PHARMACIA

Pharmacia 72: 1–13
DOI 10.3897/pharmacia.72.e147050

Review Article

Chemical variability of fenugreek essential oil

Vanya Nalbantova[1,2], Cedric Delattre[3,4], Niko Benbassat[1,2]

1 *Department of Pharmacognosy and Pharmaceutical Chemistry, Faculty of Pharmacy, Medical University of Plovdiv, 4002 Plovdiv, Bulgaria*
2 *Research Institute, Medical University of Plovdiv, 4002 Plovdiv, Bulgaria*
3 *Université Clermont Auvergne, Clermont Auvergne INP, CNRS, Institut Pascal, 63000 Clermont-Ferrand, France*
4 *Institut Universitaire de France (IUF), 1 rue Descartes, 75005 Paris, France*

Corresponding author: Vanya Nalbantova (vanya.nalbantova@mu-plovdiv.bg)

Received 17 January 2025 ♦ **Accepted** 12 February 2025 ♦ **Published** 14 March 2025

Citation: Nalbantova V, Delattre C, Benbassat N (2025) Chemical variability of fenugreek essential oil. Pharmacia 72: 1–13. https://doi.org/10.3897/pharmacia.72.e147050

Abstract

Fenugreek (*Trigonella foenum-graecum* L.) is a famous dicotyledonous aromatic medicinal plant that belongs to the Fabaceae family. The numerous biological activities it exhibits are attributed to the rich variety of primary and secondary metabolites it contains, among them essential oil. It is present not only in the seeds but also in the aerial parts of the plant. Essential oil's chemical composition differs according to various factors. The methods used for essential oil isolation, such as hydrodistillation, steam distillation, liquid-liquid extraction, solid-phase micro-extraction, static headspace solid-phase microextraction, solvent extraction, secondary distillation, steam distillation of oleoresin, and headspace vacuum entrainment of seeds, have a great impact on its composition. In addition, the time and place of harvest, the maturity of the plant and soil treatment with biofertilizers, and seed pre-treatment such as germination, baking, or microwave heating can also have an influence.

Keywords

aerial part, essential oil, fenugreek, seeds, *Trigonella foenum-graecum* L.

Introduction

Fenugreek (*Trigonella foenum-graecum* L.) is one of the earliest known medicinal plants belonging to the Fabaceae family. It is an annual dicotyledonous aromatic plant, with the Latin name 'Trigonella,' meaning 'little triangle,' a reference to its yellowish-white, triangular-shaped flowers. The name literally means ‚Greek hay,' highlighting its historical significance as a forage crop alongside the widely used alfalfa (*Medicago sativa* L.) (Ahmad et al. 2016; Basu et al. 2019; Ruwali et al. 2022).

The species originates from the Mediterranean region, the Middle East, South Asia, and North Africa. Nowadays, it is cultivated practically all over the world—China, India, Turkey, Pakistan, and Egypt. India is considered the leading producer of fenugreek in the world, where the plant is known as 'Methi' (Srinivasan 2006; Hasan et al. 2015; Shukla et al. 2017; Rashid et al. 2018; Basu et al. 2019; Sarwar et al. 2019; Tewari et al. 2024).

Trigonella foenum-graecum L. seeds measure approximately 5 mm in length and 3 mm in width, are hard, rectangular, slightly flattened, and elongated rhomboid in shape. The immature seeds` color is green, which changes to yellowish brown, golden brown, or thick brown after they mature. They are formed by a yellow solid central embryo, which is enclosed by a large, white, semi-transparent, horny endosperm. Due to their specific pungent odor and slightly bittersweet taste, resembling the aroma of maple syrup, they are used as a flavoring agent in various food products.

Its leaves and seeds are widely used all over the world, not only as a remedy but also as a condiment. They are one of the main components in the world-famous Indian spice "Curry" as well as the traditional Bulgarian condiment 'Sharena sol' (Hasan et al. 2015; Khorshidian et al. 2016; Mandal and DebMandal 2016; Basu et al. 2019).

Fenugreek seeds possess numerous biological activities and applications, which are attributed to their great variety of primary and secondary metabolites. They are a rich source of carbohydrates, in particular galactomannan. Its structure is of linear β-mannopyranose residues with (1→4) linkages to which single α-D-galactopyranose groups are attached at position O-6 of the D-mannopyranosyl backbone, where the galactose: mannose ratio is 1:1 (Nayak et al. 2015; Zhang et al. 2019; Liu et al. 2022). Furthermore, the content of fatty acids isolated from nonpolar fractions of the species ranged from 15.2% to 16.9%, depending on the species, while the amount of monounsaturated fatty acids from 13.0% to 17.5%. The ratio of n-6 to n-3 fatty acids ranges between 2.1 and 2.7, making fenugreek seeds a good source of polyunsaturated fatty acids (Ciftci et al. 2011). The seeds are well known for their content of steroidal compounds, with spirostanol and furostanol types identified from the saponin group (Król-Kogus et al. 2018; Zhang et al. 2020). In addition, 1 to 2% flavonoids, with main aglycones apigenin and luteolin, have been identified (Wang et al. 2017). Among the alkaloid fraction contained in the plant, the major representative is trigonelline, which has been initially isolated from *Trigonella foenum-graecum* seeds (Srinivasa and Naidu 2021; Singh et al. 2022).

The study was conducted in the following databases: Google Scholar and PubMed, and collected results over the last 40 years. The aim of the present work is to summarize and evaluate the current knowledge of fenugreek essential oil isolated from its seeds and aerial parts, as well as the various factors affecting its component composition.

Essential oils

Essential oils (EOs), as defined by the International Organization for the Standardization of Essential Oils and the European Pharmacopoeia, are extracted from raw plant materials using hydrodistillation, steam distillation, dry distillation, or appropriate mechanical methods for citrus. Due to their thermolabile nature, citrus oils are typically obtained by processes without heating (cold pressing).

The term ‚essential oil' does not encompass other aromatic products derived through methods such as solvent extraction, including absolutes and concretes, microwave extraction, or supercritical fluid extraction (Zuzarte and Salgueiro 2015).

