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REVIEW ARTICLE

HIGH VALUE OF BIOACTIVE COMPOUNDS FROM *CORIANDRUM SATIVUM* L FOR MULTIPLE BIOTHERAPEUTIC APPLICATIONS

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Abstract

Currently, people demanding nutrient-rich food products that provide additional health benefits. In this sense, *Coriandrum sativum* L, the most consumed spice around the world increasing its popularity due to its high nutritional value and confirmed pharmacological effects. Bioactive compounds derived from coriander have a wide variety of medical and biotherapeutic applications that extend beyond their well-established gastronomic relevance. Here, the information currently available on the presence, diversity, and extraction methods of the main components of coriander are reviewed. The multiple benefits of include cilantro in the diet and its effect on the treatment of global impact chronic diseases of such as cancer, heart disease, Alzheimer's disease, diabetes, kidney disease, cerebrovascular diseases, among others, are also highlighted. Likewise, the primary biological activities of coriander are detailed, such as antioxidant capacity and antimicrobial activity derived from specific phytochemicals.
This update shows the composition and describe the mixture of bioactive constituents included in the herbaceous plant and/or extracts, emphasizing the biological functions mainly as antimicrobial agents and its confirmed antioxidant function. Coriander is a reservoir of bioactivities combined, with promising potential to use and/or increase health and promote well-being.
Keywords: Antimicrobial, antioxidant, coriander, phytochemicals.

INTRODUCTION

Coriander (*Coriandrum sativum* L.) is a potential source of high-value compounds and is globally recognized for its multiple beneficial health effects, such as natural antioxidant and antimicrobial capabilities that have been successfully studied and confirmed, primarily in the fields of medicine and the food industry[1].

In this review, a brief overview of the chemical composition of Coriander leaves and seeds as well as the biological importance of phytochemical components, is summarized. In addition, concepts about the oxidation and reduction processes and/ or microbial control are contextualized to explain how the phytochemicals compounds of coriander act as natural antioxidant and/or antimicrobial agents. Likewise, several important investigations that successfully evidenced the effectiveness of highlighted several important investigations that have successfully demonstrated the effectiveness of coriander phytochemicals under various experimental conditions for food preservation and medical treatments.

Corianderis a widely cultivated crop. Generally known as a popular herb, it is characterized by being an erect plant with pronounced main root, slender stems with develop branching grow up between 20 to 70 cm in height. Crop maturity is reached approximately 2 to 3 months, after that is harvested including the thin roots[1].

The taxonomic data of the PLANTS database from the United States Department of Agriculture[2], provides standardized information that describes coriander as a flowering plant of the *Magnoliophyta* division, *Magnoliopsida* class, *Rosidae* subclass and Apiales order. The genus *Coriandrum* L. and the species *Coriandrum sativum* L. belong to the *Apiaceae* family, also known as the Carrot family.

It is important to know the differences between both *C. sativum* species, *vulgare* and *microcarpum.* In the *vulgare* variety produces larger fruits than the *microcarpum*, while the *vulgare* variety has lower yields of essential oils (0.1-0.35% (v/w)) than the *microcarpum* (0.8-1.8% (v/w)[3,4]. The uses of *C. sativum* are well known in global gastronomy, food preservation, traditional medicine, and natural therapies. The coriander as a therapeutic herb date back to prehistoric times, long before these properties were attributed to its diverse range of bioactive phytochemical components. This review includes a comprehensive overview of the taxonomic classification of coriander, the nutritional and phytochemical profile of the species, and emphasizes the chemical compounds with important biological activities, such as antimicrobial and antioxidant properties Likewise, some generalities are included about the pharmacological properties of the coriander plant that are involved in health care and the well-being of the population.

Phytochemicals brief overview

Plants in general, including coriander, synthesize primary and secondary metabolites. Plant growth is driven by primary metabolites; on the other hand, secondary metabolites, while not essential for the general development of the plant, are crucial for adaptation and chemical protection processes. Plant secondary metabolites are called phytochemical compounds, characterized by their broad biological activities.

The type and concentration of phytochemicals synthesized by plants are determined by the species, genotype, physiology, stage of development, and environmental conditions during growth[5]. Phytochemicals, or chemicals in plants, play an important role in their growth and development, but these are also the best source of bioactive compounds when included in people´s diets.

According to their chemical structure, two main groups of phytochemicals can be distinguished. The first is a very diverse group that includes non-phenolic compounds such as carotenoids, tocopherols, phytosterols, and organo-sulfur. The second group includes phenolic compounds. Phenolic compounds are mainly isolated from leaves and seeds and are the most studied and reported in plant research[6]. Specifically, polyphenolic compounds are the main components found in aqueous extracts of coriander leaves[7].

