-32 (a neuroblastoma cell line) (Salam *et al.*, 2023). Studies have revealed that fenugreek seeds promote apoptosis and enhance the expression of pro-apoptotic genes, leading to anticancer effects against

MCF-7 human immortalized breast cells (El Bairy *et al.*, 2017). Furthermore, fenugreek seeds have exhibited notable inhibitory effects on the proliferation of MCF-7 breast cancer cells. Significant inhibition was observed when the cells were exposed to a concentration of 400 $\mu\text{g}/\text{mL}$ of fenugreek seeds for 72 h. These findings suggest that fenugreek seeds possess the potential to serve as a potent anticancer agent (Al-Timimi, 2019).

Antioxidant effects

The seeds of *Trigonella foenum-graecum* are used for the treatment of diabetes, and fever. In addition, these are applied as poultices for eruptions, boils, and wound-healing (Chehregosha *et al.*, 2024). The presence of flavonoid and phenolic compounds in fenugreek seeds enhances its antioxidant capability. Bioactive compounds contribute to the powerful antioxidant properties of fenugreek seeds, which have a positive impact on the liver and pancreas (Tewari *et al.*, 2020). Reactive oxygen species (ROS) play a significant role in numerous clinical disorders. These ROS may cause human ailments such as cerebrovascular diseases, heart disease, diabetes, and cancer via numerous mechanisms. Thus, antioxidants are helpful in therapies for these ailments (Lohvina *et al.*, 2021).

In vitro hydro alcoholic extracts of seeds of fenugreek were examined for antioxidant and antiradical properties in several models and results advocate that the seeds have potential antioxidant actions (Aylanc *et al.*, 2020). In a rat study, an aqueous extract of fenugreek (seeds) was

utilized to assess its effects. To induce toxicity, mice were fed ethanol for 60 days, resulting in increased activities of serum aspartate transaminase, alkaline phosphatase, and alanine transaminase. However, concurrent administration of the aqueous extract led to elevated antioxidant levels and prevented further elevation of lipid peroxidation. The administration of the seed extract demonstrated a preventive effect on enzymatic leakage, lipid peroxidation, and improved antioxidant potential. Histopathological examination of the liver and brain of mice further confirmed the protective role of the seed extract against ethanol-induced toxicity (Martinez-Hurtado *et al.*, 2018).

In addition, diabetic mice exhibited hypoglycemic and antihyperglycemic effects in response to the antioxidant carotenoid present in fenugreek seeds (Idris *et al.*, 2021). It is also stated that extract of fenugreek seeds, rich in polyphenol, significantly decreased hydrogen peroxide (H₂O₂)-induced oxidative alterations in erythrocytes of diabetic and normal humans, signifying powerful antioxidant effects of fenugreek seed extract (Yu *et al.*, 2019). Fenugreek extracts possess the capability to neutralize effectively free radicals, making them a valuable contender for mitigating the detrimental impact of different diseases. As a result, fenugreek can be considered as a promising option for therapeutic interventions and alleviating the adverse consequences associated with various ailments.

Hypocholesterolemic effect

Fenugreek seeds are shown to possess hypocholesterolemic properties. A study conducted on diabetic dogs found that elevated cholesterol levels often result as a secondary effect of diabetes. However, defatted fenugreek seeds, which are rich in dietary fiber, can play a crucial role in alleviating both hyperglycemia and glycosuria associated with diabetes. By effectively managing diabetes, these seeds also reduce cholesterol levels, thus addressing the underlying cause of hypercholesterolemia in diabetic dogs. Interestingly, this cholesterol-lowering effect extends to non-diabetic dogs as well. An analysis of fenugreek seeds' components reveals a substantial composition in the defatted portion, such as high fiber content (53.9%) and saponins (4.8%), which exhibit notable viscosity (Singh *et al.*, 2023). Research has demonstrated that viscous materials, such as dietary fibers, can effectively reduce serum total cholesterol levels. However, the extent of their effectiveness can vary depending on the source of the fiber (Jenkins, 1979). Variation in the cholesterol-lowering effect could be associated with the varying saponin levels found in different sources of dietary fiber (Tak *et al.*, 2024). Moreover, fenugreek seeds contain diosgenin and tigogenin in glycoside form, and these compounds are documented to influence