The EOs are usually colorless and possess a strong flavor. They are insoluble in water but well soluble in organic solvents. They are intricate multi-component mixtures, which can contain more than 200 compounds. Monoterpenes, sesquiterpenes, and their oxygenated derivatives, including alcohols, aldehydes, and esters, constitute the majority (90–95%) of the volatile fraction of these oils. Phenylpropanoids, along with nitrogen and sulfur derivatives, are also occasionally present. The non-volatile component of the oils, comprising up to 10% of the total weight, includes hydrocarbons, fatty acids, waxes, sterols, carotenoids, and flavonoids (Zuzarte and Salgueiro 2015; Hanif et al. 2019; Todorova et al. 2023; Ivanova et al. 2024b, 2024a; Pashova et al. 2024).

Extraction methods

There is a variety of methods known for isolating EOs. Some authors have classified them into two groups—conventional and unconventional (Kant and Kumar 2022). Traditional methods include steam distillation, hydrodistillation, hydrodiffusion, and solvent extraction. Microwave extraction without solvent, supercritical fluid extraction, subcritical fluid extraction, ultrasound-assisted extraction, and microwave extraction without solvent may be classified as so-named 'advanced' or unconventional methods.

Each of these approaches is characterized by some advantages and disadvantages. Conventional methods consume more time and, consequently, a greater amount of energy to heat. In addition, lower yields and efficiencies are observed compared to non-conventional methods (Kant and Kumar 2022).

Therefore, selecting an appropriate method for essential oil isolation depends on several factors, such as the type of plant material, the harvesting period, the influence of the environment, etc.

Fenugreek seed essential oil

Fenugreek essential oil's composition is shaped by a variety of factors. The bioactive components and their amount of essential oil could be significantly influenced not only by the isolation method but also by the pretreatment of the seeds (Table 1).

Rajhi et al., who subjected fenugreek seeds to pretreatments such as germination, roasting, boiling, and microwave heating while isolating EO by solid-phase microextraction, observed significant differences in its chemical composition. They established a predominance of non-terpene derivatives in all investigated samples. Phenylpropane derivatives were detected in both treated and raw seeds, though in small amounts. Sesquiterpene representatives were only observed in the raw and microwaved seeds and were not detected in the other samples. In microwave-heated seeds, the presence of nitrogen-containing compounds (2,5-dimethylpyrazine) was detected to be about 17 times higher compared to raw seeds. Regarding the identification percentage of oxygenated monoterpenes (1,8-cineole, dihydrocitronellol, carvone, and carvacrol) and monoterpene hydrocarbons (limonene, methyl eugenol), an increase was observed due to roasting, boiling, and germination processes (Rajhi et al. 2022).

Table 1. Chemical composition of fenugreek seed essential oil.

№	Compound	Amount, %	Extraction method	Sources
		Monoterpenes		
1.	Linalool	-	LLE	(Blank et al. 1997)
2.	*β*-Linalool	0.32	SD	(Nalbantova et al. 2023)
3.	*α*-Ocimene	5.23	HD	(Naimi et al. 2022)
4.	Geranial	5	-	(Al-Tamimi et al. 2016)
		4.81	HD	(Hamden et al. 2011)
5.	Neral (*cis*-Citral)	17	-	(Al-Tamimi et al. 2016)
6.	*γ*-Terpinen	2.08	HD	(Hamden et al. 2011)
7.	*α*-Terpineol	2.77	HD	(Hamden et al. 2011)
8.	*α*-Pinene	2	-	(Al-Tamimi et al. 2016)
		2.64	HD	(Hamden et al. 2011)
9.	*β*-Pinene	15	-	(Al-Tamimi et al. 2016)
		15.05	HD	(Hamden et al. 2011)
10.	Camphor	17	-	(Al-Tamimi et al. 2016)
		16.32	HD	(Hamden et al. 2011)
		0.44	SD	(Nalbantova et al. 2023)
		-	STD	(Girardon et al. 1985)
11.	*δ*-3-Carene	0.01	SE/MeOH	(Mebazaa et al. 2009)
		0.02	SE/EtOH	(Mebazaa et al. 2009)
		0.36	SHS-SPME	(Mebazaa et al. 2009)
12.	Limonene	1.54	SHS-SPME	(Mebazaa et al. 2009)
13.	*p*-Cymene	0.46	SHS-SPME	(Mebazaa et al. 2009)
14.	Menthol	0.94/1.06	SD	(Nalbantova et al. 2023)
15.	1,8-Cineol (Cineol)	-	STD	(Girardon et al. 1985; Naimi et al. 2022)
16.	Dihydroactinidiolide	0.01	SE/MeOH	(Mebazaa et al. 2009)
		0.17	SHS-SPME	(Mebazaa et al. 2009)
		-	HSVE	Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
		Sesquiterpenes		
17.	*γ*-Cadinol	-	STD	(Kahaleq et al. 2015)
18.	*α*-Bisabolol	-	STD	(Kahaleq et al. 2015)
		0.67	SD	(Nalbantova et al. 2023)
19.	*α*-Endesmol	-	STD	(Kahaleq et al. 2015)
20.	Farnesol	-	STD	(Kahaleq et al. 2015)
21.	(E,Z)-*α*-Farnesene	1 ± 0.02	SPME	(Rajhi et al. 2022)
22.	Cubenol	29.88/38.17	SD	(Nalbantova et al. 2023)
23.	*epi*-Cubenol	28.78	HD	(Naimi et al. 2022)
24.	1-*epi*-Cubenol	1.74	SE/MeOH	(Mebazaa et al. 2009)
		1.79	SE/MeOH	(Mebazaa et al. 2009)
		3.26	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		2.32	SHS-SPME	(Mebazaa et al. 2009)
25.	Caryophyllene	15	-	(Al-Tamimi et al. 2016)
26.	*β*-Caryophyllene	14.63	HD	(Hamden et al. 2011)
27.	Murolan-3,9(11)-diene-10-peroxy	2.95	HD	(Moniruzzaman et al. 2015)
28.	Calamenene	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
29.	*cis*-Calamenene	0.16	SE/MeOH	(Mebazaa et al. 2009)
		0.04	SE/EtOH	(Mebazaa et al. 2009)
		0.03	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		1.86	HD	(Moniruzzaman et al. 2015)
		0.04	SHS-SPME	(Mebazaa et al. 2009)
30.	*α*-Muurolene	0.03	SE/MeOH	(Mebazaa et al. 2009)
		0.01	SE/EtOH	(Mebazaa et al. 2009)
		0.07	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.4	SHS-SPME	(Mebazaa et al. 2009)
		-	HSVE	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
31.	*ε*-Muurolene	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
32.	*γ*-Muurolene	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)

