HANDBOOK OF CORIANDER

(*Coriandrum sativum*)

Chemistry, Functionality, and Applications

Edited by

Mohamed Fawzy Ramadan

CRC Press
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Handbook of Coriander (*Coriandrum sativum*)

Coriander (*Coriandrum sativum* L., family Umbelliferae/Apiaceae) is one of the most popular spices globally. Different parts of *Coriandrum sativum* are edible and widely used as a seasoning due to their unique flavor and aroma. *Coriandrum sativum* medical uses have been recognized since ancient times. Coriander leaves (cilantro) and coriander fruit (seed) are used in different ethnic foodstuffs, meat and poultry dishes, soup, pudding, bread, and seafood dishes. *Coriandrum sativum* is rich in linalool, vitamin A, vitamin B12, vitamin C, folate, and phenolics. *Coriandrum sativum* fixed oil is rich in sterols, tocols, and bioactive phytochemicals. Petroselinic acid is the major fatty acid in *Coriandrum sativum* fixed oil and exhibits health-promoting traits.

Coriandrum sativum is recommended as a food preservative to replace synthetic antioxidants because of its antioxidant and antibacterial traits. Furthermore, *Coriandrum sativum* cilantro and seeds are rich in water-soluble and lipid-soluble phytochemicals with unique anticancer, anxiolytic, neuroprotective, migraine-relieving, hypoglycemic, hypolipidemic, anticonvulsant, analgesic, and anti-inflammatory traits. Those medical benefits and their integration into daily life render *Coriandrum sativum* an excellent functional food. Regarding the cosmetic industry, *Coriandrum sativum* is used as an ingredient in conventional Ayurvedic cosmetic formulations to normalize skin color. In addition, *Coriandrum sativum* volatile oil finds use as an ingredient in perfumes.

Handbook of Coriander (**Coriandrum sativum*****): Chemistry, Functionality, and Applications*** is a valuable resource for pharmaceutical and nutraceutical developers, as well as novel food developers and R&D researchers in a variety of fields that use herbs, spices, and medicinal plants.

Key Features:

- Explores the chemistry of *Coriandrum sativum* phytochemicals, oils, and extracts
- Discusses *Coriandrum sativum* active constituents and their health-enhancing traits
- Presents the applications of *Coriandrum sativum* phytochemicals, oils, and extracts
- Addresses the growing application areas, including horticulture, functional food, clinical nutrition, pharmaceuticals, and cosmetics

Authored by international scientists and industry experts, this book is a great resource for food chemistry, clinical nutrition, biochemistry, pharmacology, and horticulture researchers and students, as well as developers of novel food, cosmetics, and pharmaceuticals, in addition to R&D researchers in different sectors that utilize herbs, spices, and medical plants.

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Dedicated to the soul of my father, Professor Fawzy Ramadan Hassanien, and my beloved family.

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SECTION V Coriander Extracts: Chemistry, Technology, Functionality, and Applications

Preface

Spices, herbs, and medicinal plants that have been shown to have health-promoting properties are fascinating. *Coriandrum sativum* leaves, seeds, and roots are rich in volatile oils, fixed oils, fatty acids, tocols, sterols, and carotenoids. Their yields and compositions are influenced by ecotype, variety, genotype, planting season and condition, plant part, growth stage, harvesting time, and extracting process. The health-promoting effects of *C. sativum* include its protective traits against cancer, neurodegenerative diseases, and metabolic syndrome.

Regarding the several published contributions on the functional, nutritional, and pharmacological effects of *Coriandrum sativum*, this handbook tries to create multidisciplinary discussions of the chemical profile and biological potential, as well as food and non-food uses of *C. sativum*, *C. sativum* oils, *C. sativum* bioactive compounds, and *C. sativum* extracts. The book also explores the proper uses of *Coriandrum sativum* in developing nutraceuticals, pharmaceuticals, novel food, and drugs.

The book contains chapters within various sections:

Section I. Coriander: Cultivation, Composition, and Applications
Section II. Coriander Leaves: Chemistry, Technology, Functionality, and Applications
Section III. Coriander Fixed Oil: Chemistry, Technology, Functionality, and Applications
Section IV. Coriander Essential Oil: Chemistry, Technology, Functionality, and Applications
Section V. Coriander Extracts: Chemistry, Technology, Functionality, and Applications

Intending to provide a comprehensive contribution to the scientific community involved in food science, horticulture, clinical nutrition, health, and pharmacology, this book comprehensively reviews the aspects that led to the recent advances in *C. sativum* biochemistry, production, and functionality. The editor hopes that the handbook will be a rich source for researchers and developers in related disciplines.

The editor sincerely thanks all contributors for their valuable contributions and their cooperation. In addition, the help and support of the Taylor & Francis staff, especially Stephen Zollo and Laura Piedrahita, were essential for completing the project and are highly appreciated.

Prof. Mohamed Fawzy Ramadan
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About the Editor

Mohamed Fawzy Ramadan is a Professor of Food Chemistry and Biochemistry at the Department of Clinical Nutrition, Faculty of Applied Medical Sciences Umm Al-Qura University, Makkah, Saudi Arabia. Since 2014, Prof. Ramadan has been a Professor in the Agricultural Biochemistry Department, Faculty of Agriculture at Zagazig University, Egypt.

Prof. Ramadan earned his PhD (*Dr. rer. Nat.*) in Food Chemistry from the Berlin University of Technology (Germany, 2004). He conducted post-doctoral research at ranked universities such the University of Helsinki (Finland), the Max-Rubner Institute (Germany), Berlin University of Technology (Germany), and the University of Maryland (USA). In 2010, he was appointed Visiting Professor (100% research) at King Saud University. In 2012, he was appointed Visiting Professor (100% teaching) at the School of Biomedicine, Far Eastern Federal University, in Vladivostok, Russian Federation.

Prof. Ramadan has published more than 300 research papers and reviews in international peer-reviewed journals. He has also edited and published several books and book chapters (with a Scopus *h*-index of 44 and more than 6000 citations). In addition, he has been an invited speaker at several international conferences. Since 2003, Prof. Ramadan has been a reviewer and editor of several highly cited international journals such as the *Journal of Medicinal Food* and *Journal of Advanced Research*.

Prof. Ramadan has received several prizes, including the Abdul Hamid Shoman Prize for Arab Researcher in Agricultural Sciences (2006), Egyptian State Prize for Encouragement in Agricultural Sciences (2009), European Young Lipid Scientist Award (2009), AU-TWAS Young Scientist National Awards (Egypt) in Basic Sciences, Technology and Innovation (2012), TWAS-ARO Young Arab Scientist (YAS) Prize in Scientific and Technological Achievement (2013), and Atta-ur-Rahman Prize in Chemistry (2014).

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1 Introduction to Handbook of Coriander (*Coriandrum sativum*)

Chemistry, Functionality, and Applications

Mohamed Fawzy Ramadan

CONTENTS

1.1 UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS AND HEALTH-ENHANCING PLANTS

The United Nations Sustainable Development Goals (UNSDGs, https://sustainabledevelopment.un.org) comprise a vision of a peaceful, fairer, and sustainable world. "*Good Health and Well-Being*" is the third UNSDG (https://sdgs.un.org/goals/goal3), which aims to enhance health using health-enhancing plants and environmentally friendly methodologies in the food industry (Ramadan, 2021).

New plant-based products with functional traits could be designed to enhance human health. Current innovations will affect the way we eat in the future (McClements, 2019). Novel nutraceuticals and pharmaceuticals have been developed from spices, herbs, and medicinal plants. Globally, the World Health Organization (WHO) mentioned that approximately 80% of the global population depends upon traditional medicine. WHO highlighted the importance of exploring medicinal plants for healthcare benefits (i.e., safety, efficacy, quality control, quality assurance, dosage, clinical trials, toxicity, drug interaction, and therapeutic uses). With the developments in clinical nutrition, there is tremendous interest in aromatic plants as phytoconstituent-rich sources for nutraceuticals, novel foods, and drugs. Interest in plant-based active constituents and oils has increased due to their health-promoting roles (Kiralan et al., 2014; Ramadan, 2021; Elimam et al., 2022).

1.2 CORIANDER (*CORIANDRUM SATIVUM*): CHEMISTRY, FUNCTIONALITY, AND APPLICATIONS

The consumption of spices, medicinal plants, and herbs rich in health-enhancing phytoconstituents might expand consumers' life span. The abundant manifestation of bioactivity of phytoconstituents

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in medicinal plants, herbs, and spices makes them natural active compounds (Ramadan and Moersel 2003; Singh et al., 2006; Gantait et al., 2022).

Coriandrum sativum Linn. (coriander, family Umbelliferae or Apiaceae) is one of the earliest used spices (Yousuf et al. 2014; Moniruzzaman et al. 2014; Meena et al. 2014; Gantait et al. 2022) having beneficial medicinal impacts (Rajeshwari and Andallu 2015; Gantait et al. 2022; Sobhani et al. 2022). *Coriandrum sativum* originated in the eastern Mediterranean and is grown in Europe, Africa, and Asia. Different parts of *C. sativum* are edible and utilized as a seasoning due to their unique flavor. The medical uses of *Coriandrum sativum* have been recognized since ancient times. Coriander leaves (cilantro) and coriander fruit (seed) are used in curry meat dishes, puddings, bread, soups, poultry and seafood dishes, and various ethnic foodstuffs. *C. sativum* contains high levels of vitamin B12, folate, vitamin C, vitamin A, and phenolics. Besides, *C. sativum* is considered an alternative food preservative due to its antioxidant and antimicrobial potential (Moniruzzaman et al., 2014; Meena et al., 2014; Gantait et al., 2022).

C. sativum cilantro, roots, and seeds contain bioactive phytochemicals (i.e., gallic acid, thymol, and bornyl acetate) that exhibit unique neuroprotective, anticancer, anxiolytic, migraine-relieving, hypolipidemic, anticonvulsant, analgesic, hypoglycemic, and anti-inflammatory effects. Linalool is the main bioactive constituent responsible for several coriander therapeutic traits. Other *C. sativum* active constituents are volatile oil, fatty acids, tocols, sterols, and carotenoids, wherein their yields and compositions are affected by variety, genotype, ecotype, planting season and condition, plant part, growth stage, harvesting time, and extracting process (Ramadan and Moersel, 2002; 2003, 2004; Ramadan, Kroh, Moersel, 2003; Ramadan, Amer, and Awad, 2008). Meanwhile, *C. sativum* essential oils, fixed oils, extracts, water-soluble compounds, and phenolics exist in aerial parts and seeds (Meena et al., 2014; Gantait et al., 2022). Besides, *C. sativum* volatile oil ranks second highest in the global annual production.