Plant phenolics compounds, such as carotenoids, anthocyanins, and tocopherols, have been used in different medical studies confirming their beneficial impact on human health. For instance, some antioxidant properties found in plants are attributed to vitamins, anthocyanins, phenolics and tannins[8]. Regarding flavonoids, the main identified groups are flavonols, including quercetin, kaempferol, isorhamnetin, and cyanidin as the most representative. These flavonols differ significantly in qualitative and quantitative profiles between species. Flavonoids such as flavones, isoflavones, flavonoids, flavonols, flavanones, and anthocyanins also have significant antioxidant activity[9].

Table 1: Nutritional values of Coriander seeds and fresh leaves (per 100 g).

***Coriandrum sativum* L**				
	Seed		**Leaves**	
Principle	**Nutrients value**	**RDA*(%)**	**Nutrients value**	**RDA*(%)**
Energy	298 Kcal	15	23 Kcal	1
Carbohydrates	54.99 g	42	3.67 g	3
Protein	12.37 g	22	2.13 g	4
Total Fat	17.77 g	60	0.52 g	2
Cholesterol	0 mg	0	0 mg	0
Dietary Fiber	41.9 g	110	2.80 g	6.50
Vitamins				
Folates	1 µg	<1	62 µg	15.50
Niacin	2.130 mg	13	1.114 mg	7
Pantothenic acid	-	-	0.570 mg	11
Pyridoxine	-	-	0.149 mg	11
Riboflavin	0.290 mg	22	0.162 mg	12
Thiamin	0.239 mg	20	0.067 mg	5.50
Vitamin A	0 IU	0	6748 IU	225
Vitamin C	21 mg	35	27 mg	45
Vitamin E	-	-	2.50 mg	17
Vitamin K	-	-	310 mcg	258
Electrolytes				
Sodium	35 mg	2	46 mg	3
Potassium	1267 mg	27	521 mg	11
Minerals				
Calcium	709 mg	71	67 mg	7
Iron	0.975 mg	108	1.77 mg	22
Magnesium	16.32 mg	204	26 mg	6.50
Manganese	330 mg	83	0.426 mg	18.50
Phosphorus	1.900 mg	82	48 mg	7
Selenium	409 mg	39	0.9 mg	2
Zinc	4.70 mg	43	0.50 mg	4.50
Phyto-components				
Carotene-α	-	-	36 µg	-
Carotene-ß	-	-	3930 µg	-
Crypto-xanthin-ß	-	-	202 µg	-
Lutein-zeaxanthin	-	-	865 µg	-

*Recommended Dietary Allowance. (USDA: National Nutrient data base *https://ndb.nal.usda.gov*).

Table 2: Methods for extraction of essential oils[42-55].

	Fundamental bases	General process
Hydro-distillation by Clevenger's apparatus	The oldest oil extraction by distillation using water	Fresh samples immersed into water are hydro-distilled in a Clevenger's apparatus (3–6 h)
Hydro-diffusion	Developed for large quantities of dried and sensitive to boiling plants	Collecting hydrosol and essential oils separately
Soxhlet extraction (SE)	Plant samples with solvents are heated and condensed.	Samples with hexane, methanol or acetonitrile are heated and condensed several times
Extraction in solvents	Plant oils extracted with solvents acetone, ether, ethanol, hexane, methanol and using heating.	The process includes heating, filtration, and evaporation of the solvents.
Steam distillation	Widely used method to produce large quantities of EOs (8-9 h).	Volatile oils pass through condenser, and water and oil are mixed in the liquid.
Cold pressing	Extraction of essential oils mechanical means, cold press technique	Oil is pressed at low pressures and temperatures
Microwave-assistedextraction (MAE)	Heating by absorption of microwave energy disrupts plant cells increasing the coming out rate of EOs	Plant materials are ground and soaked in solvent and the mixture is placed into a microwave oven
Super-critical fluid extraction method	The EOs are extracted from fluids with carbon dioxide and water	Reusing fluids in repeated steps of compression and decompression
Solvent-free microwave extraction (SFME)	Combines heating with microwave oven and dry distillation by atmospheric pressure without solvents	Rapid, high yield and selective EOs separation from aromatic herbs, spices and dried seeds
Microwave hydro-diffusion and gravity (MHG)	Technique based on the microwave oven heating combined with earth gravity	Uses microwaves for hydro-diffusion of plant EOs, separate and collect them with atmospheric pressure
Solar hydro-distillation system	Thermal decomposition of leaves with solar energy (120-180 min)	Vacuum-type solar energy tube or panel with a temperature controller and EOs collection unit

Flavonoids and linalool are the main bioactive compounds in the water-soluble extracts of coriander and have a significant anxiolytic effect[10]. Non-flavonoids or phenolic acids (benzoic and cinnamic compounds) are found in very low concentrations, can be present bound, and especially in the free form. Other compounds such as stilbenes, tannins, lignins, and lignans, also exhibit beneficial effects on health, due to their antioxidant properties[11,12].