cholesterol metabolism within the liver (Valette *et al.*, 1984). Saponins found in fenugreek seeds have the potential to affect cholesterol absorption in the intestinal tract, possibly by creating complexes with cholesterol (Del Hierro *et al.*, 2021). Finally, the amino acid composition of fenugreek proteins, similar to that of soybeans, could play a role in lowering cholesterol levels, as observed in research on plant-based proteins. Dietary fiber consumption leads to a reduction in blood sugar levels and a decrease in serum lipids (Srivastava *et al.*, 2022). The hypocholesterolemic effect was observed from the defatted portion of fenugreek seeds (Türker *et al.*, 2022). The effect of fenugreek extract on blood lipid levels was examined in diabetic mice and it was found that mice treated with the extract had reduced triglycerides and total cholesterol as well as an increase in high-density lipoprotein (HDL) levels (Hoseini *et al.*, 2022). Fenugreek seeds are a good source of dietary fiber and contain a significant amount of gum primarily composed of galactose and mannose. These compounds have demonstrated a cholesterol-lowering effect (Cheurfa *et al.*, 2022). The defatted component of fenugreek seeds triggers a cholesterol-lowering effect that is beneficial for health.

Anti-inflammatory effects

The fenugreek plant, found extensively across the globe, has useful phytochemicals, such as flavonoids, alkaloids, saponins, steroids, and other beneficial compounds (Khatri and Rao, 2020). Inflammatory mediators are discharged by the body's immune cells accountable for the manifestations of infection/inflammation on stimulation, which are identified as pathogen-related molecular patterns (PRMPs), such as loss of function, pain caused, tissue damage, warmth (heat), swelling, and redness. These stages lead to foreign substances or pathogens that are then cleared by the body's immune cells, though the devastating response of inflammation is risky for body tissues. Thus, anti-inflammatory constituents are significant in decreasing inflammation. Fenugreek seeds are known to combat inflammation because of the availability of chief compounds, such as flavonoids, saponins, and alkaloids, accountable for anti-inflammatory properties (Aylanc *et al.*, 2020). A study examining the anti-inflammatory characteristics of fenugreek seed petroleum ether extract (FSPEE) discovered that administering FSPEE to mice led to a notable decrease in inflammation. The study reported a 37% reduction in inflammation in the paw induced by carrageenan, while in the case of formaldehyde-induced paw edema, the inflammation was reduced by an impressive 85% (Almatroodi *et al.*, 2021). When formulated as an emulsifying ointment, fenugreek exhibits significant potential of an anti-inflammatory agent for effectively treating acute inflammatory disorders (Narapogu *et al.*, 2021).

Fenugreek seeds' effect on blood glucose levels

Diabetes mellitus is a severe health condition characterized by elevated blood sugar levels. When left untreated, it leads to significant complications, such as heart attack, vision loss, stroke, kidney failure, and amputation (Jeffery *et al.*, 2022). Diabetes mellitus is a metabolic syndrome caused by an abnormality in the production or functioning of insulin. This deficiency of insulin results in persistent high levels of glucose in the bloodstream, leading to disruptions in the metabolism of carbohydrates, lipids, and proteins (Szablewski, 2024). Diabetes mellitus, characterized as a chronic metabolic disorder, is a rapidly increasing global issue with substantial social, health, and economic consequences (Priya and Kalra, 2018). Consistent intake of functional foods and herbal supplements is associated with potential benefits, including improved anti-inflammatory and antioxidant effects, enhanced insulin sensitivity, and better management of cholesterol levels. These factors play a crucial role in the prevention and management of symptoms associated with diabetes mellitus (Alkhatib *et al.*, 2017). Fenugreek is known for its rich content of bioactive compounds, such as alkaloids, flavonoids, steroids, saponins, etc. Moreover, it is recognized as a valuable source of soluble fiber, which plays a role in reducing blood sugar levels by inhibiting the absorption and digestion of carbohydrates (Malhosia *et al.*, 2022).