№	Compound	Amount, %	Extraction method	Sources
33.	*α*-Copaene	0.12	SHS-SPME	(Mebazaa et al. 2009)
34.	*γ*-Cadinene	0.02	SHS-SPME	(Mebazaa et al. 2009)
		0.31	SD	(Nalbantova et al. 2023)
35.	*δ*-Elemene	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
36.	*β*-Elemene	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
37.	*γ*-Elemene	-	HSVE	(Girardon et al. 1985)
38.	*α*-Selinene	4.5	-	(Al-Tamimi et al. 2016)
		4.04	HD	(Hamden et al. 2011)
39.	*β*-Selinene	-	HSVE	(Girardon et al. 1985)
	Aromatic hydrocarbons			
40.	Naphthalene	6.50 ± 1.11	SPME	(Rajhi et al. 2022)
		0.02	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.2	SHS-SPME	(Mebazaa et al. 2009)
41.	(*E*)-Anethole	3.80 ± 1.06	SPME	(Rajhi et al. 2022)
42.	*m*-Xylene	0.03	SE/EtOH	(Mebazaa et al. 2009)
		0.18	SHS-SPME	(Mebazaa et al. 2009)
	Phenols			
43.	Eugenol	-	LLE	(Blank et al. 1997)
		0.01	SE/MeOH	(Mebazaa et al. 2009)
		0.20/0.19	SD	(Nalbantova et al. 2023)
		tr	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
44.	Methyleugenol	0.21	SD	(Nalbantova et al. 2023)
45.	*p*-Vinylguaiacol	0.06	SE/MeOH	(Mebazaa et al. 2009)
46.	2,4-*Bis*(1,1-Dimethylethyl)-phenol	tr	SE/MeOH	(Mebazaa et al. 2009)
		tr	SE/EtOH	(Mebazaa et al. 2009)
		tr	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.01	SHS-SPME	(Mebazaa et al. 2009)
47.	Phenol	0.02	SHS-SPME	(Mebazaa et al. 2009)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
48.	Carvacrol	0.81	SD	(Nalbantova et al. 2023)
49.	Thymol	9.56	HD	(Naimi et al. 2022)
		0.21	SD	(Nalbantova et al. 2023)
		-	STD	(Girardon et al. 1985)
	Aldehydes			
50.	Diacetyl	-	LLE	(Blank et al. 1997)
51.	*α*-Campholenal	2.63	HD	(Hamden et al. 2011)
52.	Nonanal	15.3 ± 1.08	SPME	(Rajhi et al. 2022)
53.	Decanal	36.50 ± 2.03	SPME	(Rajhi et al. 2022)
54.	Undecanal	2.20 ± 0.98	SPME	(Rajhi et al. 2022)
55.	Dodecanal	1.40 ± 0.12	SPME	(Rajhi et al. 2022)
56.	*p*-Anisaldehyde	0.7 ± 0.01	SPME	(Rajhi et al. 2022)
57.	*2*-Methyl-2-butenal	0.32	SE/MeOH	(Mebazaa et al. 2009)
		0.2	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		3.88	SHS-SPME	(Mebazaa et al. 2009)
58.	*5*-Methylfurfural	0.01	SE/MeOH	(Mebazaa et al. 2009)
59.	*2*-Butyl-2-octenal	0.03	SE/EtOH	(Mebazaa et al. 2009)
		0.15	SHS-SPME	(Mebazaa et al. 2009)
60.	*p*-Cuminaldehyde	1.19	SD	(Nalbantova et al. 2023)
61.	2,4-Decadienal	tr	SD	(Nalbantova et al. 2023)
62.	*n*-Heptanal	-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
	Ketones			
63.	1-Octene-3-one		LLE	(Blank et al. 1997)
64.	3-Octen-2-one	4.32	HD	(Hamden et al. 2011)
		tr	SD	(Nalbantova et al. 2023)
		0.42	SHS-SPME	(Mebazaa et al. 2009)
		-	STD	(Girardon et al. 1985)
		-	STDOR	Girardon et al. 1985)