Occurrence and role of major constituents of coriander

In recent decades, scientific reports on the phytochemistry of coriander have increased and diversified. Therefore, this review highlights the importance of phytochemical composition of coriander, as well as the contribution of every component to the attractive nutritional content and its impact on human health[13]. The above includes a description of the specific biological activities of coriander´s main components, as well as therapeutic applications. These characteristics have generated greater attraction among habitual consumers of this spice and have led to an increase in the number of scientific investigations in recent years. First, it is important to note that there is a lot of confusion in the common nomenclature of the herb, such as cilantro or coriander, in different places around the world. While the herb is recognized as coriander in the United Kingdom, in the United States, the fresh herb is called cilantro, but the seeds are commonly known as coriander. Cilantro and coriander are undoubtedly two coined names for the same herb, and both are correct. Here, the term *C. sativum* refers to both parts of the plant equally, and when a specific part of the plant is discussed, the terms cilantro or coriander seed will be used. The actual differences considered here focus on the chemical or phytochemical composition of the leaves, stems and seeds, whether fresh or dehydrated[14]. Both the seeds and the fresh leaves of this small apiaceous herb contain a wide range of chemical components (nutrients) with unique properties that are directly associated with the nature and quantity of each constituent[15].

Coriander not only provides nutrients but also a large amount of heterogeneous phytochemicals (non-nutrients) that have been beneficial for well-being and preserving health since ancient times (460–377 BC)[16]. Sometimes these phytochemicals are inappropriately recognized as phytonutrients, however they are not essential such as fats, proteins, minerals and vitamins[17]. Table 1 show the outstanding nutritional value of coriander seeds and fresh leaves (per 100 g) (USDA National Nutrient data base.

Since the 1990s, more than 5,000 phytochemicals have been detected and identified, however, many of them have not been adequately studied to take advantage of the many benefits they could bring to human health[18,19]. Phytochemicals are recognized for providing plants with unique organoleptic properties, such as their color, taste, smell, and flavor[20]. The nature of phytochemical compounds is diverse; therefore, their classification is also complex, generally defined according to their origin, their synthesis during the stages of plant growth, or the composition of each plant product (grains, legumes, beans, fruits, herbs, nuts, roots, leaves, seeds)[21].

Table 3: Antioxidant activity in Coriander compounds[64-74].

Phytochemical compound	Bioactivity	Assay	Mechanism of action effect
Coriander EOs (β-linalool 66.07%, camphor 8.34%, geranylacetate 6.91%, cymene 6.35%)	Antioxidant	Total antioxidant capacity of biomolecules 39.38 mg TEAC/L	Radical scavenging activity (AA%=51.05 %) mg/L of Trolox equivalents
Coriander EOs (1.2%)	Antioxiant scavenging assay	Scavenged DPPH	Inhibit oxidation and quench free radicals Inhibition DPPH (I %=66.2%)
Coriander APEOs mixture with *Apium graveolens* L, *Thymus vulgaris* L	Antioxiant activity potentiation	FRAP, ABTS adical scavenging methods	AA=16.7%
Coriander SEOs (polyphenols)	Enhancedanti oxidant activity	DPPH, FRAP and cellular antioxidant activity assays	% FRAP reduction 0.951 mg/mL DPPH radical scavenging=1.053 to 2.221 mg/mL
Coriander SEOs	Antioxidant activity	Scavenged DPPH %	% DPPH radical scavenging=72.05 %
Coriandrum SEOs (100 g/mL)	Antioxidant profiling	Scavenged DPPH %	% DPPH radical scavenging=78 %
Coriander FEOs (Heneicos-1-ene, 200 ppm)	Antioxidant activity	Scavenged DPPH %	% DPPH radical scavenging=89.6
Coriandrum EOs		Scavenged DPPH % IC_{50}, TPC (μg GAE/mg)	% DPPH (IC_{50})=756.43 μg/mL TPC=6.20 μg/mg
Coriander SEOs (200 μg/mL)	Antioxidant activity	Rradical scavenging DPPH, Anti-lipid peroxidative activity (PV), Iron chelating activity, IC_{50}	% Free radical scavenging =70. % iron chelating=0.73 PV=1.64I meq/kg oil IC_{50}=82.1 mg/mL
Coriander SEOs	Antoxidant activity	DPPH (IC_{50}) activity, FRAP assay, NO activity	DPPH(IC_{50})=121.8 μg/mL FRAP=662.92 μmol Fe(II)/g NO (IC_{50})=14.06 μg/mL
Coriandrum SEOs	Antioxidant activity	TPC, TF, % DPPH (IC_{50})	TPC=126-555 GAE/g TF=64-455 mg QE/g IC_{50}=3.10-7.57 mg/mL
Linalool, α-pinene, β-pinene, p-cymene, γ--terpinene (seeds)	Antioxidant activity	RSA High antioxidant activity	RSA=66.48% Inhibiting oxidation processes (57.3%)