Consumption of the seeds is linked to the regulation of blood sugar levels through various mechanisms. These include reducing the rate of glucose absorption in the gastrointestinal tract, enhancing the functioning of pancreatic beta islet cells (which produce insulin), improving insulin sensitivity, and enhancing the utilization of glucose within cells (Dilworth *et al.*, 2021). Fruits and vegetables typically contain more insoluble fiber, but fenugreek stands out as a source of soluble fiber (Man *et al.*, 2019). Studies have indicated that the soluble fiber found in fenugreek delays the digestion and absorption of carbohydrates, leading to an improvement in glucose homeostasis. Moreover, the study emphasizes that soluble fiber has beneficial effects on dyslipidemia (abnormal lipid levels) and can inhibit platelet aggregation in mice with type II diabetes (Hosseini *et al.*, 2023; Shashikumar *et al.*, 2019). Fenugreek contains galactomannan, a type of soluble dietary fiber compound that has the ability to lower blood glucose levels in diabetic mice (Jiang *et al.*, 2017). Dietary fibers, essential constituents of plant-based foods, are complex carbohydrates that play a vital role in maintaining a healthy diet (Wang *et al.*, 2019). Researchers demonstrated that incorporating 100 g of fenugreek powder, which contains 50% dietary fiber, into the diet of type II diabetes patients for 10 days caused a significant 25% drop in blood glucose levels (Hasan and Rahman, 2016). The experimental study consisted of

40 patients who consumed fenugreek seeds for 8 weeks. Results showed a significant decrease of 13% in urinary sugar levels and a reduction of 12.2% in glycosylated hemoglobin (Khorshidian *et al.*, 2016). Furthermore, studies indicated that fenugreek seeds improved glucose tolerance by enhancing peripheral glucose utilization. Its hypoglycemic effects are attributed to its action on both insulin receptor and gastrointestinal system (Hassan *et al.*, 2020).

The presence of amino acid 4-hydroxyisoleucine in fenugreek seeds is shown to stimulate the release of insulin in response to glucose. This effect is observed in both laboratory experiments (*in vitro*) and in living organisms (*in vivo*) (Pereira *et al.*, 2019). The administration of fenugreek to diabetic mice for 6 days significantly enhanced their glucose tolerance. The liver exhibited a decrease in the activity of glycolytic enzymes whereas the kidney showed an increase in activity. This resulted in the glycolytic enzyme activity reaching a regulated level, with decrease in the activity of gluconeogenic enzymes (Kamalakkannan and Prince, 2006; Pradeep and Srinivasan, 2018). Owing to their nutraceutical properties, fenugreek seeds are recommended and incorporated into regular diet, as their safe and widespread consumption offers numerous health advantages. Hence, this natural herb offers a diverse range of health benefits.

Fenugreek, more precisely its seeds (seed powder and extract), has been investigated for its potential antidiabetic properties. Notably, double-blind placebo studies showed that fenugreek improved insulin sensitivity and glucose control (Hota *et al.*, 2024). Furthermore, a study on type 2 diabetic mice offered insightful findings. It showed that fenugreek could increase liver glycogen levels, which serve as an essential energy reservoir, while simultaneously lowering serum glucose levels (Jiang *et al.*, 2018).

Researchers investigated the antioxidant activity of fenugreek seeds and discovered some intriguing results. They discovered strong antioxidants in the extracted aqueous essence of fenugreek seeds. This extract had the remarkable capacity to scavenge dangerous radicals, acting as a cell defender and shielding it from oxidative damage (Khole *et al.*, 2014; Syeda *et al.*, 2008). Inquisitive about the seeds' potential as antioxidants, another group of scientists conducted more investigation. They discovered that extract from fenugreek seeds might prevent radical damage as well as delay lipid peroxidation. They discovered a protector of cell membranes. This observation was made in mice treated with cyclophosphamide (Bhatia *et al.*, 2006). Antioxidants in fenugreek seeds can also improve kidney functions. Researchers examined the impact of seeds on the kidneys of diabetic mice. It showed that seeds had a remarkable capacity to enhance

Table 4. Therapeutic potential of fenugreek.