№	Compound	Amount, %	Extraction method	Sources
65.	*E*,*E*-3,5-Octadien-2-one	0.51	SHS-SPME	(Mebazaa et al. 2009)
		0.47	SD	(Nalbantova et al. 2023)
66.	*E*,*Z*-3,5-Octadien-2-one	0.36	SHS-SPME	(Mebazaa et al. 2009)
67.	6-Methyl-5-hepten-2-one	4.48	HD	(Hamden et al. 2011)
		tr	SE/MeOH	(Mebazaa et al. 2009)
		tr	SE/EtOH	(Mebazaa et al. 2009)
		tr	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.19	SHS-SPME	(Mebazaa et al. 2009)
68.	3-Amino-4,5-dimethyl- 3 ,4-dihydro-2(5H)-fyranone	-	LLE	(Blank et al. 1997)
69.	5-Fluoro-1,1,3,3-tetramethyl-1,3-dihydroisobenzofuran	3.54	HD	(Moniruzzaman et al. 2015)
70.	Sotolone	-	LLE	(Blank et al. 1997)
	[or 3-Hydroxy-4,5-dimethyl-2(5H)-furanon]	0.09	SE/MeOH	(Mebazaa et al. 2009)
		0.06	SE/EtOH	(Mebazaa et al. 2009)
		0.02	SHS-SPME	(Mebazaa et al. 2009)
71.	2-Pentadecanone, 6,10,14-trimethyl	1.82	HD	(Moniruzzaman et al. 2015)
72.	(*E*)-Geranylacetone	9.50 ± 2.11	SPME	(Rajhi et al. 2022)
73.	2-Heptanone	0.01	SE/MeOH	(Mebazaa et al. 2009)
		0.03	SE/EtOH	(Mebazaa et al. 2009)
		0.25	SHS-SPME	(Mebazaa et al. 2009)
		-	STD	(Girardon et al. 1985)
74.	2,5-Dimethyl-4-hydroxy-3(2H)-furanone	0.2	SE/MeOH	(Mebazaa et al. 2009)
		0.02	SE/EtOH	(Mebazaa et al. 2009)
75.	Pantolactone	0.03	SHS-SPME	(Mebazaa et al. 2009)
	[or 4,5-dihydro-4,4-imethyl-3-hydroxy-2(3H)-furanone]	0.1	SE/MeOH	(Mebazaa et al. 2009)
		0.08	SE/EtOH	(Mebazaa et al. 2009)
76.	Menthone	0.14	SHS-SPME	(Mebazaa et al. 2009)
77.	Carvone	0.12	SHS-SPME	(Mebazaa et al. 2009)
		tr	SD	(Nalbantova et al. 2023)
78.	*α*-Ionone	0.01	SHS-SPME	(Mebazaa et al. 2009)
		0.24/0.17	SD	(Nalbantova et al. 2023)
79.	*β*-Ionone	-	STD	(Girardon et al. 1985)
80.	Trans-geranyl-acetone	0.01	SHS-SPME	(Mebazaa et al. 2009)
81.	Isophorone	0.20/0.25	SD	(Nalbantova et al. 2023)
82.	*γ*-*n*-Amylbutyrolactone	1.78/3.59	SD	(Nalbantova et al. 2023)
83.	Geranylacetone	0.28/0.45	SD	(Nalbantova et al. 2023)
84.	5-Methyl-*δ*-caprolactone	-	HSVE	(Girardon et al. 1985)
85.	*γ*-Nonalactone	0.04	SHS-SPME	(Mebazaa et al. 2009)
		-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
		Acids		
86.	Acetic acid		LLE	(Blank et al. 1997)
		1.14	SE/MeOH	(Mebazaa et al. 2009)
		0.11	SE/EtOH	(Mebazaa et al. 2009)
		0.85	SHS-SPME	(Mebazaa et al. 2009)
87.	Propanoic acid	0.03	SE/MeOH	(Mebazaa et al. 2009)
		0.16	SHS-SPME	(Mebazaa et al. 2009)
88.	2-Methylbutyric acid	0.15	SD	(Nalbantova et al. 2023)
89.	Butanoic acid	-	LLE	(Blank et al. 1997)
90.	Decanoic acid	0.05	SHS-SPME	(Mebazaa et al. 2009)
		tr	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
91.	Valeric acid	0.05	SHS-SPME	(Mebazaa et al. 2009)
92.	Isovaleric acid	-	LLE	(Blank et al. 1997)
93.	Benzoic acid	0.07	SHS-SPME	(Mebazaa et al. 2009)
94.	Caproic acid	-	LLE	(Blank et al. 1997)
		0.59	SE/MeOH	(Mebazaa et al. 2009)
		0.48	SE/EtOH	(Mebazaa et al. 2009)
		0.13	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.71	SHS-SPME	(Mebazaa et al. 2009)
95.	Non-anoic acid	0.06	SE/MeOH	(Mebazaa et al. 2009)
		0.07	SE/EtOH	(Mebazaa et al. 2009)
		0.08	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.07	SHS-SPME	(Mebazaa et al. 2009)

№	Compound	Amount, %	Extraction method	Sources
96.	Dodecanoic acid	0.56	SHS-SPME	(Mebazaa et al. 2009)
		tr	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
97.	Tetradecanoic acid	0.34	SE/MeOH	(Mebazaa et al. 2009)
		0.25	SE/EtOH	(Mebazaa et al. 2009)
		0.38	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		1.21	SHS-SPME	(Mebazaa et al. 2009)
		0.4	SD	(Nalbantova et al. 2023)
98.	Pentadecanoic acid	tr	SE/MeOH	(Mebazaa et al. 2009)
		0.23	SE/EtOH	(Mebazaa et al. 2009)
		tr	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.91	SHS-SPME	(Mebazaa et al. 2009)
		0.77	SD	(Nalbantova et al. 2023)
99.	Linoleic acid	10.35	SE/MeOH	(Mebazaa et al. 2009)
		15.95	SE/EtOH	(Mebazaa et al. 2009)
		22.8	SE/CH_2Cl_2	(Mebazaa et al. 2009)
100.	Linolenic acid	3.18	SE/MeOH	(Mebazaa et al. 2009)
		4.42	SE/EtOH	(Mebazaa et al. 2009)
		5.62	SE/CH_2Cl_2	(Mebazaa et al. 2009)
101.	Oleic acid	3.69	SE/MeOH	(Mebazaa et al. 2009)
		6.97	SE/EtOH	(Mebazaa et al. 2009)
		8.76	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		1.61	SHS-SPME	(Mebazaa et al. 2009)
102.	Palmitic acid	15.07	HD	(Naimi et al. 2022)
		2.75/0.90	SD	(Nalbantova et al. 2023)
103.	Hexadecanoic acid	5.7	SE/MeOH	(Mebazaa et al. 2009)
		9.35	SE/EtOH	(Mebazaa et al. 2009)
		14.1	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		2.1	SHS-SPME	(Mebazaa et al. 2009)
104.	Heptadecanoic acid	0.14	SE/MeOH	(Mebazaa et al. 2009)
		0.64	SE/EtOH	(Mebazaa et al. 2009)
		0.73	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
105.	Hexadecanoic acid, methyl ester	18.81	HD	(Moniruzzaman et al. 2015)
106.	Hexadecanoic acid, ethyl ester	2.84	HD	(Moniruzzaman et al. 2015)
107.	6-Octadecenoic acid	1.14	HD	(Moniruzzaman et al. 2015)
108.	Octadecenoic acid	1.06	SE/MeOH	(Mebazaa et al. 2009)
		3.02	SE/EtOH	(Mebazaa et al. 2009)
		3.33	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		1.19	SHS-SPME	(Mebazaa et al. 2009)
109.	Octadecanoic acid, methyl ester	3,28	HD	(Moniruzzaman et al. 2015)
110.	Oxiraneoctanoic acid, 3-octyl-, methyl ester, cis-	3,05	HD	(Moniruzzaman et al. 2015)
		Alcohols		
111.	2-Ethylhexanol	6.32	HD	(Naimi et al. 2022)
112.	1-Nonanol	5.90 ± 1.01	SPME	(Rajhi et al. 2022)
113.	1-Decanol	1.00 ± 0.01	SPME	(Rajhi et al. 2022)
		tr	SD	(Nalbantova et al. 2023)
114.	Furfuryl alcohol	0.1	SE/MeOH	(Mebazaa et al. 2009)
115.	2-Methyl-2-buten-1-ol	3.11	SHS-SPME	(Mebazaa et al. 2009)
116.	6-Methyl-5-hepten-2-ol	0.58	SHS-SPME	(Mebazaa et al. 2009)
117.	Benzyl alcohol	0.04	SHS-SPME	(Mebazaa et al. 2009)
118.	2-Phenylethyl alcohol	0.06	SHS-SPME	(Mebazaa et al. 2009)
119.	Nerol	0.16	SD	(Nalbantova et al. 2023)
120.	*p*-Cymen-7-ol	2.66	SD	(Nalbantova et al. 2023)
121.	Lauric acid	0.97/2.04	SD	(Nalbantova et al. 2023)
122.	*n*-Cetyl alcohol	0.82	SD	(Nalbantova et al. 2023)
123.	1-Octadecanol	0.82	SD	(Nalbantova et al. 2023)
124.	Phytol	1.14/0.29	SD	(Nalbantova et al. 2023)
125.	*n*-Hexanol	-	HSVE	(Girardon et al. 1985)
			STD	(Girardon et al. 1985)
			STDOR	(Girardon et al. 1985)