EOs: Essential oils; SEOs: Seed Essential oils; APEOs: Aerial parts essential oils; TAC: Trolox equivalent antioxidant capacity; AA: Antioxidant activity; DPPH: Difenilpicrilhidrazilo; FRAP: Ferric Reducing Antioxidant Power; ABTS: (2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulfonic) acid); IC_{50}: Half maximal inhibitory concentration; TPC: Total phenolic content; TFC: Total flavonoid content; PV: Peroxide values; GAE: Gallic acid equivalents; RSA: Radical scavenging activity.

In general, the thousands of phytochemicals identified are classified as primary metabolites (chlorophyll, amino acids, proteins, common sugars or simple carbohydrates, membrane lipids, pyrimidines and purines of nucleic acids) and secondary metabolites (alkaloids, terpenoids, phenolic compounds, lignins, plants steroids, curcumins, glucosides, flavonoids, saponins), according to their rolein the plant´s metabolism[22]. Plants synthesize a wide arsenal of secondary metabolites as part of their defense system and constitute a group of molecules with a broad diversity of functions in the plant[23]. These metabolites also provide plants with many beneficial properties for health of people who regularly consume them in the diet[24,25].

Focusing on the essential nutrients of coriander, they are currently widely involved in the formulation and production of new foods, whether fortified with the vast number of nutritional components (vitamins, minerals, proteins, fibers, among others), as well as functional and nutraceutical foods. These essential coriander compounds are also very important ingredients as a commercial strategy to enhance color and flavor in food products[26]. On the other hand, the beneficial effects of the consumption of phytochemicals considered non-nutritive compounds of coriander, have an important role in the generation of new biotherapeutics for the prevention of chronic diseases, and many other conditions that compromise human health and well-being, including the perspective of coriander agrobiotechnology[27-31].

It is important to know that the bioavailability of essential dietary nutrients and non-nutrient phytochemicals related to coriander consumption can be influenced by several factors, such as maturity, part of the herb (root, leaves, flowers, seeds), different growth stages, cultivation conditions, phytochemical extraction method, food matrix incorporation, human microbiota, and physiological state of each consumer[21,32].

Diversity of phytochemicals in coriander

The plant essential oils (EOs) generally contain two chemical constituents: terpenes and phenyl-propanoids[33]. The first group is classified into terpenes with a hydrocarbon structure, including monoterpenes, sesquiterpenes, diterpenes, and their oxygenated by-products (acids, alcohols, aldehydes, ketones, phenols, esters, oxides and lactones)[34]. The second group comprises phenylalanine-derived molecules (C6-C3) such as flavonoids (anthocyanins, flacons, flavonones, flavanols and flavanonols, condensed tannins, and lignans), as well as non-flavonoids (non-carboxylic phenols, phenolic acids), which possess useful biological activities for medical applications[35].

Table 4: Antimicrobial activity in Coriander compounds[81-90].