Therapeutic properties	Plant part	Effects	Model	References
Antidiabetic action	Seeds (seed extract, seed powder)	Enhances glucose regulation and reduces insulin resistance	Double-blind placebo study	Hota <i>et al.</i> , 2024
		An increase in liver glycogen and reduction in serum glucose	Type 2 diabetic rat	Jiang <i>et al.</i> , 2018
Antioxidant activity	Seeds (aqueous extract)	Exhibits radical scavenging activity	Biochemical assay	Khole <i>et al.</i> , 2014; Syeda <i>et al.</i> , 2008
		Retard lipid peroxidation and enhance enzymatic antioxidant activity	Cyclo-phosphamide-treated rat	Bhatia <i>et al.</i> , 2006
Anticancer	Seeds (seed extract)	Improves kidney function	Diabetic mice	Xue <i>et al.</i> , 2011
		Demonstrates a powerful cytotoxic effect in whole-seed, compared to purified compound	Prostate, pancreatic, and breast CCLs	Al-Timimi, 2019; Shabbeer <i>et al.</i> , 2009
		Fenugreek extracts exhibit selective cytotoxicity	T cell lymphoma	Alsemari <i>et al.</i> , 2014
Anti-inflammatory	Seeds and leaves	Anti-inflammatory properties, and humoral immune stimulation	Ethanollic fenugreek extract-treated mice	Almatroodi <i>et al.</i> , 2021
Hypoglycemic	Seeds	Control Glycemic index among diabetic patients (type 2)	Type II diabetic patients	Snehkata and Payal, 2012
		Fenugreek enhances peripheral glucose tolerance and utilization.	Non-insulin-dependent diabetic patients	ElNour <i>et al.</i> , 2015
Hypocholesterolemic	Seeds	Reduced triglycerides, total cholesterol, and LDL	Patients with newly discovered type 2 diabetes are treated with seed powder	Geberemeskel <i>et al.</i> , 2019
		Lower total cholesterol while higher HDL levels	Mice with diabetes mellitus	Xue <i>et al.</i> , 2007
Antimicrobial	Seeds, leaves, and stem	Exhibit anti-bacterial activity in methanolic extracts, while the aqueous extracts show no effect The magnitude of the effects varies depending on the types of microbe and plant parts employed and extraction solvent	<i>E. coli</i> , <i>P. aeruginosa</i> , <i>B. cereus</i> , and several fungi strains were involved in diffusion	Hadi <i>et al.</i> , 2022

renal function (Xue *et al.*, 2011). Recent studies have found that fenugreek seed extracts have promising anticancer properties, particularly in case of prostate, pancreatic, and breast CCLs. Notably, these investigations suggested that whole-seed extracts have stronger cytotoxic effects than isolated compounds (Al-Timimi, 2019; Shabbeer *et al.*, 2009). Additionally, fenugreek extracts have demonstrated a specific cytotoxic impact, especially in the context of T-cell lymphoma (Alsemari *et al.*, 2014). Collectively, these results highlight the potential of seed extracts as valuable candidates for anticancer treatment. The ethanolic extract of fenugreek seeds and leaves was found to have anti-inflammatory effects and is able to promote humoral immune response in a study conducted by Almatroodi *et al.* (2021). These effects were shown in mice treated with the extract, indicating its potential as an effective all-natural treatment for reducing inflammation and boosting humoral defensive mechanisms of the immune system. The study provided important insight

in the possible benefits of fenugreek seeds in improving glycemic control in patients with type 2 diabetes (Snehkata and Payal, 2012). According to their research, fenugreek supplementation can improve individuals' peripheral glucose tolerance and utilization. This is a significant result because the control of blood sugar levels depends on peripheral glucose tolerance and utilization. A recent study explored the hypoglycemic effects of fenugreek seeds, and focused on how it affected patients with type 2 diabetes not dependent on insulin. According to the study, fenugreek may have a positive impact on glycemic control in this particular group of patients. The study filled a crucial gap in the field of diabetes research and clinical management by focusing on non-insulin-dependent diabetic individuals (ElNour *et al.*, 2015).