According to WHO (2019), cardiovascular diseases are the leading cause of mortality globally. *C. sativum* phytochemicals have high potential in cardiovascular health and have exhibited cardioprotective, antihyperlipidemic, cardiometabolic disorder-inhibiting traits, and angiotensin-converting enzyme-inhibiting effects. On the other hand, due to the COVID-19 pandemic, the conventional Ayurvedics system showed an impact compared to modern medicine, and they have the advantage of being cost-effective with lesser side effects (Gidwani et al., 2022).

The antioxidant potentials of *C. sativum* provide a key mechanism in its health-promoting effects against cancer, neurodegenerative diseases, and metabolic syndrome. These therapeutic effects and their integration into daily life render *C. sativum* a promising novel food. *C. sativum* has been conventionally utilized as digestive and appetite stimulants, and diuretic, lipid-lowering, glucose-lowering, and antimicrobial agents. It has also been used for treating digestive disorders, central nervous system diseases, and airway disorders (Gantait et al., 2022; Sobhani et al., 2022).

C. sativum is utilized as an ingredient in conventional Ayurvedic cosmetic formulations to normalize skin color in the cosmetic industry. *C. sativum* volatile oil as an ingredient in cosmetics and perfume was spotlighted in 2000 BCE. Moreover, *C. sativum* fixed oil is rich in sterols, tocols, and other bioactive phytochemicals. Petroselinic acid is the main fatty acid in coriander crude oil and exhibits several biological and health-promoting traits (Mahleyuddin et al., 2022).

1.3 CORIANDER (*CORIANDRUM SATIVUM*) MARKET

The popularity of healthy cuisines is linked to the increased demand for *Coriandrum sativum* worldwide. *C. sativum* has an outstanding international market because of the increase in the world population with its consumption requirements. FAOSTAT (https://www.fao.org/faostat) reported that, in 2020, the total yield of anise, badian, fennel, and coriander reached 11,362 hectograms per hectare (hg/ha). Arizio and Curioni (2011) reported that the *Coriandrum sativum* importing countries (*ca*. 63% of world imports) are led by Malaysia, Sri Lanka, the United Kingdom, the USA, and Japan.

Europe accounts for *ca*. 15.0% of global *Coriandrum sativum* seed imports. In Europe, the UK is the highest *Coriandrum sativum* seed importer. However, opportunities for other suppliers could exist in other growing or large markets, including the Netherlands, Poland, Germany, and France.

Coriander seeds are the round-shaped, brown-colored, dried fruit of *C. sativum*. *Coriandrum sativum* farmers remove the fruit seeds from the stem with threshing machines or combine harvesters, or beat them with sticks. '*Microcarpum*' and '*Macrocarpum*' are the major *Coriandrum sativum* varieties utilized for seed production. European *C. sativum* seed imports are likely to increase at a *ca*. 2% annual growth rate. Consumption growth and imports are anticipated to be driven by healthy eating trends, high usage of *C. sativum* seeds as an ingredient in food products, the volatile oil industry, and the increasing interest in healthy cuisines. Between 2015 and 2018, European *C. sativum* seed imports increased to *ca*. 24,000 tonnes worth €26 million. Bulgaria is the leading EU producer of *C. sativum*, where high volumes are used in the volatile oil industry. The second-highest European producing country is Spain, wherein the production targets spice production more. After Bulgaria, Italy is considered the second-highest European exporter and producer of *C. sativum* seeds; Italy focuses on producing *C. sativum* seeds for sowing (https://www.cbi.eu/market-information/spices-herbs/coriander-seeds/market-potential).

1.4 CORIANDER (*CORIANDRUM SATIVUM*) IN THE INTERNATIONAL SCIENTIFIC LITERATURE

Coriandrum sativum is highly attractive for international research. Hundreds of contributions were published on *Coriandrum sativum*. A search with the keyword '*Coriandrum sativum*' in PubMed (March 2022) resulted in 593 published contributions belonging to *Coriandrum sativum* production, cultivation, and the bioactivity of phyto-extracts, amino acids, seed oil, fatty acids, active compounds, and industrial uses.

A careful search for *Coriandrum sativum* in Scopus (www.scopus.com) showed that the number of documents published on *Coriandrum sativum* is exceptionally high (*approx*. 2200 till March 2022). Of the published contributions, *ca*. 1970 were research contributions, 70 conference articles, 100 review contributions, and 17 book chapters. The contributions counts on *Coriandrum sativum* from 2000 to 2020 are presented in Figure 1.1. The contributions annually published on *Coriandrum sativum* have increased from 23 articles in 2000 to 145 articles in 2020. In the scientific community, these indicators reflect the interest and importance of *Coriandrum sativum* as a research topic. Between 2000 and 2020, Figure 1.2 represents the distribution of document types

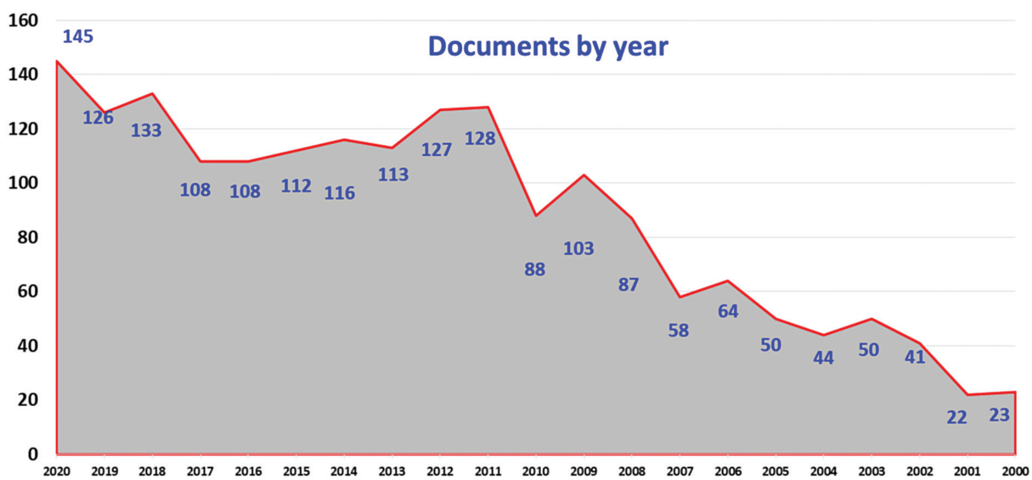

FIGURE 1.1 Scholarly output on *Coriandrum sativum* from 2000 to 2020 (www.scopus.com).

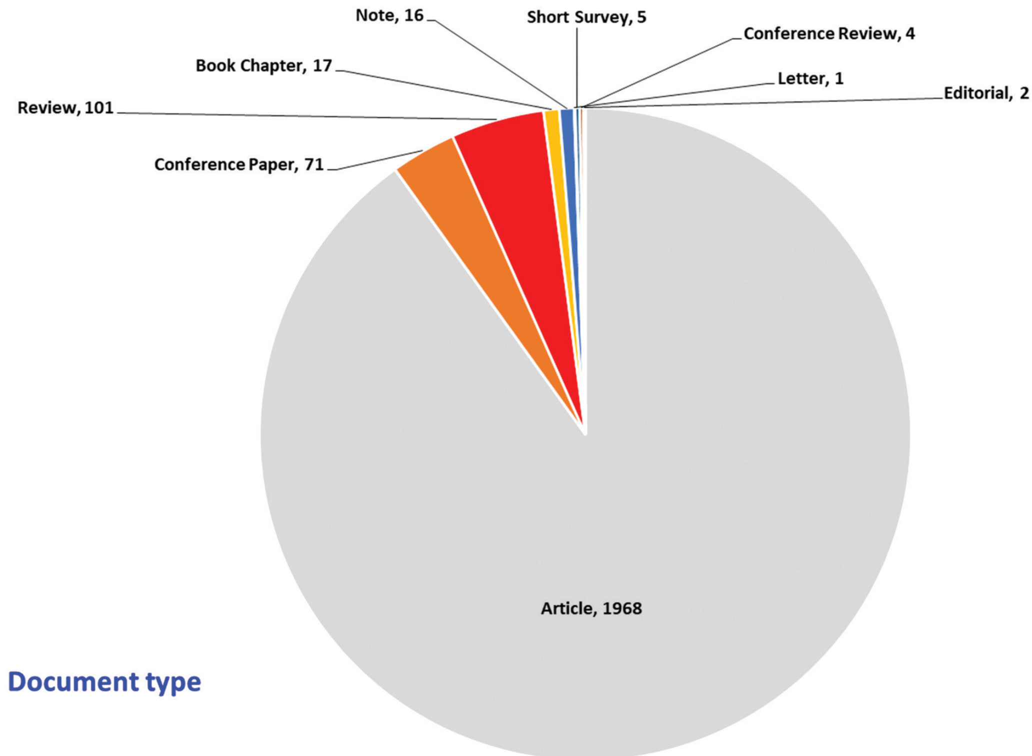

FIGURE 1.2 Distribution by types of document on *Coriandrum sativum* from 2000 to 2020 (www.scopus.com).

on *Coriandrum sativum*, which include research contributions (1968), review articles (101), and conference papers (71). The contributions are related to the subject fields (Figure 1.3) of agricultural and biological sciences (1227 contributions), biochemistry, genetics, and molecular biology (432 contributions), pharmacology, toxicology, and pharmaceutics (406 contributions), chemistry (321 contributions), medicine (308 contributions), environmental science (264 contributions), immunology and microbiology (128 contributions), and engineering (97 contributions).

Scientists from India (604), the USA (189), Brazil (152), Iran (142), Pakistan (106), Turkey (91), Egypt (80), China (70), Italy (63), Germany (59), Japan (57), and Saudi Arabia (51) emerged as major authors (Figure 1.4). The scientific journals with the highest numbers of contributions were *Acta Horticulturae* (40), *Food Chemistry* (37), *Industrial Crops and Products* (34), *Journal of Ethnopharmacology* (34), *Indian Journal of Agricultural Sciences* (26), *Journal of Agricultural and Food Chemistry* (24), *Journal of Essential Oil Bearing Plants* (24), *Journal of Essential Oil Research* (23), *Horticultura* Brasileira (21), and *Journal of Food Science and Technology* (19).