Phytochemical	Bioactivity	Effect	Assay	Target	Mechanism of action
Coriander EOs (1.2%)	Antifungal	*In-vitro* MFC	Broth microdilution	*C. albicans*	Inhibites fungal growth (0.02 mg/mL)
Coriander EOs + conventional antibiotics	Antibacterial	*In-vitro* Improve antibiotics action MIC detrmiantion	Microdilution broth susceptibility assay	*A. baumannii*	Synergistic interaction (EOs+CHL, CIP, GEN. TET); Additive interaction (EOs + PIP, CFP)
Coriander EOs (*β*-linalool 66.07%; camphor 8.34%, geranylacetate 6.91%, cymene 6.35%)	Antibacterial	*In-vitro* Inhibition of cellular growth	Agar disc diffusion method	*B. subtilis* (10.69 ±0.47 mm) *Stenotropomonas maltophilia* (9.22±0.08 mm)	Inhibites bacterial growth (inhibition halos)
Coriander SEOs (5 µL/mL)	Antibacterial	*In-vitro* and *In-situ* MIC, MBC, effectiveness in carrots	Broth micro dilution method	*S. enterica*	Reduce and contain the growth of *Salmonella*
Coriander EOs (*β*-linalool 66.07% camphor 8.34%,	Antifungal	*In-situ* Antifungal analysis on bread	Agar microdilution method (MIC)	*P. expansum* MK-SF 33	Reduces mycelial growth and sporulation
Coriander SEOs (500 µg/mL)	Antiviral	Antiviral activity by plaque assay *IC_{50}, SI	Plaque reduction assay (Vero cell line)	Herpes simplex Virus (HSV-1) 50 PFU	HSV-1 Inhibition (99%) *IC_{50}=350-250 µg/mL
Coriander SEOs (1.2%)	Antibacterial	*In-vitro* MIC against Clinical pathogens	Broth microdilution method	Clinical pathogens *E. coli* (0.64mg/mL),	Inhibits bacterial growth (turbidity detection)
Coriander ESOs (4%)	Antibacterial	*In-vitro* MIC determination	Agar diffusion method	Clinical pathogen *S. aureus*	Inhibition of cell growth and death (inhibition 14.3 mm)
Coriander EOs (Linalool 73.5%, α-pinene 5.3%), γ-terpinene 4.5%)	Antiparasitic activity	*In-vitro* Anti-promastigote screening	Cytotoxic activity MTT assay	*L. amazonensis*	Inhibition against *L. amazonensis* IC_{50} =19.1 ± 0.7 µg/mL,
Coriander LEOs (40 mg/mL)	Anthelmintic activity	*In-vitro* Immersion assay	Paralysis/death elapsed time	*Pheretima posthuma*	paralysis (31 min) and death (78 min)
Coriander SEOs	Anthelmintic activity	*In-vitro* and *in-vivo* anthelmintic activity	White Balb/c mice	*Hymenolepis nana*	Anthelmintic agent (500-750 mg/kg B.W.)
Coriander HEs	Antimicrobial Antibiofilm	Serial agar dilution (MIC); Biofilm	*Galleriamellonella* L	*E. coli, S. enterica, P. aeruginosa,*	Antimicrobial effect (MIC=1 mg/mL*); S. aureus, E. coli*
Coriander EOs (*β*-linalool 66.07% camphor 8.34%,	Antibiofilm formation	*In-vitro* Glass and wood surfaces	Agar microdilution method	*Bacillus subtilis* 7.42 µL/mL *S. ltophilia*	Reduces biofilm formation (50% planktonic cells; 50% reduction in the cell
Coriander LEs and seeds extract	Antibacterial	*In-vitro* antibacterial screening	Disc-diffusion method	Human pathogenic *E. coli,*	Inhibitory growth effect except against *P. aeruginosa*
Coriander EOs (linalool 70.93%, monoterpenes 77.34%)	Antibacterial	*In-vitro* Antimicrobial activity and viable count cells	Agar-well diffusion method	*E. coli* ATCC 8739 *Micrococcus luteus ATCC 9341*	Viable count cfu/mL (99.99 % killing)

EOs: Essential oils; SEOs: Seed Essential oils; LEs: Leaves extracts; HEs: Hexane extract; MFC: Minimum Fungicidal Concentration; MIC: Minimum Inhibitory Concentration; MBC: Minimum bactericidal concentration; CHL: Chloramphenicol; CIP: Ciprofloxacin; CFP: Cefoperazone; GEN: Gentamicin; TET: Tetracycline; PIP: Piperacillin; PFU: Plaque-forming unit; MTT: 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; CLSM: Confocal laser scanning microscopy; SEM: Scanning electron microscopy; QS: Quorum sensing.

The phytochemical composition of coriander herb is similar to essential oil (EO) constituents, and additionally contains tannins, terpenoids, reducing sugars, alkaloids, phenols, flavonoids, fatty acids, sterols, and glycoside. The main components responsible for the characteristic odor of the herb are characterized by the presence of chemical groups such as various types of monoterpenes (oxide, alcohol, carbonyl, hydrocarbon, ester), aliphatic compounds (alcohol, aldehyde, hydrocarbon), phenolic compounds (phenols), sesquiterpenes, as well as some minor compounds such as acetic acid and α -p dimethyl styrene[36,37].

The essential oil of coriander is rich in phytochemicals, and the most recent quantitative analysis indicates the following compounds in mg/g: linalool (256.65) as main compound, α-pinene (19.85), geranyl acetate (15.76), γ-terpinene (12.08), camphor (8.51), p-cymene (6.10), geraniol (5.78), myrcene (3.25), limonene (2.90), sabinene (1.15), citronellal (0.77), borneol (0.76), geranial (0.60), neryl acetate (0.31), neral (0.28), eucalyptol (0.15), caryophyllene (0.06), thymol (< 0.01), carvacrol (< 0.01), α-terpineol (< 0.01), nerol (< 0.01).