Fenugreek seeds also have cholesterol-lowering (hypocholesterolemic) potential, particularly for patients with diabetes, especially type 2 diabetes. A study conducted

by Geberemeskel *et al.* (2019) showed that seed powder significantly decreased levels of triglycerides, total cholesterol, and low-density lipoprotein (LDL) cholesterol in type 2 diabetes patients. A study conducted by Xue *et al.* (2007), investigating the impact of seeds on the cholesterol levels of diabetic mice, showed a decrease in total cholesterol levels and an increase in high-density lipoprotein (HDL) cholesterol, also known as good cholesterol. Many findings provide a comprehensive overview of the antimicrobial potential of complete fenugreek plant (seeds, stems, and leaves). A study conducted by Hadi *et al.* (2022) indicates that methanolic extracts from different parts of fenugreek exhibited antimicrobial effects. Aqueous extracts, on the other hand, which use water as a solvent, don't have any antibacterial properties.

Allelopathic potential of fenugreek

Plants, like humans and animals, encounter various forms of competition within their ecosystems. However, unlike mobile organisms, plants are rooted in place and cannot actively avoid or manipulate their competitive environment. As a result, many plants develop a strategy to deal with these limitations by producing secondary metabolites. Certain compounds found in fenugreek possess allelopathic properties, which means they can inhibit the growth of surrounding plants (Yadav *et al.*, 2019). These compounds offer effective weed control in intercropping systems and possess herbicidal potential, making them promising candidates for the development of new herbicides or as templates for such products (Malunekar *et al.*, 2022). A recent study has reported that different crops, specifically soybean and sesame, exhibit varying responses to different concentrations of fenugreek extract. Fenugreek demonstrated an allelopathic effect, causing a reduction in both seed germination and number of germinated seeds. A significant decrease in germination proportion was observed with increase in the concentration of fenugreek extract from 0% to 64%. In the case of soybean, the leaf extract of fenugreek had the most pronounced reduction in germination percentage and rate, with respective figures of 74% and 91%, while the pod extract had the least impact, showing a respective reduction of 9% and 25% in germination percentage and rate.

Interestingly, soybean germination did not exhibit a consistent trend with different extracts from stem and the entire fenugreek plant. For sesame, the stem and seed extracts of fenugreek had the highest and lowest inhibition effects on germination percentage. The seed and pod extracts of fenugreek had the most substantial negative effect on germination rate. In the case of pigweed, as the fenugreek extract concentration increased from 0% to 64%, the stem and seed extracts had the most significant

decrease in both germination percentage and rate, while the pod and whole plant extracts showed the lowest allelopathic effects. Overall, seeds, pods, and the entire fenugreek plant exhibited the most pronounced negative effects on the germination percentage and rate of velvet leaf (Azizi *et al.*, 2011). Abbas *et al.* (2019) demonstrated that the infection of *Orobanche crenata* decreased due to an allelopathic interference in parasitic life cycle during germination. The reduction in *O. crenata* infection is attributed to the inhibition of *O. crenata* seed germination caused by allelochemicals released from fenugreek roots.

Furthermore, the Fenugreek extract not only hindered seed germination but also reduced seedling growth across various species. In all the species studied, as the extract concentration from different parts of fenugreek increased from 8% to 64%, a noticeable decrease was observed in both radicle and plumule growth. Notably, extracts from different parts of fenugreek exhibited a stimulatory effect at lower concentrations and an inhibitory effect at higher concentrations for all species. These findings underscore that the response of crop and weed species to allelopathic substances is influenced by the species' characteristics and the number of allelopathic substances present in different parts of fenugreek (Perisoara *et al.*, 2023). It is reported that seed and leaf extracts were found to exhibit the most pronounced allelopathic effects. Fenugreek species exhibit weedicide, insecticidal, and antifungal properties, indicating their potential as agents for controlling weeds, insects, and fungal pathogens (Kandhare *et al.*, 2022). However, additional experimental studies are required to explore the practical applications of using fenugreek as a weed-suppressing plant within intercropping systems.