1.5 AIMS AND FEATURES OF THE BOOK

To the best of our knowledge, it is not easy to find a book reporting on *Coriandrum sativum* cultivation, biochemistry, and functionality in the international scientific literature. Therefore, this book aims to be a scientific base for multidisciplinary discussions on *Coriandrum sativum*, emphasizing its cultivation, harvest, biochemistry, functionality, health-enhancing traits, processing, and technology. The impact of conventional and innovative processing on the recovery of bioactive constituents from *Coriandrum sativum* bio-wastes and agro-byproducts is discussed. In addition, this handbook reports the potential uses of *Coriandrum sativum* in foodstuffs, cosmetics, and pharmaceuticals.

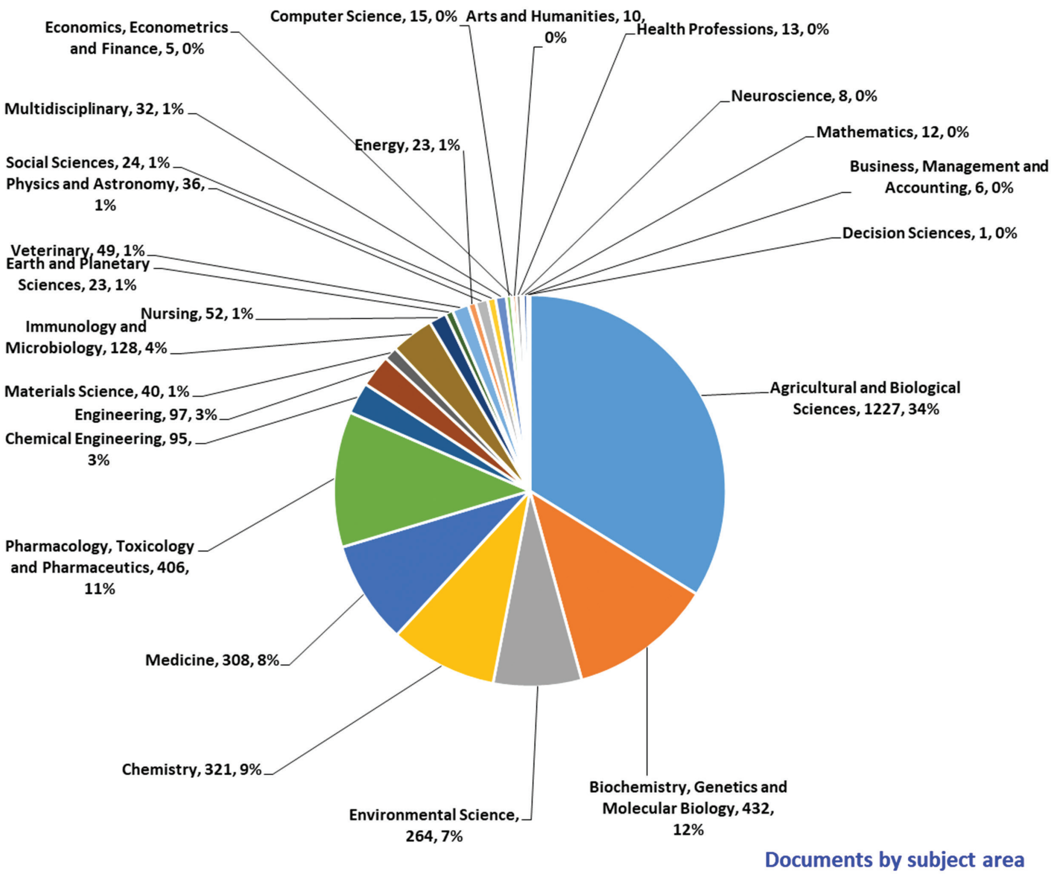

FIGURE 1.3 Distribution by subject area of documents on *Coriandrum sativum* from 2000 to 2020 (www.scopus.com).

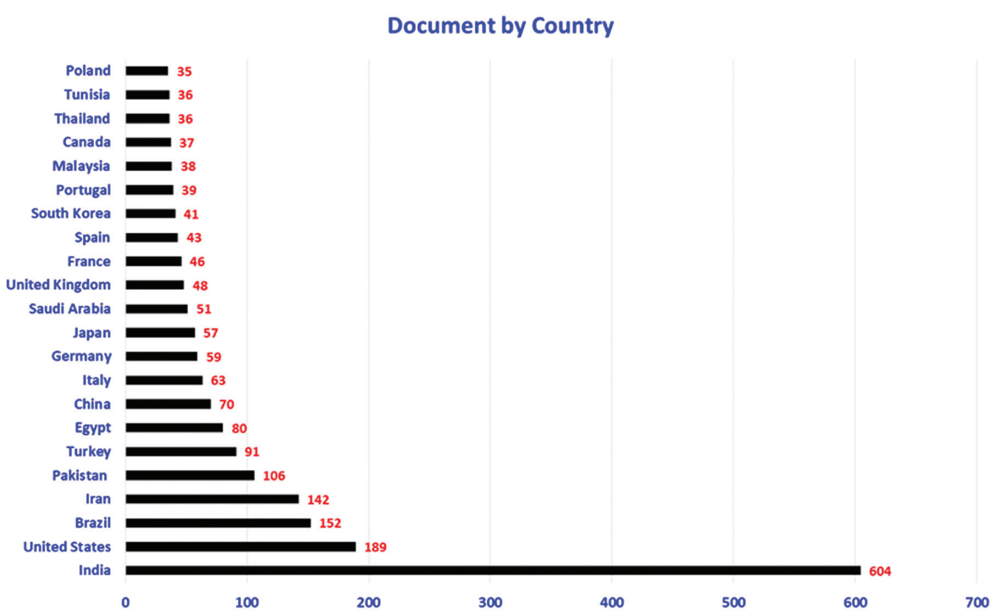

FIGURE 1.4 Distribution by country of documents on *Coriandrum sativum* from 2000 to 2020 (www.scopus.com).

The book chapters discuss recent advances in phytochemistry, cultivation, and food sciences research. The book contains comprehensive chapters under main sections, namely:

Section I: Coriander: Cultivation, Composition, and Applications
Section II: Coriander Leaves: Chemistry, Technology, Functionality, and Applications
Section III: Coriander Fixed Oil: Chemistry, Technology, Functionality, and Applications
Section IV: Coriander Essential Oil: Chemistry, Technology, Functionality, and Applications
Section V: Coriander Extracts: Chemistry, Technology, Functionality, and Applications

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Section I

Coriander

Cultivation, Composition, and Applications

2 Coriander Cultivation and Agricultural Practices

Lydia N. Horn, Eduardo P. Mulima and Felicitas M. Fwanyanga

CONTENTS

2.1 INTRODUCTION

Coriander (*Coriandrum sativum* L.) is an important spice plant that has been known to humankind since 5000 BC (Arora *et al*., 2021; Al-Snafi, 2016). This annual spice crop belongs to the Apiaceae family and has been cultivated for many years worldwide; it contains 3700 species, including carrots, celery, and parsley. It is known to be one of the first spices to be used by humankind as a flavoring substance. It is indigenous to the Mediterranean region and famous in India, Morocco, Russia, Hungary, Poland, Romania, Guatemala, Mexico, Turkey, and Argentina (Coskuner and Karababa, 2007). The belief in the Mediterranean region as its origin was based on discovering its desiccated fruits in various archaeological sites in that region (Arora *et al*., 2021). In addition, it has a wide range of diversity that could be distinguished in different groups (Diederichsen, 1996). The most commonly used parts of the plant are the fresh leaves and dried seeds during cooking. It is a good source of antioxidants, and it may help people use less salt and reduce their sodium intake (Rao and Garg, 2020). In addition, coriander fruits have an aromatic odor and pleasant aromatic taste (Banerjee, 2020). The odor and taste are due to the essential oil content that varies from 0.1 to 1% in the dry seeds (Arora *et al*., 2021; Sharmeen *et al*., 2021; Shivanand, 2010). The main components of the essential oil include linalool, linalyl acetate, geranial, camphor, limonene, geranyl acetate, and

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γ-terpinene (Shivanand, 2010; Sharmeen *et al*., 2021). Linalool is the extract's main bioactive compound (70%). It is used as an additive for processed food, beverages, and fragrance ingredients in cosmetics and household detergent (Sarkic and Stappen, 2018). It is the main compound responsible for cilantro seeds' antimicrobial and anti-diabetic effects. As a medicinal plant, coriander has been used as an antifungal (Basilico and Basilico, 1999), antioxidant (Chithra and Leelamma, 1999), hypolipidemic, antimicrobial (Silva and Domingues, 2015 and Sourmahi *et al*., 2015), hypocholesterolemic, and anticonvulsant agent (Raza and Choudhary, 2000). In the traditional medicinal system, the leaves and fruits of the plant have been used to treat skin disease, and its paste is applied by mixing in water to wash the face and forehead. Also, it has been used as a carminative, stimulating, diuretic, tonic, stomachic agent to get rid of bad breath and mouth diseases (Aissaoui *et al*., 2008). Coriander is a warm-climate crop and could be well cultivated on almost all soils even though it prefers fertile and well-drained soil for maximum performance (Kassu *et al*., 2018).

2.2 HISTORY AND ORIGIN

Coriandrum sativum originated in the Italian parts of the Mediterranean region, and it spread as a spice plant to India, China, Russia, Central Europe, and Morocco, wherein the plant has been cultivated since human antiquity (Arora *et al*., 2021; Foudah *et al*., 2021; Al-Snafi, 2016). Pathak *et al*. (2011) reported that coriander is indigenous to Italy. However, it is widely cultivated in the Netherlands, Central and Eastern Europe, the Mediterranean (Morocco, Malta, and Egypt), China, India, and Bangladesh. Coriander is mentioned in the papyrus of Ebers and the writings of Cato and Pliny and was also well known in England before the Norman Conquest (Shivanand, 2010). Ukraine is the major producer of coriander oil and controls the world price on a supply and demand basis. In India it is chiefly found in Madhya Pradesh, Maharashtra, Rajasthan, Andhra Pradesh, Tamil Nadu, Karnataka, and Bihar (Shivanand, 2010).