In recent years, advanced methods have been applied to extract new phytochemicals in plants such as coriander and its extracts. The heneicos-1-enes are new molecules isolated through chromatography[38]. Furthermore, sophisticated nuclear magnetic resonance (NMR) techniques have enabled structural resolution with the support of high-resolution mass spectrometry (HRMS). Likewise, the increase in the extraction yield of the heneicos was increased using techniques like ionic liquid-based microwave-assisted extraction (IL-MAE) and the application of the response surface methodology[39]. Microwave-assisted extraction based on ionic liquid is a fast and environmentally friendly extraction method applied to secondary metabolites in medicinal plants, in this case, coriander. Additionally, it is one of the unconventional extraction methods that has been developed and rapidly applied in recent years[40]. In general, heneicos-1-ene belongs to the class of organic compounds known as unsaturated hydrocarbons; they are aliphatic hydrocarbons that contain one or more unsaturated carbon atoms. These compounds, with a molecular formula of $C_{21}H_{42}$, contain one or more double or triple bonds and a molecular weight of 294.567 g/moL[41].

The value of the bioactive compounds of *Coriandrum sativum* L treated in this manuscript are increased by molecules of heneicos-1-ene due to the outstanding potential to eradicate free radicals and proven antibacterial activity, as same as molecules isolated from coriander foliage, as confirmed by modern scientific studies[42].

Extraction of bioactive compounds from plant extracts

Coriander oil is a natural compound, and its availability is extensive. Methods for oil extraction are very diverse and include both, traditional and modern techniques. Traditional and modern methods commonly applied for oil extraction, as well as the fundamental and general processes are briefly described in Table 2[42-55].

Methods for the extraction of phytochemicals from coriander

The most popular methods for EOs extraction are still solvent extraction and steam distillation because they are relatively inexpensive, safe, and can provide a high-quality end product[46]. After extraction, chemical identification and accurate quantification of the molecules contained in EOs are performed using Gas Chromatography coupled to Mass Spectrometry (GC-MS), High Resolution Gas Chromatography (GC-FID), and High-Performance Liquid Chromatography (HPLC) techniques[51].

It is important to note that that the success of EOs extraction depend on the type of method(s) and operating conditions selected for the process. Modern Green Extraction (MGE) methods have been reported to provide advantages in terms of performance compared to traditional methods (hydrodistillation) and improved selectivity compared to Soxhlet extraction[56].

To achieve the extraction of EOs from Coriander, traditional methods (hydrodistillation, solid-liquid extraction) were compared with modern methods (supercritical fluid extraction -SCFE-and subcritical water extraction -SCWE-). The comparison show yields of primary compounds (γ-(+)-limonene, terpinene, geraniol, camphorandlinalool). Soxhlet extraction provides high proportions of oxygenated monoterpenes (camphor, geraniol, and linalool) in seeds, while the extraction yields of γ- terpinene and (+)-limonene were higher with MGE SFE, which contained high levels of camphor, geraniol and linalool[45].

The variations in EOs of coriander fruits depend not only on the extraction methods but also on the concentration of phytochemicals, which is directly related to the stage of growth or maturity, the season of herb harvest, and the prevailing climate and environmental conditions in the region of growth[1].

Regarding the growth of coriander, the quantity of Eos varies with the maturity stage of the herb, especially in the seeds[43]. The linalool, the main component in coriander, increases as the herb grows, ranging from 36% during the first (flowering) stage to 78% during the last stage (maturity). These variations have also been confirmed in crop yields in different regions of the world[2,57].

Outstanding biological activities of coriander

Antioxidant capacity of Coriander

During the metabolic processes of cells, biochemical reactions can generate free radicals, which are considered an oxidative process that needs to be controlled to avoid endangering cell function and integrity. Reactive oxygen species (ROS) can be produced, generating oxygen ions, free radicals and peroxides, reactive species derived from oxygen that cause ovidative stress. Reactive nitrogen species (RNS) can also be produced, such as nitric oxide, nitrogen dioxide, among others, causing nitrosative stress[58,59].

Free radicals can accumulate in cells and damage DNA, certain lipids and proteins, causing significant harmful effects on human health, and promoting the development of chronic degenerative diseases[60]. This has generated enormous interest in developing scientific research, including epidemiological research, to counteract the effects of oxidative and nitrosative stress. Naturally, cells react by counteracting ROS through enzymatic mechanisms (catalase -CAT-, superoxide dismutase -SOD- glutathione peroxidase -GPX-) and non-enzymatic mechanisms (vitamins E and C, flavonoids, among others).