№	Compound	Amount, %	Extraction method	Sources
	Nitrogen compounds			
126.	Pyridine	0.16	SE/MeOH	(Mebazaa et al. 2009)
		0.03	SE/EtOH	(Mebazaa et al. 2009)
127.	Diphenylamine	-	STD	(Girardon et al. 1985)
128.	3-Isobuty-2-methoxypyrazine	-	LLE	(Blank et al. 1997)
129.	3-Isopropyl-2-methoxypyrazine	-	LLE	(Blank et al. 1997)
130.	2,3-Dimethylpyrazine	0.03	SE/MeOH	(Mebazaa et al. 2009)
		0.01	SE/CH_2Cl_2	(Mebazaa et al. 2009)
131.	2,5-Dimethylpyrazine	7	-	(Al-Tamimi et al. 2016)
		6,14	HD	(Hamden et al. 2011)
132.	2-Ethylpyrazine	0.26	SE/MeOH	(Mebazaa et al. 2009)
133.	2-Ethyl-6-methylpyrazine	0.02	SE/MeOH	(Mebazaa et al. 2009)
134.	Trimethylpyrazine	0.07	SE/MeOH	(Mebazaa et al. 2009)
135.	3-Ethyl-2,5-dimethylpyrazine	0.16	SE/MeOH	(Mebazaa et al. 2009)
136.	Methyl nicotinate	0.03	SE/MeOH	(Mebazaa et al. 2009)
		0.01	SE/EtOH	(Mebazaa et al. 2009)
137.	5,10-Diethoxy-2,3,7,8-tetrahydro-1H,6H-dipyrrolo[1,2-a;10,20-d]pyrazine	5.81	HD	(Moniruzzaman et al. 2015)
138.	Pyrrolo[1,2-a]pyrazine-1,4-dione, hexahydro-3-(2-methylpropyl)-	3.63	HD	(Moniruzzaman et al. 2015)
139.	N-Deacetylisocolchicine	7.36	HD	(Naimi et al. 2022)
140.	2-Chloroadenosine	3.85	HD	(Naimi et al. 2022)
141.	1,2,3,4-Tetrahydroisoquinolin-6-ol-1-carboxylic acid	1.66	HD	(Moniruzzaman et al. 2015)
142.	*β*-Picoline	0.02	SE/MeOH	(Mebazaa et al. 2009)
143.	Aniline	-	STD	(Girardon et al. 1985)
	Sulfur compounds			
144.	Dimethyl sulfoxide	0.03	SE/MeOH	(Mebazaa et al. 2009)
		0.01	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.02	SE/EtOH	(Mebazaa et al. 2009)
		0.16	SHS-SPME	(Mebazaa et al. 2009)
145.	Dimethyl sulfid	29.15	SHS-SPME	(Mebazaa et al. 2009)
146.	Dimethyl sulfone	0.04	SHS-SPME	(Mebazaa et al. 2009)
	Furans			
147.	*2*-Pentylfuran	0.02	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		0.97	SHS-SPME	(Mebazaa et al. 2009)
148.	Coumaran	0.84	SE/MeOH	(Mebazaa et al. 2009)
		0.13	SE/EtOH	(Mebazaa et al. 2009)
149.	Dihydrobenzofuran	-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
150.	2-Hexylfuran	-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
	Other compounds			
151.	Dihydroactinolide	10,84	HD	(Naimi et al. 2022)
		0.01	SE/MeOH	(Mebazaa et al. 2009)
		tr	SE/CH_2Cl_2	(Mebazaa et al. 2009)
		tr	SE/EtOH	(Mebazaa et al. 2009)
		0.17	SHS-SPME	(Mebazaa et al. 2009)
152.	Neryl acetate	17.32	HD	(Hamden et al. 2011)
153.	Dihydro methyl jasmonate	10.99	HD	(Moniruzzaman et al. 2015)
154.	Decane,5,6-bis(2,2-dimethylpropylidene)-, (E,Z)-	19.58	HD	(Moniruzzaman et al. 2015)
155.	4'-Hydroxychalcone	3.69	HD	(Naimi et al. 2022)
156.	*n*-Tetradecane	2.60 ± 0.43	SPME	(Rajhi et al. 2022)
		-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
157.	1-Tetradecene	-	HSVE	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
158.	1-Hexadecene	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
159.	*n*-Tridecane	1.00 ± 0.05	SPME	(Rajhi et al. 2022)
		-	HSVE	(Girardon et al. 1985)
160.	*n*-Pentadecane	0.60 ± 0.001	SPME	(Rajhi et al. 2022)
161.	Hexadecane	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)