2.3 PRODUCTION PRACTICES

Even though coriander production can be done at any time of the year, the crop is highly sensitive to dry and warm climates, and its production is mainly for leaf purposes and a higher grain yield (Banerjee, 2020). The best season for grain production is when it is grown in dry and cold weather, free from frost, especially during the flowering and fruit setting stage (Banerjee, 2020). Cloudy weather is not favorable, especially during the flowering and fruiting stages, because this weather attracts pests and diseases which attack the crop. In addition, heavy rain is detrimental to the crop as it causes much damage; therefore, irrigation while undercover in a shaded place is much recommended for coriander (Singh *et al*., 2020). The crop can be cultivated on almost all types of soils, supplied by sufficient organic matter (Banerjee, 2020). Coriander yield is determined by the interaction of various agronomic factors, with the main factors being soil nutrition and pest control. The coriander's nutrition is crucial, of which nitrogen is the most important external nutrient for seed yield and plant growth. Coriander yield is determined by the interaction of various agronomic factors, wherein the main factors are soil nutrition and pest control. According to Singh *et al*. (2020), plant nutrition is crucial to coriander, with nitrogen being the most important external nutrient factor that regulates seed yield. Well-maintained nutrients and proper irrigation could enhance coriander seed yield by 10–70% (Singh *et al*., 2020).

2.4 MORPHOLOGY

Coriander is an annual herb up to 90 cm tall or 20 to 140 cm depending on agro-climatic conditions (Yasir *et al*., 2019). The plant has many branches and sub-branches with small leaves used as an herb. The new leaves are oval, but aerial leaves are elongated, while the flowers are white, having slightly brinjal-like shades, while fruits are round in shape (Pathak *et al*., 2011). The whole plant, especially the unripe fruit, is characterized by a strong disagreeable odor (Shivanand, 2010). Different varieties of *Coriandrum sativum* that differ in fruit size have been reported (Al-Snafi, 2016). In addition, coriander plant is characterized by its aromatic smell and flavor (Burdock and Carabin, 2009). The lower leaves are broad with crenate-lobed margins, and the upper one is finely cut with linear lobes. The flowers can be white or pinkish arranged in compound terminal umbels, while the fruits are nearly globular in shape and yellow-brown schizocarp. The plant requires a warm, dry summer with short, rainy winters and is cultivated as a cold-weather crop (Foudah *et al.*, 2021).

2.5 PHYTOCHEMISTRY

Coriander has been known and used as a flavor plant for many dishes, and it is also used to treat some diseases and could be used for its anticancer and antifungal properties, to reduce pain and inflammation, to improve skin health, and as a natural preservative (Mandal and Mandal, 2015). According to Shivanand (2010), green coriander seeds contain up to 1.8% volatile oil. Depending on the source, the distilled oil contains 65–70% of (+)-linalool (coriandrol) and smaller amounts of α-pinene, γ-terpinene, limonene, and ρ -cymene together with various non-linalool alcohols and esters. Other constituents isolated from the fruits include flavonoids, coumarin, *iso*-coumarines, phthalides, and phenolic acids. Al-Snafi (2016) reported that the phytochemical screening of coriander displayed the presence of essential oil, tannins, terpenoids, reducing sugars, alkaloids, phenolics, flavonoids, fatty acids, sterols, and glycosides. Equally important, the essential oil from coriander leaves was reported to be dominated by aldehydes and alcohols. The major constituents were 2E-decenal (15.9%), decanal (14.3%), 2E-decen-1-ol (14.2%), and n-decanol (13.6%). Other constituents present in fairly good amounts are 2E-tridecen-1-al (6.75%), 2E-dodecenal (6.23%), dodecanal (4.36%), undecanol (3.37%), and undecanal (3.23%) (Matasyoh *et al.*, 2009). The nutritional composition is important to determine its contribution to people's health. According to USDA (2013), the nutrient composition of coriander is based on the leaves and seeds (Table 2.1).

2.6 PHARMACOLOGICAL USES

2.6.1 Antioxidant Properties

The properties of coriander cannot be underestimated due to its nutritional benefits and its health or medicinal benefits. One of the most well-known and characterized functions of coriander is the antioxidant activity. Antioxidants are compounds that inhibit oxidation, a chemical reaction that can produce free radicals and chain reactions that may damage the cells of organisms. Marangoni and Moura (2011) reported that the use of coriander essential oil presented a stronger synthetic antioxidant effect than that of butylhydroxytoluene (BHT) on the retardation of lipid oxidation. Coriander seeds were also reported to possess antioxidative traits (Deepa and Anuradha, 2011).

Jia *et al.* (2012) suggested that coriander can be safely used as a natural antioxidant and an alternative to synthetic additives for long-term storage in the feed or food industry. A study on the antioxidant properties of coriander root suggested another potential antioxidant property of coriander oil in preventing oxidative stress-related diseases (Tang *et al.*, 2013). Furthermore, Crespo *et al.* (2019) evaluated antioxidant activity in mixtures of three essential oils: *Apium graveolens*, *Thymus vulgaris*, and *Coriandrum sativum*, using the Simplex Lattice Mixture Design, and the mixture of the three oils showed the best antioxidant activity and also had the highest synergistic effect. Another study investigating the anti-inflammatory and antioxidant effects of coriander extract on liver ischemia reperfusion injury at light microscopic and biochemical levels revealed decreased apoptotic cell death and liver enzymes in liver ischemia/reperfusion injury (Kükner *et al.*, 2021). The essential oil extracted from the coriander chemotype grown in the Al-Kharj region of Saudi Arabia was noted to contain low antioxidant potential (Foudah *et al.*, 2021).

TABLE 2.1
Nutrient Composition of Coriander Found in Leaf and Seed (USDA, 2013)

	Amount (per 100g)	
Nutrient	**Coriander Leaf**	**Coriander Seed**
Water	7.30 g	8.86 g
Energy	279 kcal	298 kcal
Protein	21.9 g	12.3 g
Total lipid (fat)	4.78 g	17.7 g
Carbohydrate, by difference	52.1 g	54.9 g
Fiber, total dietary	10.4 g	41.9 g
Calcium, Ca	1246 mg	709 mg
Iron, Fe	42.4 mg	16.3 mg
Magnesium, Mg	694 mg	330 mg
Phosphorus, P	481 mg	409 mg
Potassium, K	4466 mg	1267 mg
Sodium, Na	211 mg	35.0 mg
Zinc, Zn	4.72 mg	4.70 mg
Vitamin C, total ascorbic acid	566 mg	21.0 mg
Thiamin	1.25 mg	0.24 mg
Riboflavin	1.50 mg	0.29 mg
Niacin	10.7 mg	2.13 mg
Vitamin B-12	0.00 sg	0.00 sg
Vitamin A, RAE	293 sg	0.00 sg
Vitamin A, IU	5850 IU	0 IU
Vitamin D (D2 + D3)	0.00 sg	0.0 sg
Vitamin D	0 IU	0 IU
Fatty acids, total saturated	0.115 g	0.990 g
Fatty acids, total monounsaturated	2.23 g	13.5 g
Fatty acids, total polyunsaturated	0.32 g	1.75 g
Cholesterol	0.0 g	0.0 g

2.6.2 Antimicrobial Effects

The antibacterial activities of different medicinal plants have been known for a long time, and several research activities on the antibacterial effect of spices, essential oils, and their derivatives have been reported. Matasyoh *et al.* (2009) screened coriander oil for antimicrobial activity against both Gram-positive and Gram-negative bacteria and a pathogenic fungus. The oil showed pronounced antibacterial and antifungal activity against all microbes tested (Matasyoh *et al.*, 2009). The study by Oudah and Ali (2010) on cold aqueous extract of seeds for 48 h revealed antibacterial activity for all tested bacteria. Another study on ethanol extracts of seeds, leaves, and stems for 48 h showed antibacterial activity (Soares *et al.*, 2012). According to Duarte *et al.* (2012), apart from being widely used as an essential oil, coriander oil can act as a potential improver agent of antibiotics against *Acinetobacter baumannii*. Sambasivaraju and Za's (2016) study on five bacteria (*Staphylococcus aureus*, *Escherichia coli*, *Klebseilla*, *Pseudomonas*, and *Salmonella*) using antibiotic coriander oil revealed a highest antibacterial action against *E. coli* which was better than Gentamicin. Recently, Foudah *et al.* (2021) explored the antimicrobial effects of coriander leaf essential oil cultivated in Saudi Arabia, and they confirmed that the essential oil extracted from coriander possesses superior antimicrobial effect.

2.7 TRADITIONAL/MEDICINAL BENEFITS

Coriander is one of the well-known and favored traditional spices (Choudhary and Punjabi, 2012). Green coriander contains about 169 mg/100 g of vitamin C and 12 mg/100 g of vitamin A. Coriander has a high nutrition component, being rich in vitamins, minerals, and iron, basically due to its green leaves and dried fruits (Bhat *et al*., 2014). It is very low in saturated lipids and cholesterol, and it has abundant thiamine, zinc, and dietary fiber. Apart from aromatic and culinary value, the main component of the essential oil, which is made up of hydrocarbon and oxygenated compounds, produces several fragrant substances with various smells. The plant parts are used to treat different disorders in traditional medicine (Foudah *et al*., 2021).

2.8 CULTIVATION

2.8.1 Varieties

Coriander is an annual herb that prefers cool weather, and it is cultivated either as a summer or winter annual crop (Banerjee, 2020; Al-Snafi, 2016). The genus *Coriandrum* contains *C. sativum* and *C. tordylium* (Fenzl) Bornm, of which *C. sativum* is widely cultivated, while *C. tordylium* grows wild (Turin *et al*., 2021). Being a tropical plant, coriander prefer a frost-free tropical climate that is cool and comparatively dry during flowering and seed formation (Kassu *et al*., 2018). Coriander cultivation is strongly related to its leaves or seeds (Bhat *et al*., 2014; Yasir *et al*., 2019). There are varieties bred for each purpose, where the varieties for seed will produce seed quicker than a leaf variety. The leaf varieties will also develop flowers but not faster than the seed varieties to ensure the plants focus their energy on growing new leaves as required.