However, to help counteract the body's natural oxidation process, antioxidants can be acquired through diet. Vegetable consumption with being an important source of antioxidants such as polyphenols to neutralize free radicals[58,61]. Polyphenols are capable of transferring electrons from the hydroxyl groups of their molecule, exerting an antioxidant action by reducing the free radicals in the environment[62]. Medicinal plants such as cilantro, in particular the extract of the oil from the seeds, are a source of potent antioxidant properties that have been investigated for their valuable biotherapeutic potential[63].

The antioxidant properties of cilantro are associated with or derived from polyphenolic and flavonoid compounds, and some others bioactive compounds. Especially the essential oil of coriander, linalool, has enormous antioxidant properties that neutralize the effect of lipid oxidation and/or lipid peroxidation[64].

Table 3 summarizes several representative studies of the potential and confirmed antioxidant capacity of coriander and/or some of its constituents[64-74].

The high natural antioxidant properties of coriander constituents in EOs extract are widely used in the food industry protection, as substitutes for dangerous synthetic/chemical antioxidants. These chemical antioxidants traditionally including butylhydroxy-anisole, butylhydroxytoluene, tertbutyl hydroxyl-quinone and propyl gallate[65].

Likewise, the table shows the activity exerted and the assessments carried out to determine its effect by any of the action mechanisms (Radical scavenging activity, Ferric reducing ability of plasma, Nitric oxide radical scavenging, among others).

Antimicrobial activity derived from Coriander

Currently, pharmaceuticals, mostly synthetic drugs, are the dominant therapeutic agents in modern medicine. However, the phytomedicinal drugs derived from plants, are becoming more popular as a potential alternative strategy against antimicrobial resistance. In this regard, the WHO reports clearly show that more and more countries are recognizing the role of traditional and complementary medicine in their national health systems. The WHO strives to implement and follow up the WHO Traditional Medicine Strategy 2014-2023 worldwide.

Coriander is a globally important crop used as a vegetable, spice, fragrance, and traditional medicine[57]. Also, coriander has been used since ancient times for its ability to control various organisms due to its recognized antibacterial activity. In general, antimicrobial activity refers to the process of killing or inhibiting disease-causing micro-organisms, mostly bacteria. Many antimicrobial agents are used to reduce or eliminate microbial growth by different modes of action and mechanisms. Anti-microbials can be antibacterial, antifungal, or antiviral, and they all have different modes of action by which they act to suppress the infection. The antimicrobials act on specific targets identified as nucleic acids synthesis, cell wall synthesis (peptidoglycan), and structural and/or functional damage to the cell membrane by depolarization, disruption or permeability[75].

Human mycosis is one of the most important health problems worldwide. However, abundant research in the field of antifungal drug fungal treatment research slowly than bacterial infections control. The common antifungal activity may include the inhibition of ergosterol synthesis by lanosterol 14-α demethylase activity in fungal endoplasmic reticulum (azoles). Also, antifungals binding to ergosterol causing disruption of the fungal cell membrane (polyenes), and the inhibition of (1,3) β-D-glucan synthase stops glucan synthesis (echinocandins). The fungistatic nature of many popular antifungals and the emergence of resistance limit their success, and new approaches to fungal treatment are being sought.

These new approaches include phytochemical screening in medicinal plants to isolate bioactive compounds as therapeutic tools against fungal diseases. In this regard, linalool has shown *in vitro* antifungal activity against *Candida albicans*, and inhibits activity in 1, 3 beta-glucan synthase, lanosterol 14 alfa-demethylase, and delta 14-esterol reductase, damaging the cell wall and plasmatic membrane in fungi[75-77]. Also, both clinical investigations and *in vivo* experiments have confirmed the antifungal activity of flavonoids[78,79]. The efficacy of linalool against *L. monocytogenes* in the planktonic stage and biofilm formation has been explored, as well as its putative mechanism of action. The evidence shown strong anti-listeria activity in the planktonic stage by linalool[80].

Table 4 summarizes several representative studies of the potential and confirmed antimicrobial capacity of coriander and/or some of its constituents[81,82-90].

Coriander´s multiple health benefits

In recent years, coriander and its phytochemical components have been studied from a medical perspective primarily for their great potential to promote health as curative agents for therapeutic managementof many diseases. As mentioned above, phytochemical content of coriander is linked to its biological functions,so high expectations for the use of coriander in biotherapeutic treatments against chronic and degenerative diseases[10]. Chronic diseases, both in developing and developed countries, encompass a wide range of medical conditions, including cancer, heart disease, Alzheimer's disease, diabetes, kidney disease, and cerebrovascular diseases, among others.