№	Compound	Amount, %	Extraction method	Sources
162.	6-Methylheptyl 2-propenoate	5.6 ± 1.07	SPME	(Rajhi et al. 2022)
163.	1,2-Benzisothiazole	2.40 ± 0.75	SPME	(Rajhi et al. 2022)
164.	1,4-Dichlorobenzene	0.08	SHS-SPME	(Mebazaa et al. 2009)
165.	Methyl anthranilate	0.33	SD	(Nalbantova et al. 2023)
166.	Longipinocarveol	0.72/0.91	SD	(Nalbantova et al. 2023)
167.	Ledene oxide	1.05	SD	(Nalbantova et al. 2023)
168.	Octanal,2-(phenylmethylene)-	0.55	SD	(Nalbantova et al. 2023)
169.	Benzyl benzoate	3	SD	(Nalbantova et al. 2023)
170.	Docosane	10.41	SD	(Nalbantova et al. 2023)
171.	Undecane	-	HSVE	(Girardon et al. 1985)
172.	1-Dodecene	-	HSVE	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)
173.	Methylcyclohexyl acetate	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
174.	Dodecane	-	HSVE	(Girardon et al. 1985)
175.	Calarene	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
176.	Pentadecane	-	HSVE	(Girardon et al. 1985)
		-	STD	(Girardon et al. 1985)
		-	STDOR	(Girardon et al. 1985)

*Where **LLE**: liquid-liquid extraction**; SD**: secondary distillation**; HD**: hydrodistillation**; STD**: steam distillation; **SE/MeOH**: solvent extraction (MeOH); **SE/EtOH:** solvent extraction (EtOH); **SE/CH_2Cl_2:** solvent extraction (CH_2Cl_2); **SHS-SPME:** static headspace solid-phase microextraction (SHS-SPME); **HSVE:** headspace vacuum entrainment of seeds; **SPME:** solid-phase microextraction; **STDOR:** steam distillation of oleoresin; **WD:** water distillation.

The chemical composition of fenugreek seeds, and consequently the composition of the essential oil contained therein, is significantly influenced by the nature of the soil. This is demonstrated by the change in the growth rate of the plant, the size and width of the pods formed, the grain yield, and the amount of essential oil released by the addition of biofertilizer. Vermicompost is an inorganic fertilizer widely used in sustainable agriculture to increase the biomass produced and the utilization of microelements by plants. Vermiwash, as an extract of vermicompost, is a liquid fertilizer containing enzymes (amylase, protease, and phosphatase) beneficial for plant growth and development. There was a 47% higher EO content compared to the control when treated with 15 tons of vermicompost per hectare.

Although the effect of vermiwash was lower compared to vermicompost, the application of biofertilizers influenced all parameters, including essential oil percentage and its yield. For this reason, their use in fenugreek cultivation is recommended (Tadayyon et al. 2018).

The importance of the influence of the origin of the plant substance is also proved by the analysis of the composition of EO isolated from seeds cultivated in Bulgaria and India. The data obtained from the chromatographic analysis shows the similarities in the component composition of the two oils but also some differences. Although in both oils the main representative of oxygenated sesquiterpenes is cubenol, its amount is different. Additionally, some components are found in the Bulgarian oil, but they are missing in Indian samples and vice versa. On the other hand, differences in composition were also observed due to the secondary distillation of the hydrolates to isolate the two EOs (Nalbantova et al. 2023).

Chromatographic analysis of commercially purchased fenugreek essential oil by Al-Tamimi et al. determined the highest content of the acyclic monoterpene aldehyde neral (17%) as well as the bicyclic monoterpene camphor (17%). Among the sesquiterpenes, caryophyllene (15%) and α-selinene (4.5%) were detected in the highest amounts (Al-Tamimi et al. 2016).

Essential oil obtained by hydrodistillation of the seed contained the highest percentage of epi-cubenol (28.78%), palmitic acid (15.07%), and dihydroactinolide (10.84%). Among the aromatic monoterpenes, thymol was found in the highest amount (9.56%) (Naimi et al. 2022). Using the same essential oil isolation method, Hamden et al. identified the highest content of neryl acetate (17.32%), camphor (16.32), β-pinene (15.05), and β-caryophyllene (14.63%) (Hamden et al. 2011).

Fenugreek aerial part essential oil

Besides the fenugreek seeds, its aerial part may also be a source of essential oil. Its component composition could differ from that of the essential oil isolated from the seeds (Table 2).

Biological activities and applications

Fenugreek seeds and leaves possess a wide range of biological activities, making them useful in various fields because of the essential oil they contain and their rich component composition (Fig. 1).

Nowadays, the excessive use of antimycobacterial drugs is lead to a significant increase in the multidrug resistance. Therefore, there is a constant search for new agents that could be successfully involved in the control of infectious diseases and, at the same time, be associated with safety and

Table 2. Chemical composition of fenugreek aerial part essential oil.