2.8.2 Field Preparation

Coriander is grown well in the winter season; however, the timing of sowing depends on the purpose. For example, it can be grown throughout the year for leaf purposes (Kassu *et al*., 2018). For good germination and growing, it is recommended that coriander seeds be planted in light, and well-drained soil (Singh and Singh, 2014). It is recommended that planting be done immediately after ploughing to avoid soil moisture loss and break the clods. Where the soil moisture is insufficient, watering before planting is recommended to help germinate seeds. Where cultivation depends on the rain, especially in communal areas or farms where dry land cultivation is practiced, ploughing should be done immediately after the rain for soil moisture conservation.

2.8.3 Sowing

Coriander herb likes cold-weather, well-cultivated soils, and can tolerate poor soil fertility and withstand full sun, with the best month for leaf production being late spring and autumn (Kassu *et al*., 2018). The plant can also grow well in pots or trays filled with good multipurpose compost. Planting can be done with five seeds per hill at the spacing of 20 cm between rows and 20 cm between plants (Singh and Singh, 2014). This is done to allow the plants to grow to their full size. The seed rate is 10–15 kg/ha, and seeds should be soaked in plain water overnight and split in two halves in the morning before sowing for better germination (Singh and Singh, 2014). When planting, the best and recommended practice is to plant directly into the soil to avoid transplanting, which distorts the crop and negatively affects it. Germination takes up to three weeks; therefore, it is better for the seeds to be sown at three-week intervals (Turin *et al*., 2021). The plants need to be watered in dry periods; ensure that the soil never dries out.

2.8.4 Pest and Diseases

Coriander is susceptible to various disease-causing pathogens such as vascular wilt, stem root, root rot, charcoal rot, seedling blight, stem gall, leaf blight, anthracnose, powdery mildew, seed rot, grain mold, bacterial blight, soft rot, seedling root rot, reniform and root-knot nematodes, and phyllody as well as virus diseases (Khare *et al*., 2017). Several known resistant varieties are the best option to control the diseases and nutrition effects. In order to achieve year-round cultivation, production can be done under protected structures such as shade nets and greenhouses (Turin *et al*., 2021). In a field investigation on an insect-pests scenario of coriander in Rabi, it was reported that the coriander crop received an infestation of 15 pest species from different orders and families (Meena *et al*., 2018). Three species of aphids (*Hyadaphis coriandri*, *Aphis gossypii*, and *Myzus persicae*) and thrips (*Thrips tabaci*, *Scirtothrips dorsalis*, and *Frankliniella schultzei*), and one species each of seed wasp (*Systole albipennis*), seed bug (*Nysius* sp.), painted bug (*Bagrada hilaris*), and tobacco caterpillar (*Spodoptera litura*) were reported as pests of major status (Meena *et al*., 2018).

2.9 HARVESTING

Coriander reaches maturity 100–150 days after sowing, and this depends on the variety used and climatic conditions in an area. According to Kassu *et al*. (2018) and Singh and Singh (2014), straw yield (q/ha) of coriander under irrigation is obtained from 10 to 15 q/ha. Under unirrigated (barani) cultivation, the average yield is low, being 4 to 5 q/ha, and in a mixed crop, it is 1.5 to 3.0 q/ha. Under managed conditions, yields up to 20 q/ha in unirrigated, and up to 25 q/ha in irrigated conditions can be obtained. The crop grown exclusively for leaf purposes yielded green leaves of about 50–80 q/ha with 3–4 cuttings depending upon cultivars, climate, and management practices. For fresh leaves, 1 or 2 cuttings are taken 45 and 60 days after sowing (Kassu *et al*., 2018). Depending on the purpose of the plant, for leaves harvest when the plants are big and robust enough to cope, while for seeds, wait until the flowers have died off. It has to be done when the grain changes its color to straw or light brown. If harvesting is delayed, seed shattering and splitting may occur. Harvesting leaves is done by plucking the leaves, cutting each leaf off the stem, or sniping the whole stem. For seeds, the stem is cut and placed in a paper bag, with stems sticking out and hanging upside down in a cool, dry place to allow drying. After three weeks, shake the bag, and seeds will fall out from the flowers; keep them dry. The seeds can be used for spices or re-sowing in the following cropping season.

2.10 POSTHARVEST TECHNOLOGY

Coriander leaves are used as fresh green vegetables or salad leaves, while the seeds are processed into oil and used for a range of medical applications (Yasir *et al*., 2019). The oil has antibacterial properties and treats colic, neuralgia, and rheumatism (Ali, 2008). The correct stage for harvesting the coriander seed is 90 days from planting, ripe with a full aroma. Since ripening is progressive on the plant, harvesting is ideal when between half and two-thirds of the seeds are ripe. The coriander is mainly consumed in an unprocessed form, but it can also be processed to simplify the international commercialization, viability, and palatability (Singh *et al*., 2020). The plant is commonly used for making sauces and salsas or blended into powder for flavoring products like meat, fish, sodas, pickles, bakery, and curry recipes. To process this herb, it is essential to know the optimum harvest period to ensure maximum plant material production and maintain the best property of the spice product (Douglas *et al*., 2005). The leaves and seed are the parts of the plant that are commonly processed, either in green or ripe fruits.

The seed is pale yellow with a characteristic odor and taste (Diederichsen, 1996). The harvested fresh leaves are properly washed and kept in shape for drying to be powdered in a disintegrator and micro-pulverized to avoid losing flavor before packing (Bhat *et al*., 2014). The drying process is carried out in different ways: sun drying, microwave drying, freeze-drying, etc. Microwave drying showed higher chlorophyll content than those drying methods, and the green color was preserved better than the air-dried and freeze-dried samples (Bhat *et al*., 2014). The other methods to process the leaves are converted into various products like purees and pastes used in fast food trades. The mature brown seeds can be used and ground to form a powder. Also, seeds can be dried and stored as whole or infused to make delicious vinegar. The ripe seeds may be sometimes processed to obtain the essential oil. Coriander seeds are an excellent source of volatile and crude oil, tannins, saponins, cellulose, pentosans, and pigments. The oil is mainly obtained by steam distillation and supercritical CO_2 extraction. It is characterized by its odor of linalool and warm aromatic flavor (Bhat *et al*., 2014).

2.10.1 Drying

There are various ways of drying coriander; this varies with the purpose of utilization. Seeds are dried in paper bags facing down with the stem sticking out, while the whole plant is spread out in the sun to dry and left to wither for two days until the moisture content is about 18% (Ali, 2008). After drying, threshing can remove the seeds, and dry them in the shade to prevent overheating until the moisture content is about 9%. This process could be done using driers at a temperature below 100°C to avoid reducing volatile oils.

2.10.2 Oil Extraction

The seed is ground immediately prior to distillation to increase oil yield and reduce the distillation time (Bhat *et al*., 2014). The essential oil content varies from 0.1 to 1.5% and contains a range of different compounds (Foudah *et al*., 2021). Steam distillation is a traditional method for the extraction of essential oil from coriander seeds. However, the alteration of chemical constituents of essential oils is a significant problem associated with hydro-distillation methods; this leads to the destruction of the heat-sensitive compounds (Geed *et al*., 2012). Solvent extraction is an alternative method to steam distillation methods, but the method also has the problem of destroying thermally liable constituents due to the application of high temperatures (Stahl *et al*., 1987). This problem could be addressed by using green processing technology, i.e., supercritical CO_2 extraction (Said *et al*., 2014).

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3 Greenhouse Production of Coriander

Mairton Gomes da Silva, Hans Raj Gheyi and Tales Miler Soares

CONTENTS

3.1 INTRODUCTION

Coriander (*Coriandrum sativum* L.) is one of the most important spices and has been used in folk medicine since ancient times (Wei et al., 2019). It is cultivated in several countries (Rashed and Darwesh, 2015; Fikadu-Lebeta et al., 2019; Fattahi et al., 2021), driven by its use in cooking, for giving flavor and aroma to different dishes (Guha et al., 2014; Sharangi and Roychowdhury, 2014a; Gastón et al., 2016; Pacheco-López et al., 2016; Abbassi et al., 2018).

Fresh coriander leaves are widely used in salads (Sagarika et al., 2014; Mandal and Mandal, 2015; Izgi et al., 2017; Almeida et al., 2019; Afshari et al., 2021; Arora et al., 2021), being rich in vitamins, proteins and other minerals (Nadeem et al., 2013; Katiyar et al., 2014; Kassu et al., 2018; Hosseini et al., 2021), with insignificant contents of cholesterol and saturated fats (Anjukrishna et al., 2021).

Dried leaves and seeds are also used as spices and food ingredients (Guha et al., 2016; Gholizadeh et al., 2018). In addition to its culinary use (leaves and seeds), its essential oil (as discussed in other chapters) is used in the food, cosmetic and pharmaceutical industries due to its medicinal properties (Khalid, 2012; Ramezani et al., 2009; Rahimi et al., 2013; Hassan and Ali, 2014; Katar et al., 2016; Unlukara et al., 2016; Izgi, 2020; Khodadadi et al., 2021).

To produce fresh biomass, coriander is cultivated throughout the year. According to Table 3.1, in the study by Gowtham and Mohanalakshmi (2018) in Coimbatore, India, the production of fresh coriander biomass varied according to the time of year, as recorded in other studies in Northeastern Brazil, such as in Mossoró, RN (Lima et al., 2007), and Itabaiana, SE (Tavares, 2016).

Due to climate change, under open field conditions, the trend is for the production of coriander, as well as other leafy vegetables, to be increasingly affected by extreme events, whether by water restriction (i.e., coriander irrigation is compromised by lack of water) or by excess. As several authors point out (Ghamarnia and Daichin, 2013; Saxena et al., 2013; Meneses et al., 2014; Sharangi and Roychowdhury, 2014b; Harisha et al. 2019), the lack of water supply, depending on the growth stage, can harm the yield and quality of coriander.

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TABLE 3.1
Leaf Fresh Biomass per Area (kg m^{-2})* of Coriander Grown in Different Months of Sowing and under Cultivation Conditions in Protected Environment and Open Field, in Coimbatore, India

	Cultivation Conditions	
Time of Sowing	**Protected Environment***	**Open Field***
September	2.34	1.16
October	2.46	1.26
November	2.17	1.13
December	2.04	1.10
January	1.83	1.05
February	1.64	0.83
March	1.83	
April	1.49	
May	2.14	

Source: Adapted from Gowtham and Mohanalakshmi (2018).
* Values originally in the unit t ha^{-1}.

