1 Introduction and Overview of Lime

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Lime, lemon and citron belong to the acid citrus fruit group. This group is characterized by an elliptical to round shaped fruit with high citric acid content. Limes can be distinguished from other fruit in the citrus family as they have both acid and sweet varieties. The differences in tree morphology and fruit characteristics may even be sufficient to confer the status of separate species for the acid and sweet types. All citrus fruits have nearly the same structure; however, the elements that comprise these structures vary according to species and variety (Loussert, 1992). The external part of the rind consists of several morphologically different tissues called flavedo because of the presence of flavonoid compounds (Ortiz, 2002). The whole surface of the fruit is covered by polygonal cells to form the isodiametric layer. This layer contains cuticles that are partially enclosed with a waxy substance to prevent excessive loss of water from the fruit. A layer made of collenchyma and parenchyma cells is present under the layer of epidermis, where many oil glands containing essential oil are located at different depths within the parenchyma tissues. The white spongy part of the parenchyma, called the albedo, is located under the layers of collenchyma and parenchyma (Ting and Attaway, 1971). The name albedo is derived from the Latin (albus = white) (Ortiz, 2002). The edible part of the fruit is divided by carpel segments or locules. There are many juice vesicles within the carpels (Ting and Attaway, 1971; Rivera-Cabrera *et al.*, 2010) (Fig. 1.1). The number of carpels vary, with acid lime fruit normally containing around 8–11 segments (Loussert, 1992).

The lime plant belongs to the kingdom Plantae; phylum Magnoliophyta; class Magnoliopsida; order Sapindales; family Rutaceae; genus *Citrus*; and species *aurantifolia* (Sethpakdee, 1992). The three main types of lime largely cultivated worldwide are Persian lime, Key lime (Mexican lime) and Makrut lime (Table 1.1). Key limes are a small rounded fruit (*Citrus aurantifolia* (Christ.) Swingle), while the Persian limes bear a larger fruit (*Citrus latifolia* Tanaka) that is triploid and seedless. The Persian lime is the most frequently grown lime variety globally and México is one of the major producing countries. The fruit has an elliptical shape, thin, smooth skin and is juicy with an acidic lime aroma. Less heat is needed for Persian lime fruit maturity than for Key limes, and they are more cold- and frost-tolerant (Reuther *et al.*, 1967). The Makrut lime is produced in smaller amounts and is very popular in South-east Asian cookery. The fruit is small sized, the skin is rough and the leaves are aromatic and used in cuisine (Reuther *et al.*, 1967).

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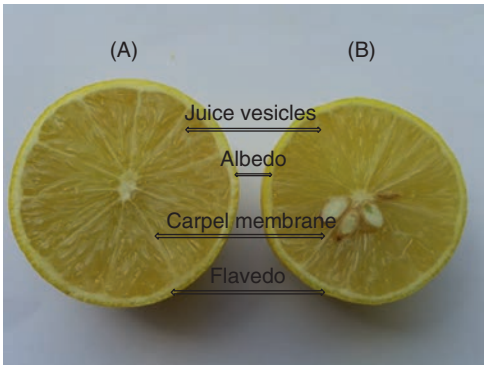

Fig. 1.1. Cross-section of lime fruit. (A) Persian lime, (B) Mexican. (Derived from Rivera-Cabrera *et al*., 2010.)

Table 1.1. Description of major lime varieties.

Lime type	Other names	Appearance
Key lime (*Citrus* × *auratifolia*)	West Indian, Bartenders, Omani, Mexican	2.5–5 cm. diameter, high acidity, strong aroma, tart and bitter,7–8% citric acid
Persian lime (*Citrus* × *latifolia*)	Shiraz limoo, Tahitian, Bearss (seedless)	5–12.7 cm. diameter, slight nippled end, ripens to yellow but sold green
Makrut lime (*Citrus* × *hystrix*)	Kaffir	5 cm. diameter rough bumpy skin, thick rind, aromatic leaves used in cooking

Source: Reuther *et al*., 1967

The Key lime (*Citrus aurantifolia* (Christ.) Swingle), is a polyembryonic species, grown globally, generally in warm tropical to subtropical regions such as India, México, the USA, Egypt and the West Indies (Morton, 1987). There are many common names used for Key lime, including West Indian lime, Mexican lime, Egyptian lime, Bilolo and Dayap, etc. The Key lime (*C. aurantifolia* Swingle) is mostly known as tri-hybrid, evolved through an inter-generic cross (a three-way hybrid where three plant species are involved and at least two different genera) of citron (*Citrus medica*), pummelo (*Citrus grandis*) and a *Microcitrus* species (*Citrus micrantha*).

The Key lime plant is spiny, less vigorous and less robust compared with Persian lime trees, and requires more heat for fruit development. It produces smaller fruit when it is grown in the Mediterranean climate due to the sporadic cold snaps and lower temperature regimes (Reuther *et al*., 1967). On the other hand, it grows vigorously in tropical environments and produces higher yields.