№	Compound	Amount, %	Extraction method	Sources
		Monoterpenes		
1.	Limonene	0.47	HD	(Weisany et al. 2024)
2.	Linalool	70.25	HD	(Weisany et al. 2024)
		1.34	HD	(Riasat et al. 2017)
3.	Camphor	6.32	HD	(Weisany et al. 2024)
4.	N-dihydrocarvone	3.57	HD	(Weisany et al. 2024)
5.	Isodihydrocarvone	2.56	HD	(Weisany et al. 2024)
6.	Carvone	8.86	HD	(Weisany et al. 2024)
7.	*p*-Cymene	0.32	HD	(Weisany et al. 2024)
8.	Carvacrol	0.08	HD	(Weisany et al. 2024)
		3.4	HD	(Riasat et al. 2017)
9.	Thymol	4.79	HD	(Riasat et al. 2017)
10.	*cis*-Sabinol	0.13	HD	(Weisany et al. 2024)
11.	*α*-Pinene	0.25	HD	(Riasat et al. 2017)
12.	*trans*-Carveol	1.67	HD	(Riasat et al. 2017)
		Sesquiterpenes		
13.	Cubenol	5.7	HD	(Ahmadiani et al. 2004)
14.	*α*-Bisabolol	2.3	HD	(Sohrevardi and Sohrevardi 2012)
		10.5	HD	(Ahmadiani et al. 2004)
15.	epi-*α*-Bisabolol	5.7	HD	(Ahmadiani et al. 2004)
16.	*δ*-Cadinene	27.6	HD	(Ahmadiani et al. 2004)
17.	*γ*-Cadinene	1.8	HD	(Sohrevardi and Sohrevardi 2012)
18.	Farnesol	0.9	HD	(Sohrevardi and Sohrevardi 2012)
19.	*α*-Cadinol	1.7	HD	(Sohrevardi and Sohrevardi 2012)
		12.1	HD	(Ahmadiani et al. 2004)
20.	*γ*-Eudesmol	0.8	HD	(Sohrevardi and Sohrevardi 2012)
		11.2	HD	(Ahmadiani et al. 2004)
21.	(*E*)-Caryophyllene	1.88	HD	(Riasat et al. 2017)
22.	Caryophyllene oxide	1.46	HD	(Riasat et al. 2017)
23.	*α*-Humulene	1.45	HD	(Riasat et al. 2017)
24.	(*E*)-Nerolidol	3.32	HD	(Riasat et al. 2017)
25.	Spathulenol	0.3	HD	(Riasat et al. 2017)
26.	*α*-Muurolol	4.2	HD	(Ahmadiani et al. 2004)
27.	*α*-Muurolene	3.9	HD	(Ahmadiani et al. 2004)
28.	Liguloxide	7.6	HD	(Ahmadiani et al. 2004)
		Aldehydes		
29.	Decanal	0.33	HD	(Weisany et al. 2024)
		1.22	HD	(Riasat et al. 2017)
30.	*trans*-2-Decenal	0.31	HD	(Weisany et al. 2024)
31.	*trans*-2-dodecenal	0.12	HD	(Weisany et al. 2024)
32.	Pentadecanal	0.2	HD	(Weisany et al. 2024)
33.	*cis*-9,17-Octadecadienal	0.31	HD	(Weisany et al. 2024)
34.	Benzaldehyde	0.67	HD	(Riasat et al. 2017)
35.	*n*-Octanal	0.22	HD	(Riasat et al. 2017)
36.	(*E*,*E*)-2,4-Heptadienal	0.75	HD	(Riasat et al. 2017)
37.	Benzene acetaldehyde	1.39	HD	(Riasat et al. 2017)
38.	*n*-Nonanal	1.66	HD	(Riasat et al. 2017)
39.	(*2E*)-Nonen-1-al	1.34	HD	(Riasat et al. 2017)
40.	(*2E*)-Hexenal	26.61	HD	(Riasat et al. 2017)
		Ketones		
41.	1-Decanol	0.09	HD	(Weisany et al. 2024)
42.	2-Pentadecanone,6,10,14- trimethyl	0.32	HD	(Weisany et al. 2024)
43.	1-Octen-3-ol	0.3	HD	(Riasat et al. 2017)
44.	3-Octanone	0.77	HD	(Riasat et al. 2017)
45.	6-Methyl-5-hepten-2-one	0.33	HD	(Riasat et al. 2017)
46.	2-Nonanone	0.27	HD	(Riasat et al. 2017)
47.	2-Tridecanone	1.21	HD	(Riasat et al. 2017)
48.	61,014-trimethyl-2-Pentadecanone	4.59	HD	(Riasat et al. 2017)
		Alcohols		
49.	Phytol	0.39	HD	(Weisany et al. 2024)
50.	*n*-Tetradecanol	1.25	HD	(Riasat et al. 2017)

№	Compound	Amount, %	Extraction method	Sources
		Acids		
51.	*n*-Hexadecanoic acid	10.14	HD	(Riasat et al. 2017)
		Furans		
52.	2-pentyl-Furan	1.57	HD	(Riasat et al. 2017)
53.	Dill-ether	0.26	HD	(Weisany et al. 2024)
		Other compounds		
54.	Elemicin	0.25	HD	(Weisany et al. 2024)
55.	Myristicin	4.71	HD	(Weisany et al. 2024)
56.	Apiole	0.65	HD	(Weisany et al. 2024)
57.	*n*-Dodecane	1.04	HD	(Riasat et al. 2017)
58.	(*2E*,*4E*)-Decadienal	0.71	HD	(Riasat et al. 2017)
59.	*n*-Tetradecane	1.68	HD	(Riasat et al. 2017)
60.	Dodecanal	0.26	HD	(Riasat et al. 2017)
61.	(*E*)-*b*-Ionone	7.99	HD	(Riasat et al. 2017)
62.	*n*-Pentadecane	1.68	HD	(Riasat et al. 2017)
63.	*n*-Heptadecane	1.89	HD	(Riasat et al. 2017)
64.	*n*-Hexadecane	2.64	HD	(Riasat et al. 2017)

* **HD**: hydrodistillation.

Figure 1. Fenugreek oil applications.

lower potential for drug resistance. Kahaleq et al. investigated potential antibacterial effects of fenugreek essential oil against *Pseudomonas aeruginosa* in a cutaneous infection sample. The oil not only exhibited its antibacterial effect but also showed a synergistic effect with gentamicin, making it more effective than gentamicin alone (Kahaleq et al. 2015).

One of the primary components to which the fenugreek flavor is attributed is sotolon. Aldawsari et al. investigated

its effect on mice and *Pseudomonas aeruginosa* and its ability to prevent it, as an alternative or adjuvant treatment for bacterial infections. The results showed a reduction in the levels of pyocyanin and exoenzymes from the *Ps. aeruginosa* arsenal as well as the ability of the bacterium to resist oxidative stress. Sotolon expresses the QS genes of the experimental mice, leading to the inhibition of bacterial biofilm formation and reduction of the resistance of bacteria (Aldawsari et al. 2021).