Excess water causes leaf burning by leaf blight (*Alternaria dauci*), which is the main disease that affects coriander in the hot and rainy season of the year, which can cause product shortage and increase its market price (Reis and Lopes, 2016).

To mitigate adverse effects of the climate, such as excess and/or lack of rain, high temperatures, etc., among other abiotic and biotic factors, cultivation in a protected environment (a greenhouse) has been used and has promoted gains in production when compared to the open field, as shown in Table 3.1 in the study by Gowtham and Mohanalakshmi (2018).

This chapter is focused on the production of fresh coriander biomass in a protected environment in different countries under different growing conditions.

3.2 IMPORTANCE OF CORIANDER IN WORLDWIDE AND IN BRAZIL

The importance of coriander globally is very high, given the large number of studies involving this crop under different growing conditions, as shown in Tables 3.1, 3.2 and 3.3. Coriander is cultivated in practically every country in the world (Elhindi et al., 2016), and its production is mostly to supply local markets (Reis and Lopes, 2016). With the cultivation of coriander throughout its territory (Godara et al., 2014; Lal et al., 2017; Chethan et al., 2019), India is the country that stands out as the largest producer, consumer and exporter in the world (Singh, 2014; Lal et al., 2014a; Verma et al., 2014; Crespo et al., 2017; Shashidhar et al., 2017; Kumawat et al., 2017; Hongal et al., 2018), followed by Mexico, Russia and Iran (Fatemi et al., 2020). Although India has a larger area cultivated with coriander, production per unit area is rather low compared to other countries (Singh et al., 2018).

In Brazil, mainly in the North and Northeast regions (Pereira et al., 2011; Almeida et al., 2014; Santana et al., 2019; Freitas et al., 2020), as well as in other countries (Meyering et al., 2020; McAusland et al., 2020; Serri et al., 2021), fresh biomass in the form of bunches is one of the main ways of marketing coriander for use in cooking and in fresh salads (Cardoso et al., 2017).

For the production of fresh biomass, coriander is cultivated throughout the year in Brazil (Souza et al., 2017; Silva et al., 2018a), in general, by small farmers, in domestic and community gardens (Ferreira Neto et al., 2014; Pinto et al., 2018; Menezes et al., 2020a), thus playing a prominent role

TABLE 3.2
Shoot Fresh Biomass (SFB) per Plant of Coriander Grown under Different Cultivation Conditions in Protected Environment

Location	Cultivar	Cultivation Conditions	Growth Days/Season	SFB (g plant^{-1})	Reference
Mossoró – RN, Brazil	'Português'	In pots with soil mixed with cotton compost at 180 g pot^{-1}	26 DAE/winter	3.33c	Pereira et al. (2011)[#I]
	'Super Verdão'			12.60b	
	'Tabocas'			16.60b	
	'Verdão'			20.40a	
Recife – PE, Brazil	'Tabocas'	In pots with sand	45 DAS	14.42aA[(1)]	Bonifacio et al. (2014)[##]
				5.11bA[(2)]	
	'Verdão'			12.61aB[(1)]	
				5.54bA[(2)]	
Cáceres – MT, Brazil	'Português'	In seedbeds in the soil	43 DAS/winter	13.65a	Marsaro et al. (2014)[###]
	'Verdão'			15.28a	
	'Português'		50 DAS/winter	17.31b	
	'Verdão'			24.76a	
Recife – PE, Brazil	'Verdão'	In pots with substrates	60 DAS/spring – summer	0.93[(3)]	Vasconcelos et al. (2014)
				1.75[(4)]	
Recife – PE, Brazil	'Verdão'	In pots with soil	22 DAS + 22 DAT	6.82[(5)]	Lira et al. (2015)[II]
				4.12[(6)]	
Tehran, Iran		In pots with soil	14 DAS + 45 DAAT	~ 4.70a	Ahmadi and Souri (2018)[$III]
				~ 2.80b	
Cruz das Almas – BA, Brazil	'Verdão SF 177'	Plastic bags with substrates using tap water for irrigation	35 DAAT	6.54	Passos et al. (2018)
Islamabad, Pakistan		In pots with soil		3.26[(7)]	Ullah et al. (2018)[I]
Jeddah, Saudi Arabia		In pots with soil using fertilizer treatment with plant growth-promoting bacteria (KB-10) and silicon	30 DAS/autumn	~ 7.90	Al-Garni et al. (2019)[$$]
Chapadinha – MA, Brazil	'King'	In pots with soil mixed with fermented organic substrate and using only water for irrigation	30 DAS/autumn–winter	2.16a	Araújo et al. (2019)[$$$IV]
	'Tabocas'			1.86a	
Tehran, Iran		In pots with sand	14 DAE + 35 DAAT/spring	~ 3.30[(8)]	Mohammadipour and Souri (2019)
Arapiraca – AL, Brazil		In pots with soil	30 DAS/winter	0.69[(9)]	Silva et al. (2019b)[I]

(*Continued*)

TABLE 3.2 (CONTINUED)
Shoot Fresh Biomass (SFB) per Plant of Coriander Grown under Different Cultivation Conditions in Protected Environment

Location	Cultivar	Cultivation Conditions	Growth Days/Season	SFB (g plant^{-1})	Reference
Cruz das Almas – BA, Brazil	'Verdão'	In pots with soil without cattle manure	40 DAS/winter	3.66(10)	Costa (2020)
		In pots with soil mixed with cattle manure		6.68(11)	
Sari, Iran		In pots with soil	45 DAS + 30 DAAT	~ 0.87a(12)	Rabiei et al. (2020)&
				~ 0.88a(12)	
				~ 0.82A(13)	
				~ 0.88B(13)	

Means followed by the same letter do not differ significantly at $p = 0.05$ by Tukey test.

Lowercase letters compare the means of the salinity levels ((1) 0 mM NaCl – control and (2) 100 mM NaCl) for each coriander cultivar, and uppercase letters compare the means of the cultivars at each salinity level at $p = 0.05$ by Tukey test.

In each cultivation period, means followed by the same letter do not differ significantly at $p = 0.05$ by Tukey test.

(3) and (4) Values obtained when the coriander plants were grown in the nutrient solutions of Castellane and Araújo (1994) and Furlani et al. (1999) under electrical conductivities (ECsol) of 2.07 dS m^{-1} (SFB = –0.176**ECsol^2 + 0.729**ECsol + 0.173; ** significant at $p \leq 0.01$ by t-test) and 1.63 dS m^{-1} (SFB = –0.664**ECsol^2 + 2.169**ECsol – 0.021; ** significant at $p \leq 0.01$ by t-test), respectively.

(5) and (6) Values obtained when the coriander plants were grown under electrical conductivity of the soil saturation extract (ECse) of 1.86 dS m^{-1} under soil moisture at 100% (SFB = –2.2841**ECse + 24.697**; ** significant at $p \leq 0.01$ by t-test) and 75% (SFB = –1.3957**ECse + 14.966; ** significant at $p \leq 0.01$ by t-test) of container capacity, respectively.

$ Means followed by the same letter do not differ significantly at $p = 0.05$ by LSD test, obtained without salt stress and under irrigation water salinity of 2.0 dS m^{-1} (from mixed K_2SO_4 + $MgNO_3$), respectively.

(7) Value obtained under ECse of 4.0 dS m^{-1}.

$$ Value obtained without salt stress.

$$$ Means as a function of the coriander cultivars followed by the same letter do not differ significantly at $p = 0.05$ by Tukey test.

(8) Value obtained when the coriander plants were grown under glycine concentration of 10 mg L^{-1}.

(9) Value obtained when the coriander plants were grown under irrigation water depth (IWD) of 171.13% of the crop evapotranspiration (SFB = –0.0004*IWD^2 + 0.1369*IWD – 4.844; * significant at $p \leq 0.05$ by t-test).

(10) and (11) Values obtained when the coriander plants were grown under doses of cassava wastewater (CW) of 60.00 m^3 ha^{-1} (SFB = 0.0521CW + 0.536) and 47.71 m^3 ha^{-1} (SFB = –0.0014CW^2 + 0.1336CW + 3.4949), respectively.

(12) Means followed by the same lowercase letter are not significantly different at $p \leq 0.05$ by LSD test, obtained under salinity levels of 0 mM NaCl – control and 80 mM NaCl, respectively.

(13) Means followed by the same uppercase letter do not differ significantly at $p \leq 0.05$ by LSD test, obtained without plant growth-promoting rhizobacteria (PGPR) and with PGPR, respectively.

& Value originally in the unit mg plant^{-1}.

[I], [II], [III] and [IV] Initially obtained yields of 10, 3, 20 and 30 plants pot^{-1}, respectively.

DAE – days after emergence; DAS – days after sowing; DAT – days after transplanting; DAAT – days after application of treatments.

TABLE 3.3
Shoot Fresh Biomass per Area (SFBA) of Coriander Grown under Different Cultivation Conditions in a Protected Environment

Location	Cultivar	Cultivation Conditions	Growth Days/ Season	SFBA (kg m^{-2})	Reference
Brasília – DF, Brazil	'Verdão'	In wooden seedbeds with substrates	33 DAS/autumn[#] 58 DAS/autumn[##]	3.05[(1)&] 1.35[(2)]	Kaneko (2006)[I]
Recife – PE, Brazil	'Tabocas'	In seedbeds in the soil under irrigation water depth of 120% of the reference evapotranspiration	46 DAS/summer 52 DAS/autumn	2.26[(3)] 2.41[(4)]	Albuquerque Filho et al. (2009)[II]
Cáceres – MT, Brazil	'Português' 'Verdão' 'Português' 'Verdão'	In seedbeds in the soil	43 DAS/winter 50 DAS/winter	0.73a 0.81a 0.92b 1.32a	Marsaro et al. (2014)[$II]
Viçosa – MG, Brazil	'Vedete'	In seedbeds in the soil	17 DAS + 29 DAT/spring	2.90[&&]	Angeli et al. (2016)[$$]
Fortaleza – CE, Brazil	'Verdão'	In trays with substrate with volume of 0.031 dm^3 $cell^{-1}$ with 12 plants	30 DAS/spring	1.56	Olimpio (2017)[II]
Capitão Poço – PA, Brazil	'Verdão'	In wooden seedbeds with soil mixed with aquatic macrophytes as substrate at 50%	37 DAS/winter	7.09a	Esteves Junior and Oliveira Junior (2019)[$$$II]
		In wooden seedbeds with soil		2.09b	
Recife – PE, Brazil	'Verdão'	In masonry seedbeds with soil	35 DAS/winter	1.51[(5)] 1.62[(6)]	Zamora et al. (2021)[I]

[#] and [##] Experiments carried out during the months from March to April and from April to June, respectively.