Adverse effects of fenugreek

Although fenugreek has a history of being deemed safe and well-tolerated, there have been reported instances of adverse effects associated with its usage (Figure 3). It is advisable to exercise caution when using fenugreek, particularly in individuals with known allergies to fenugreek or chickpeas, as there is a potential risk of cross-reactivity (Athari *et al.*, 2021). There have been reports indicating hypersensitivity reactions associated with the inhalation of fenugreek seed powder. Symptoms such as wheezing, fainting, and rhinorrhea are reported in some cases as well as facial angioedema after the application of a topical fenugreek paste for dandruff (Wijaya *et al.*, 2013). Owing to its potential to cause hypoglycemia, it is suggested to monitor blood glucose levels in case of initiating fenugreek supplementation (Mohamed *et al.*, 2019). Furthermore, studies have investigated the effects of fenugreek on hematopoietic stem cells in the bone

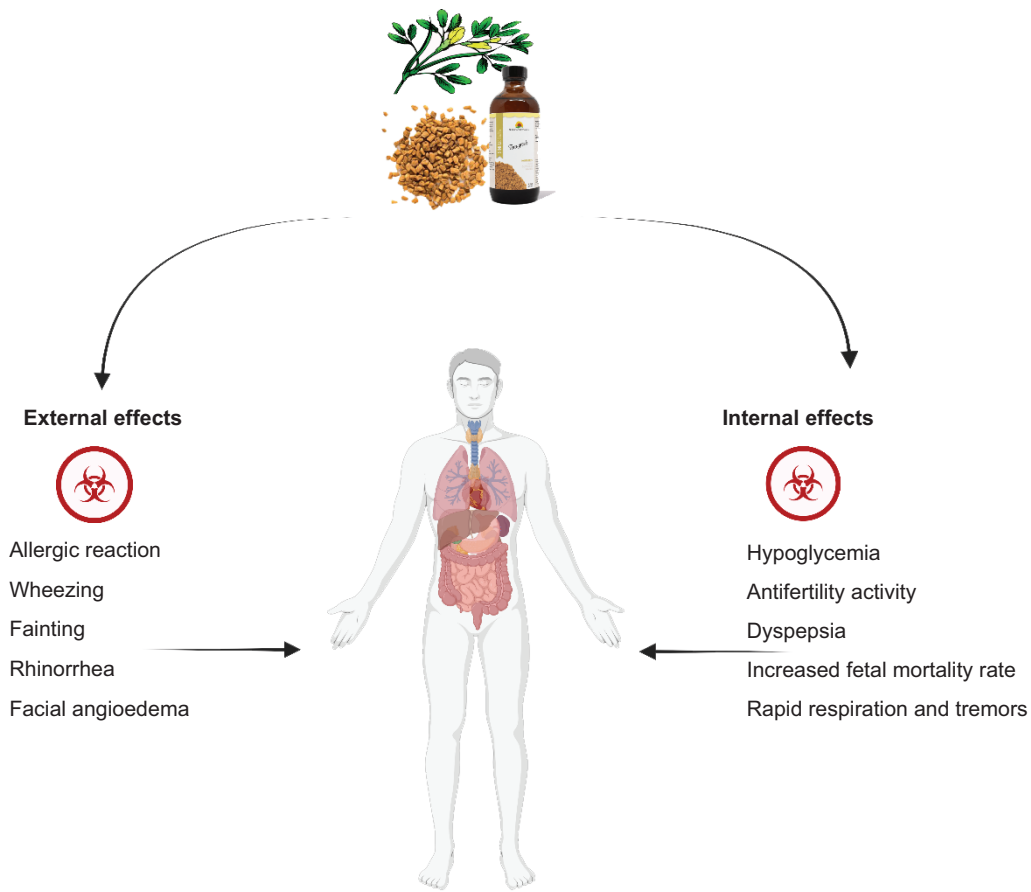


Figure 3. Fenugreek, a double-edge sword: external (e.g., skin reactions) and internal (e.g., digestive issues) adverse effects.

marrow. Findings indicate that high doses of fenugreek with teratogenic properties can result in reduced severity of bone marrow cell proliferation and an increased rate of fetal mortality (Araae *et al.*, 2009). It was reported that rabbits fed with diets containing 30% fenugreek exhibited potential antifertility activity (Athari *et al.*, 2021). Studies reported cases of dyspepsia and mild abdominal distention while using large doses of fenugreek seeds. Furthermore, the administration of high doses of aqueous extract of fenugreek was associated with mild central nervous system stimulation, rapid respiration, and tremors (Ouzir *et al.*, 2016).