In this context, the World Health Organization (WHO) reports cancer as the second leading cause of death worldwide, with an estimated 9.6 million deaths, or one in six deaths, in 2018[65]. Additionally, statistically, the American Cancer Association estimated 1.8 million new cancer cases in 2020, unfortunately resulting in approximately 606,520 cancer-related deaths in the United States. In 2024, 2,001,140 new cancer cases and 611,720 cancer deaths are projected to occur in this country[91]. The *anticancer* effect of coriander has been confirmed, specifically by affecting the survival of the cells and triggering apoptosis, thereby impacting the invasive and colony formation properties of different cell lines, such as prostate cancer[92], breast cancer[93], human colon cancer, and ovarian carcinoma[94].

Heart and cardiovascular diseases (HCVDs) are the leading cause of death globally according to the WHO, with an estimated 17.9 million deaths each year[95]. The HCVDs include heart disorders of the heart and blood vessels and encompass coronary heart disease, cerebrovascular disease, rheumatic heart disease and other conditions. In the treatment of heart disease, coriander extract can lower blood pressure as well as reduce other heart disease risk factors such as bad cholesterol levels[96]. Also, coriander seeds can create significant decrease low-density lipoproteins (LDL) and increase high-density lipoprotein (HDL). The above indicates a previously reported hypolipidemic effect and decreases in cholesterol synthesis. Cholesterol significantly increases the risk of developing cardiovascular heart diseases and mortality[97].

The treatment of chronic diseases such as *Alzheimer's* is very varied and, at the same time, very exhausting for patients and their families. In recent years, physicians have sought natural alternatives for biotherapeutic treatment, and coriander leads a very promising application. For example, the inhalation of coriander volatile oil reduces oxidative stress in a beta-amyloid (1-42) rat model of Alzheimer´s disease[98].

Nowadays, diabetes is a chronic (long-lasting) disease that affects the pathways used by the human body to metabolize food into energy. There are three main types of diabetes: type 1, type 2, and gestational diabetes (diabetes while pregnant). More than 122 million Americans are living with diabetes (34.2 million) or prediabetes (88 million)[75]. Many patients with diabetes mellitus consider medicinal plants such as coriander as complementary treatment forthis common chronic and metabolic disease and its derivative complications such as impaired wound healing[99].

Coriander may stimulate endocrine glands and pancreatic insulin secretion to increase the level of insulin in the blood. In that way, coriander regulates the absorption and assimilation of sugar, resulting in a drop in blood sugar levels[100]. Coriander helps to reduce the risk of risky fluctuations in blood sugar limits, and also promotes metabolic functions. The management of diabetes by effect of coriander can attenuate lipids, glucose and creatinine levels and decrease lipid peroxidation. In addition, it also increases the activity of antioxidant enzymes in patients[101,102].

Neurodegeneration leading to cognitive deficits and a lack of cognitive capability in humans, for which there is no cure o preventive treatment currently, can potentially be addressed through traditional The essential oils of coriander contain a great amount of linalool, a phytochemical with bioactivity against the neurotoxic effects of beta amyloid 1-42 (Aβ1-42), which is mainly responsible for the functional loss in neuronal cells such as cell viability, synaptic function and neuronal network activity[103]. Regarding older adults and the promotion of the quality of life to reach independence for people as they age, the coriander has significant value[104].

CONCLUSIONS

Coriander is phytochemical-rich herbaceous, and maybe the most popular and economically valuable spice worldwide. The recent rise in popularity is due to their multiple health benefits linked to the phytochemicals/bioactive compounds with a broad spectrum regarding to phytochemical and biological activities. These activities include antimicrobial and antioxidant properties to develop anticancer, anti-inflammatory, hypoglycemic, hypolipidemic, hypo-tensive among others. Undoubtedly, the coriander is excellent source of pharmaceuticals, and could be efficiently extracted and studied *in vitro* or *in vivo* to be applied according to their phytochemical diversity, as well as, by the wide variety of beneficial effects exerted on nutrition and human health to well-being promotion and enhance the healthy aging conditions. Multiple scientific researches about plethora of bioactivities from coriander, their medical applications to promote the well-being and enhance the healthy aging, undoubtedly could be getting closer to benefiting the world's population health.

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AUTHOR'S CONTRIBUTION

De la Fuente-Salcido NM: writing original draft, investigation, analysis of data. **Lafuente-Rincón DF:** design and conceptualization of tables. Final manuscript was approved by both authors.

DATA AVAILABILITY

Upon request, the accompanying author can furnish the empirical data used to bolster the findings of the study.

CONFLICT OF INTEREST

None to declare

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