[(1)] and [(2)] Values obtained when the coriander plants were grown in 'Cedrinho' and 'Samaúma' substrates with addition of 50.0 and 16.7% of cattle manure, respectively.

[(3)] and [(4)] Values obtained when the coriander plants were grown under doses of hydrogel polymer (HP) of 6.30 dag kg^{-1} (SFBA = $-0.054^{*}HP^2 + 0.68^{*}HP + 20.46$; * significant at $p \leq 0.05$ by t-test) and 7.91 dag kg^{-1} (SFBA = $-0.11^{***}HP^2 + 1.74^{***}HP + 17.20$; *** significant at $p \leq 0.001$ by t-test), respectively.

[I] and [II] Values originally in the units g m^{-2} and t ha^{-1}, respectively.

[$] In each cultivation period, means followed by the same letter do not differ significantly at $p = 0.05$ by Tukey test.

[&] and [&&] Productions of 96 and 29 bunches m^{-2}, respectively.

[$$] Value obtained under irrigation depth (ID) of 63 mm and nitrogen dose (ND) of 94 kg ha^{-1} (SFBA = $-0.00077^{**}ID^2 - 0.00017^{**}ND^2 + 0.09638^{***}ID + 0.03184^{***}ND - 1.60642$; *** and ** significant at $p \leq 0.001$ and $p \leq 0.01$ by t-test, respectively).

[$$$] Means followed by the same letter do not differ significantly at $p = 0.05$ by Tukey test.

[(5)] and [(6)] Values obtained when the coriander plants were grown under ID of 120% (SFBA = $14.175^{**}ID - 194.83$; ** significant at $p \leq 0.01$ by t-test) and 88.42% (SFBA = $-0.4397^{**}ID^2 + 77.753^{**}ID - 1815.5$; ** significant at $p \leq 0.01$ by t-test) of the crop evapotranspiration by continuous and pulse irrigations, respectively.

DAS – days after sowing; DAT – days after transplanting.

in economic and social development (Grangeiro et al., 2011; Sousa et al., 2011; Silva et al., 2013; Menezes et al., 2020b). Due to the fragility of fresh coriander, its leaves are susceptible to rapid loss of water after harvest (Freitas et al., 2019), so its circulation is restricted to the local market and its commercialization is daily among producers, intermediaries and final consumers in open markets and/or door-to-door sales (Bomfim, 2017).

Given this form of informal marketing of fresh coriander in Brazil (Reis and Lopes, 2016), as well as in other countries (Lal et al., 2014b), there is a great lack of statistical data on its production (Rocha, 2017), because only a small portion of what is produced reaches the fruit and vegetable distribution centers, and is thus computed. Under protected environments, coriander production data are even more scarce.

Therefore, estimates of coriander fresh biomass production per unit area are important, as shown in Table 3.3, where the result of the survey of several studies carried out under different cultivation conditions is summarized.

3.3 CULTIVATION OF CORIANDER IN A PROTECTED ENVIRONMENT

3.3.1 Advantages and Disadvantages

As an advantage, due to environmental control, coriander can be cultivated at any time of the year (Dixit, 2007; Mohanalakshmi et al., 2019), which decreases the seasonality of the product on offer (Guha et al., 2013; Rajasekar et al., 2013). As shown in Table 3.1, the cultivation of coriander in a protected environment has promoted higher yields than those obtained in outdoor cultivation (Gowtham and Mohanalakshmi, 2018), depending on the cultivation system and the degree of environmental control (Dixit, 2007; Guha et al., 2016; Desai et al., 2017).

Also according to Table 3.1, Gowtham and Mohanalakshmi (2018) evaluated different sowing dates for coriander. According to the results, they found that, even in months with lower fresh biomass yields under cultivation in a protected environment, such production was, in general, higher than those obtained in the open field. The production in a protected environment was approximately two-fold higher than those obtained in the field, for the sowing months of September, October, November and February. Similarly, Desai et al. (2017) recorded a higher yield of fresh coriander biomass (0.58 kg m^{-2})* in a protected environment (using a red screen with 50% shading) compared to the open field (0.01 kg m^{-2}).*

The main disadvantage of cultivation in a protected environment concerns the high initial financial investment for its construction (Dixit, 2007). However, as Anderson and Jia (1996) point out, the investment in a structure (cover) to protect from the adverse environment for the cultivation of coriander is justified because it is a short cycle crop, varying between 50 and 60 days for the production of fresh biomass. Therefore, this short production cycle leads to high space utilization.

3.3.2 Cultivation Techniques

Within the protected environment, coriander cultivation has been carried out in wooden beds filled with different substrates (Kaneko, 2006; Esteves Junior and Oliveira Junior, 2019; Figure 3.1A), in beds in the soil itself (Marsaro et al., 2014; Angeli et al., 2016; Figure 3.1B), in masonry beds filled with soil (Silva et al., 2019a; Zamora et al., 2019; Pamplona et al., 2021; Figure 3.1C), in tiles filled with the substrate (Cardoso et al., 2019; Figure 3.1D), in pots (Donega et al., 2013; Marichali et al., 2014; Okkaoğlu et al., 2015; Shams et al., 2016; Oliveira et al., 2017; Sá et al., 2017; Mehrabani et al., 2018; França et al., 2020; Amiripour et al., 2021; Fatemi et al., 2021; Figure 3.1E) and trays (Oliveira et al., 2010; Sales et al., 2015; Machado and Marreiros, 2016; Sá et al., 2016; Olimpio, 2017; Figures 3.1F)

* Values originally in the unit kg per 100 m^2; experiment carried out during summer season, in Navsari, India.

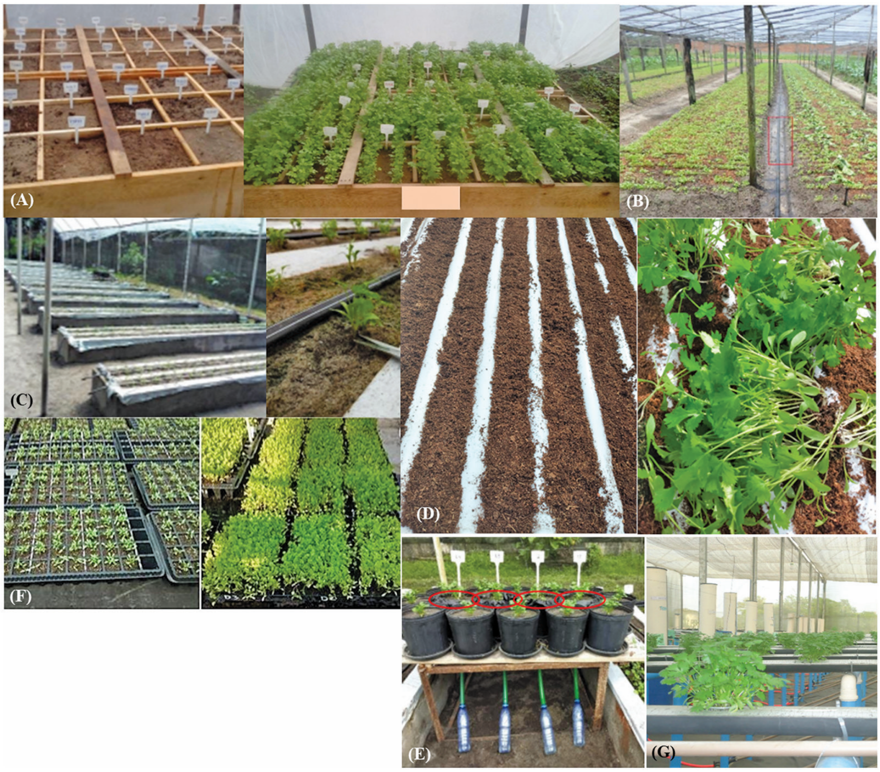

FIGURE 3.1 Coriander grown in wooden seedbeds filled with different substrates (A), seedbeds in the soil (B), masonry seedbeds filled with soil (C), in tiles filled with the substrate (D), in pots with soil (E), in trays with the substrate (F), and under hydroponic conditions (G). A – source: Esteves Junior and Oliveira Junior (2019), B – source: Barros et al. (2018), C and E – source: Menezes (2018), F – source: Olimpio (2017), and D and G – (photos by the authors).

with soil and/or combined with different substrates and in hydroponics – soilless cultivation* (Silva et al., 2016a; 2018b; 2020a; 2020b; Figure 3.1G).

As already mentioned, the commercialization of fresh coriander biomass is in the form of bunches for use in cooking. The composition of coriander bunches depends on the form of cultivation, for example, the sowing of seeds in large quantities in furrows/rows at certain spacing is more common (Oliveira et al., 2004; Agasimani, 2014; Özyazici, 2021; Figure 3.1B). Cultivation has also been carried out in holes opened at certain distances, either by direct sowing (Cavalcante et al., 2017; Figure 3.1C) or by seedlings produced in trays (Angeli et al., 2016; Santos et al., 2021; Figure 3.1F) and later taken to the field. In other words, in this last type of cultivation, the bunch of plants comes from the hole itself (Linhares et al., 2015; Zamora, 2018).

Therefore, coriander yield is directly influenced by plant density. There is no standard in terms of the mass of the coriander bunch, being variable between locations even within the same region. This is well exemplified in Table 3.3 in the studies conducted by Kaneko (2006) in Brasília and Angeli et al. (2016) in Viçosa, both in Brazil, in which the authors recorded the numbers of 96 and 29 bunches m^{-2} of coriander plants, corresponding to productions of 3.05 and 2.90 kg m^{-2}, respectively. While in the first study the bunch was approximately 30 g, in the second study it was 100 g, which explains this difference in the number of bunches per unit area. Bunches with 100 g standard

* Chapter 4 'Production of Coriander Using the Hydroponic Technique' written only on this theme.

have been adopted in the municipality of Mossoró in the Northeast region of Brazil (Barros Júnior et al., 2004).