Potential economic benefits of investing in fenugreek research

Fenugreek holds significant economic importance as both culinary ingredient and medicinal herb, which continues to grow in native areas. India stands out as the world's foremost fenugreek producer, contributing to 80% of total global production (Arshad *et al.*, 2022). In 2022, according to the Food and Agriculture Organization of

the United Nations (FAO, 2022), the worldwide fenugreek production was 350,000 metric tonnes, and it was grown across 100,000 hectares of land. It was also reported that fenugreek seeds yield ranged from 500 to 3,320 kg/hectare, with an economically viable yield of 1,800 kg/hectare (Nahar *et al.*, 2022). In addition to its positive impact on health, it provides an economic benefit, particularly in its ability to lower blood glucose levels. According to FAO data (2022), India cultivated 100,000 hectares and yielded 180,000 tonnes of fenugreek, indicating a consistent upward trend in production. In 2020, India's fenugreek output stood at 170,000 tonnes, and in 2019, it amounted to 160,000 tonnes. Meanwhile, in Morocco, fenugreek holds a significant place within the socioeconomic framework (Brogi *et al.*, 2019). Bath, England, reported a seed yield of 3,700 kg/hectare, while Morocco recorded a yield of 1,000 kg/hectare. The leading fenugreek exporting nations include India, France, Lebanon, Egypt, and Argentina (Hilles and Mahmood, 2021). It has a significant effect on soil renovators in Asia and Africa (Aasim *et al.*, 2018). Its seeds contain diosgenin, a component used to make base for oral contraceptives. It is high in protein and fixed fats, which could contribute

economically to the world's growing population by aiding in birth control and simultaneously supplying more food. Additionally, fenugreek is a plant that contributes to the world's food supply, lessens hunger, and enhances health-care by fixing atmospheric nitrogen. Consequently, the future of fenugreek appears to hold promise and numerous advantages.

Research Gap

While fenugreek has been extensively studied by medical science for its potential health benefits, it is important to note that our understanding of this medicinal plant is still limited and there is much more to discover. Fenugreek exhibits a wide distribution across different geographical regions, suggesting the presence of significant genotypic variability. Furthermore, being the least bred (artificial selection) crop, there is a possibility to have a multiple and potential allelic system against environmental stresses. In conclusion, despite the topics covered in this review, numerous issues about the biology, phytochemistry, allelopathic potential, and pharmacology of fenugreek still need to be investigated, and randomized clinical trials are required to support the therapeutic properties of nutritional components. The economic, industrial, and medical values of these natural resources could be enhanced in the future by all these factors. To unlock the full potential of fenugreek, it is crucial to conduct comprehensive genomic and agronomic characterizations, including clustering analyses. The future research would aid in identifying potential genes that could be used to develop new varieties of fenugreek with a particular focus on developing abiotic stress tolerance. Moreover, it is essential to explore and promote fenugreek as a fodder crop, particularly in arid agricultural systems, to harness its benefits in such challenging environments.

Conclusion

Fenugreek has a long-standing tradition of being consumed as a medicinal plant and is widely recognized for its benefits to human health. Its nutritional value and diverse profile of biologically active compounds are acknowledged by medical science. Moreover, fenugreek exhibits adaptability to various climatic regions and marginal lands, making it a valuable addition to agricultural systems. However, despite its potential, limited progress is made in terms of crop improvement, specifically in utilizing biotechnological approaches for breeding. Consequently, a significant gap exists, particularly in varietal development and biotechnologically assisted breeding methods. Further research and investigations are required to isolate bioactive compounds from fenugreek's crude extracts, potentially leading to drug

development. This avenue holds promising prospects in the field of natural products for disease treatment and can yield fruitful outcomes for the benefit of humanity.

Availability of Data and Materials

Data sharing is not applicable to this review as no new data were created or analyzed in this study.

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Author Contributions

Sundas Hina and Saddam Mustafa: writing—original draft preparation, software, figure preparation, and writing—review and editing. Ahmed Mahmoud Ismail, Shahid Mahmood, Amal Matar, Alaa S. Alharbi, and Hoda Ali Farag Saleh: validation, formal analysis, resources, project administration, visualization, and writing—review and editing. Wupeng Ge: conceptualization, supervision, writing—review and editing.

Conflict of Interest

The authors declared no competing financial interest.

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