Moniruzzaman et al. tested the antibacterial activity of fenugreek essential oil against gram-positive and gram-negative bacteria. They established that 150 μL of EO exhibited inhibitory effects against *P. denitrificans* [(15.0 ± 0.7) mm], *P. vulgaris* [(15 ± 0) mm], *E. coli* [(15 ± 0) mm], and *B. subtilis* [(14.0 ± 2.8) mm] as well (Moniruzzaman et al. 2015).

The beneficial effect of the combination of fenugreek essential oils and other medicinal plants, such as cinnamon, oregano, cumin, fennel, etc., on insulin sensitivity assessed by changes in systolic blood pressure in rats has been demonstrated. Applying natural essential oils could serve as an effective tool in managing insulin resistance as well as type 2 diabetes, avoiding adverse effects (Talpur et al. 2005).

Screening of fenugreek essential oil enriched with *ω*-3 fatty acids (15%) showed improvement of pancreatic and plasma *α*-amylase and maltase activities in diabetic rats. The *β*-pinene present in the oil possesses an enzyme inhibitory effect, resulting in a blood sugar-lowering effect. Application of the oil to diabetic rats regenerates the structure of the pancreatic cells, which increases insulin secretion and consequently lowers the plasma glucose level (Hamden et al. 2011).

Furthermore, the inclusion of 1% fenugreek seed oil in broiler chicken feed significantly improved body weight gain compared to experimental groups. The essential oil could serve as a substitute for antibiotic growth promoters and is a highly recommended feed additive (Kadhim and Mohammed 2020).

Essential oil of fenugreek seeds obtained by hydrodistillation showed an 88% repellent effect against *Tribolium castaneum* at a dose of 1 μl after 10 minutes of exposure. The effectiveness is suggested to be due to the identified monoterpenes thymol (9.56%) and cineole (9.30%), to which previous studies attributed repellent properties against *T. castaneum* adults. The obtained good results give evidence to consider that fenugreek EO could be used as a repellent to prevent insect infestations in the storage of products (Naimi et al. 2022).

The increasing use of single-use plastic food packaging is leading to an increase in the demand for non-renewable crude oil for their production. Conversely, the overuse of plastic is exacerbating environmental pollution, presenting a significant global ecological challenge. Accordingly, Subbuvel and Kavan developed a film by a casting technique, incorporating fenugreek essential oil and curcumin in a matrix of polylactic acid (PLA). The developed films were examined for changes in the quality of food products such as strawberries. The conducted tests showed antibacterial activity against *E. coli* and *S. aureus* under the influence of curcumin and essential oil compared to the control groups. Due to the structure of the cell wall, a stronger antibacterial effect was exhibited against gram-positive (*S. aureus*) bacteria compared to *E. coli*. Moreover, the oleic and palmitic acid content of fenugreek oil attributes to its significant antioxidant properties. Its inclusion in the composition of the investigated films would contribute to protecting foods against rancidity or fading (Subbuvel and Kavan 2022).

The addition of EO to the broiler chicks feed shows an increase in their body weight and pre-slaughter weight. On the one hand, this can be attributed to an improvement in the palatability of the feed. The weight gain may be due to the presence of fatty acids in the formulation and other biologically active components that exhibit carminative, antioxidant, anti-inflammatory, or antifungal properties. Previous studies have reported an increase in small intestinal antennal length when fenugreek was added to the diet in a range of 2–5%.

The application of fenugreek EO not only influenced the body weight of the birds but also increased their immune status, as there were differential treatments in terms of gut microflora (Parvizi et al. 2020).

Conclusion

Fenugreek (*Trigonella foenum-graecum* L.) is one of the earliest known aromatic medicinal plants belonging to the Fabaceae family. Nowadays it is cultivated worldwide. Its leaves and seeds are regarded as especially valuable and are widely used all over the world, not only as a condiment but also as a remedy. They are rich in both primary and secondary metabolites, which attribute to their numerous biological activities and applications. Fenugreek seeds as well as the aerial part of the plant contain essential oil. Essential oils are complex multicomponent mixtures that may contain hundreds of compounds.

In the present study, the different methods of essential oil isolation from the seeds and aerial part of fenugreek present in the literature, such as hydrodistillation, steam distillation, liquid-liquid extraction, solid-phase microextraction, static solid-phase microextraction in the headspace, solvent extraction, secondary distillation, steam distillation of oleoresin, and vacuum entrainment of seeds in the headspace, and their influence on EO composition are reviewed. Furthermore, the essential oil composition is also influenced by the harvesting time of the plant, its origin, and the composition of the soil in which it grows.

Fenugreek EO, due to its rich composition, could not only be used as an antibacterial agent but also exhibit a positive influence in the case of diabetes and insulin resistance. Moreover, the antioxidant properties it exhibits contribute to its use in food packaging films. In addition, it also shows good results as a repellent to prevent insect infestations in the storage of products.

Acknowledgements

This study was supported by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.004-0007-C03.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statements

The authors declared that no clinical trials were used in the present study.

The authors declared that no experiments on humans or human tissues were performed for the present study.

The authors declared that no informed consent was obtained from the humans, donors or donors' representatives participating in the study.

The authors declared that no experiments on animals were performed for the present study.

The authors declared that no commercially available immortalised human and animal cell lines were used in the present study.

Funding

This research received no external funding.

Author contributions

Conceptualization, V.N.; methodology, N.B. and C.D.; software, V.N.; investigation, N.B., V.N. and C.D.; writing—original draft preparation, V.N.; writing—review and editing C.D. and N.B.; visualization, V.N.; supervision, N.B. and C.D.

Author ORCIDs

Vanya Nalbantova https://orcid.org/0000-0001-8276-7210
Cedric Delattre https://orcid.org/0000-0003-3605-1929
Niko Benbassat https://orcid.org/0000-0001-8876-2728

Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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