3.4 PRODUCTION OF CORIANDER UNDER DIFFERENT GROWING CONDITIONS IN A PROTECTED ENVIRONMENT

Table 3.2 shows the compendium of several studies for the variable shoot fresh biomass (SFB) of coriander per plant, in which different aspects were addressed, such as the performance of coriander cultivars (Pereira et al., 2011; Bonifacio et al., 2014; Marsaro et al., 2014; Araújo et al., 2019), salt stress (Bonifacio et al., 2014; Lira et al., 2015; Ahmadi and Souri, 2018; Ullah et al., 2018; Al-Garni et al., 2019; Rabiei et al., 2020), irrigation depths (Silva et al., 2019b), the application of attenuators to mitigate salt stress (Mohammadipour and Souri, 2019; Rabiei et al., 2020) and the use of cassava wastewater in combination with cattle manure (Costa, 2020).

There is a wide variation in coriander SFB values (Table 3.2). This can be due to different factors, such as cultivar, planting time and duration of the crop, in addition to the cultivation conditions used (imposed treatments). In the studies carried out in Brazil, in general, there are higher productions of SFB per plant of 'Verdão' coriander.

Therefore, in Brazil, the realization of a large number of studies with the 'Verdão' cultivar is explained, as it tolerates higher temperatures compared to other cultivars. For example, Pereira et al. (2011) evaluated different cultivars of coriander and recorded SFB production of 'Verdão' coriander six-fold greater than that of 'Portuguese' coriander. In the study by Marsaro et al. (2014), when the plants were harvested at 43 days after sowing (DAS), there was no significant difference between the means of the 'Portuguese' and 'Verdão' coriander cultivars. At 50 DAS, the SFB production of 'Verdão' coriander was higher; however, this superiority did not exceed 1.5-fold compared to that of 'Portuguese' coriander. In these studies, the SFB of 'Verdão' coriander was greater than 20 g plant^{-1} (Table 3.2). Therefore, these results show that the cultivation of 'Portuguese' coriander is more suitable for the climatic conditions of the second study site.

As shown in Table 3.2, according to the study by Pereira et al. (2011), the SFB production of 'Tabocas' coriander was only lower than that of 'Verdão' coriander. Different results were observed by Bonifacio et al. (2014), who recorded 14% higher SFB production of 'Tabocas' coriander compared to 'Verdão' coriander under cultivation without salt stress (0 mM NaCl), while under salinity (100 mM NaCl) there was no significant difference between cultivars. However, when evaluating the relative yield (RY),* expressed as RY = (with salinity/without salinity – control) × 100, 'Verdão' coriander was superior (RY ~ 44%) compared to 'Tabocas' coriander (RY ~35 %). These results show that the effect of salt stress varied according to the coriander cultivar, as well as the concentration of salts to which the plants were exposed, as in the study by Rabiei et al. (2020), who found no significant difference between the means of SFB obtained without (0 mM NaCl) and with salt stress (80 mM NaCl).

The use of one cultivar to the detriment of others is often done for cultural reasons, that is, without considering the production capacity and edaphoclimatic conditions of those places. This type of behavior is characteristic of small producers who live in places far from big centers. Therefore, under contrasting climate conditions, studies involving the evaluation of different coriander cultivars are of great importance (Pereira et al., 2011; Bonifacio et al., 2014; Marsaro et al., 2014; Araújo et al., 2019).

Also according to Table 3.2, the SFB of 'Verdão' coriander did not exceed 1.80 g plant^{-1} in the study by Vasconcelos et al. (2014), while Lira et al. (2015) recorded values above 4.00 g plant^{-1}. Such studies were carried out in the same place but at different times. This partially explains this discrepancy in the results; another complementary explanation concerns the density of plants since 16 and 3 plants pot^{-1} were cultivated in these studies, respectively. This was reinforced in the study by Silva

* Variable established by the authors of this chapter.

et al. (2019b), also conducted in Northeastern Brazil; they recorded coriander SFB less than 0.70 g $plant^{-1}$ under cultivation with 10 plants pot^{-1}. That is, the greater the number of coriander plants per unit area, the lower the production per plant, as reported by other authors (Silva et al., 2016b; Martins et al., 2018), reaching the point that the increase in density attains a point of maximum production per unit area (Almeida et al., 2019), and from this point onwards there is a decrease in production due to the competition that is established (Olimpio, 2017).

As verified for the variable SFB per plant (Table 3.2), for SFB per area (Table 3.3) the results are also quite variable depending on the different conditions of coriander cultivation. For example, Kaneko (2006) recorded higher production (3.05 kg m^{-2})* in the first cycle compared to the second cropping cycle (1.35 kg m^{-2}),* both conducted in the same year, although this last cycle was carried out for a longer period. In the study by Albuquerque Filho et al. (2009), SFB† productions were close in two consecutive cycles in the same year. However, the values were lower than those recorded by Kaneko (2006) in the first cultivation cycle. This difference can be explained by the number of plants used per unit of area. Additionally, another explanation concerns the differences between cultivars, as mentioned above (as shown in Table 3.2); 'Verdão' coriander has shown higher yields of fresh biomass compared to other cultivars.

Clearly, in the study conducted by Marsaro et al. (2014), the smallest number of plants per unit area influenced the yield of coriander, for example, SFB did not exceed 1.40 kg m^{-2} (as shown in Table 3.3). In this study, only one plant was cultivated per hole, adopting a spacing of 0.05 m × 0.25 m between holes and rows, respectively. With this spacing, totaling 80‡ plants m^{-2}, this value is ten- and three-fold lower than that used in the studies of Kaneko (2006) and Albuquerque Filho et al. (2009), respectively. In the study by Angeli et al. (2016) with a total of 300‡ plants m^{-2} (3 plants $hole^{-1}$, 0.05 m × 0.20 m between holes and rows, respectively), a production of SFB (2.90 kg m^{-2}) approaches the value recorded by Kaneko (2006) in the first cultivation cycle.

Also according to Table 3.3, the highest SFB of coriander was recorded in the study of Esteves Junior and Oliveira Junior (2019), of the order of 7.09 kg m^{-2} under cultivation with the incorporation of organic compost into the soil, this value being more than three-fold the production obtained when the cultivation was only in soil.

3.5 WATER PRODUCTIVITY OF CORIANDER IN A PROTECTED ENVIRONMENT

Water productivity, expressed by the production of fresh coriander biomass divided by the volume of water applied, ranged between 7.52 and 49.81 kg m^{-3} (Table 3.4). Therefore, there is a large variation in water productivity values, reinforcing what has already been mentioned for SFB production per plant (Table 3.2) and per area (Table 3.3).

This higher water productivity (49.81 kg m^{-3}) in the study by Angeli et al. (2016) is due to the smaller volume of water used to produce 1 kg of fresh biomass. For example, the production of SFB was approximately 28 and 20% higher than the SFB obtained by Albuquerque Filho et al. (2009) in the first and second cycles, respectively; while water productivity was approximately 100 and 51% higher in the study by Angeli et al. (2016).

3.6 CONCLUSIONS

Due to climate change, crops have been increasingly affected, especially leafy vegetables such as coriander. Therefore, maintaining regularity in terms of production and, above all, quality is a great challenge for producers. In this context, to mitigate the adverse effects of unfavorable weather, the

* 800 plants m^{-2} were cultivated, estimated from plot size of 0.25 m × 0.20 m (40 plants $plot^{-1}$) by the authors of this chapter.

† 240 plants m^{-2} were cultivated, estimated from plot size (lysimeter with 1.38 m in diameter, with a surface area of 1.50 m^2 – 360 plants $lysimeter^{-1}$) by the authors of this chapter.

‡ Values calculated by the authors of this chapter.

TABLE 3.4
Water Productivity (WP) of the Shoot Fresh Biomass of Coriander Grown under Different Cultivation Conditions in Protected Environment

Location	Cultivar	Cultivation Conditions	WP (kg m^{-3})	Reference
Recife – PE, Brazil	'Tabocas'	In seedbeds in the soil	23.58(1) 32.89(2)	Albuquerque Filho et al. (2009)[I]
Viçosa – MG, Brazil	'Vedete'	In seedbeds in the soil	49.81(3)	Angeli et al. (2016)[I]
Viçosa – MG, Brazil	'Vedete'	In seedbeds in the soil	7.52(4)	Delazari et al. (2019)[II]
Recife – PE, Brazil	'Verdão'	In masonry seedbeds with soil	20.40(5) 12.98(6)	Zamora et al. (2019)[I]

(1) and (2) Values obtained when the coriander plants were grown under doses of hydrogel polymer (HP) of 16.00 dag kg^{-1} (WP = 0.39*HP + 17.34; * significant at $p \leq 0.05$ by t-test) and 8.18 dag kg^{-1} (WP = –0.11***HP^2 + 1.80**HP + 25.53; *** and ** significant at $p \leq 0.001$ and $p \leq 0.01$ by t-test, respectively), and irrigation water depths (ID) of 60 and 120% of the reference evapotranspiration, respectively.

(3) Value obtained under ID of 63 mm and nitrogen dose (ND) of 105 kg ha^{-1} (WP = –0.5844***ID + 0.2036***ND + 65.2479; *** significant at $p \leq 0.001$ by t-test);

(4) value obtained under ID of 25% of the crop evapotranspiration (ETc) and ND of 70 kg ha–1 (WP = – 0.037***ID + 8.4452; *** significant at $p \leq 0.001$ by t-test).

(5) and (6) Values obtained (originally in the unit g L^{-1}) when the coriander plants were grown under ID of 71.60% ETc (WP = –0.0045**ID^2 + 0.6444**ID – 2.6691; ** significant at $p \leq 0.01$ by t-test) and 97.42% ETc (WP = –0.0013**ID^2 + 0.2533**ID + 0.6378; ** significant at $p \leq 0.01$ by t-test) by pulse and continuous irrigation, respectively.

I Same growth periods and cultivation conditions shown in Table 4.3.

II Experiment carried out during the spring season for 15 days after sowing + 29 days after transplanting.

cultivation of coriander in a protected environment has been increasingly recurrent, not only in research but also in commercial production. Therefore, based on the various aspects covered in this chapter, it is concluded that there is great potential for growing coriander in a protected environment, thus ensuring regularity in the production of fresh biomass throughout the year. Additionally, a database regarding the production of fresh coriander biomass per unit area was generated from the compendium of several studies conducted under different climatic conditions, which may serve as support in future consultations for implementing coriander cultivation in a protected environment.

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