History, Origin and Distribution

It has been suggested that the lime perhaps evolved from a tri-hybrid cross amongst *C. medica*, *C. grandis* and a *Microcitrus* species (Barrett and Rhodes, 1976). However, another study reported that mandarin was a parent of lime, while another parent could be citron, pummelo or *Papeda* (Handa *et al*., 1986). Recent studies have strongly argued that Key lime was a hybrid of *Papeda* and *Citron*. The molecular evidence of these studies offered more conclusive information compared with all previous studies reported relating to the origin of lime (Li *et al*., 2010). Like Key lime, 'Tahiti' lime is probably a tri-hybrid inter-generic cross of citron (*C. medica*), pummelo (*C. grandis*) and a *Microcitrus* species, *C. micrantha* (Moore, 2001). However, unlike Key lime, 'Tahiti' lime is a triploid.

The ancestral place of lime origin is also controversial, similar to that of other citrus species, but many researchers and historians believe that lime originated from South-east Asia around 4000 BC and its native home is the Indo-Malayan region (Nicolosi *et al*., 2000). It is believed that the Europeans were not familiar with this fruit before the crusades, and it was Arab travellers who carried it to North Africa and the Near East. After the crusades it was taken to Palestine and then finally spread to Mediterranean Europe (Cooper and Chapot, 1977; Eckert and Eaks, 1989). During the middle of the thirteenth century, it was thought to be cultivated in some parts of Italy, France, Spain and Portugal. It was introduced in México during the time of Spanish colonization. It is strongly believed that both Portuguese and Spanish voyagers took it to the Americas during the early sixteenth century (Ziegler and Wolfe, 1961). Once introduced as an exotic plant, it has

shown wide adaptation to diverse climates and was largely naturalized in México, the Caribbean, tropical areas of South America, Central America and the Florida Keys. During 1839 its cultivation started to expand in Florida and it was developed as a common home yard fruit. By 1883 it began to be produced on a small scale commercially in south-central Florida.

A hurricane in 1906 along with soil nutrient depletion resulted in the pineapple culture being abandoned. At that time, people began to plant limes as a substitute crop on the west coast of Florida. Lime fruit pickles became a prime snack choice among schoolchildren in Boston. A small-scale lime pickle business was active from 1913 to 1923 but it crumbled in 1926 due to the devastating impact on lime groves of another hurricane. Afterwards, the lime was largely grown as a common yard and garden plant in the Keys and the southern part of the Florida mainland.

In the Middle East, lime is a major traditional crop that has been used for a variety of culinary and medicinal purposes. Both fresh and dried limes are used for juice and as a condiment for food flavouring. Historically, sun-dried limes were a major export commodity of Oman, and are frequently used in sauces and as a flavouring agent in other Arab cuisines. Oman is a leading lime-producing country in the region. However, lime production has been drastically reduced in recent decades due to the spread of witches' broom disease of lime (WBDL), which has reduced the cultivated area to less than half since 1990 (Al-Yahyai *et al.*, 2012). Since its discovery in the 1970s, the disease has spread to other countries in the Middle East, including the United Arab Emirates (UAE), Saudi Arabia and Iran, threatening many major lime-producing countries.

Global Lime Production

Mexican lime is largely cultivated in tropical and subtropical areas of the globe. It is grown commercially, semi-commercially and in gardens. Lime is cultivated on a range of continents all over the globe, particularly in Asia and the Americas (Fig. 1.2a). Lime and lemon are mainly grown in India, México, China, Argentina, Brazil, the USA, Turkey, Spain, Iran and Italy (FAOSTAT, 2016). The percentage share of the top ten lime and lemon-producing countries is presented in Fig. 1.2b.

The relationship between area planted and production of the major lime-producing countries becomes clearer regarding total area under crop and the total harvest during 2013 upon examination of Fig. 1.3. Recognizing the importance of lime and lemon for both domestic and industrial uses, their cultivation has been increased considerably throughout the globe since 2000 (Fig. 1.4).

It is noteworthy to observe the tremendous increase in yields, which may be attributed to better plant material and the advancement in technologically driven crop management. The

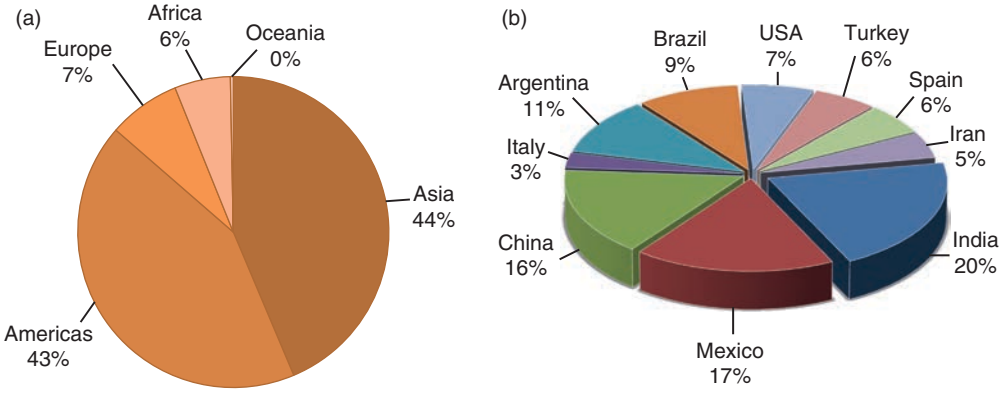

Fig. 1.2. The percentage of lime and lemon production on different continents (a) and top ten global producers in 2013 (b). (Source: FAOSTAT, 2016.)

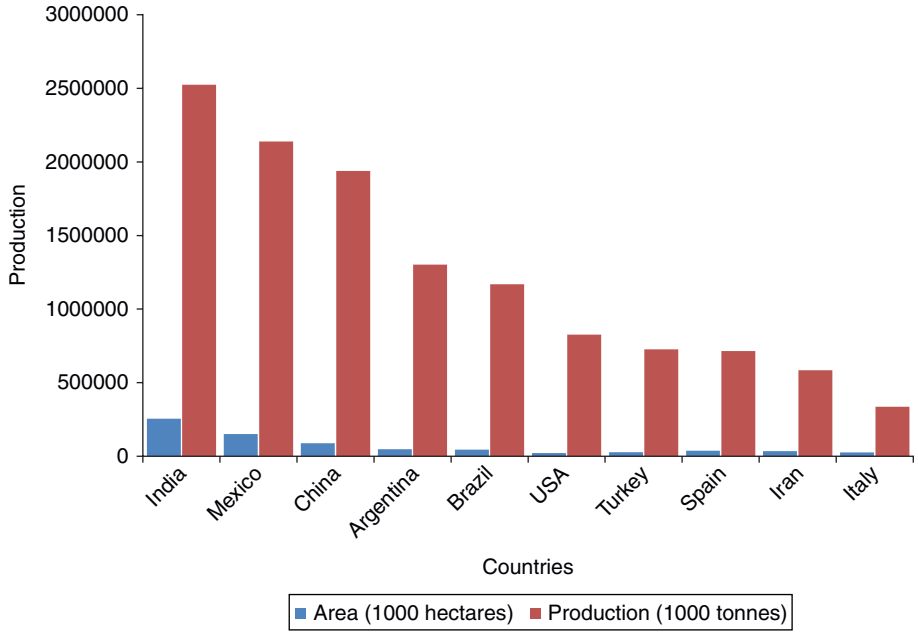

Fig. 1.3. Lime and lemon production and area harvested in top ten producing countries during 2013. (Source: FAOSTAT, 2016.)

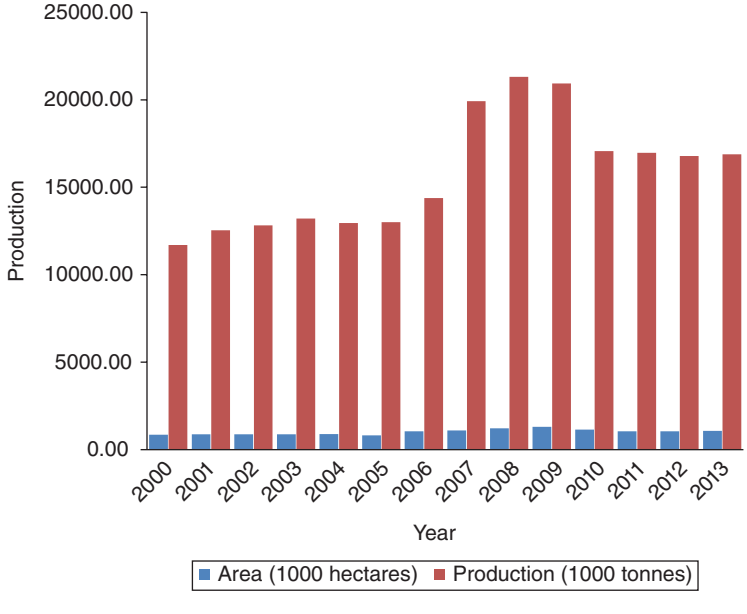

Fig. 1.4. Lime and lemon production and area harvested 2000–2013. (Source: FAOSTAT, 2016.)

fruit yield was 13 million tonnes during 2005 and has recently been maintained at approximately 18.9 million tonnes from 2010 to 2013 (FAOSTAT, 2016). Lime-producing countries harvest fruit for both domestic consumption and export. It is interesting to note that the top lime-producing country (India) has negligible lime exports, while Spain and México had the highest quantity of

lime exported during 2013 (Fig. 1.5a). Europe, the USA and Russia were the largest importers of lime and lemon (Fig. 1.5b).

Plant Description

In general, the lime plant is largely a small shrub-like tree, approximately 5 m in height. It is an evergreen, ever-bearing tree that is densely and irregularly branched and possesses short, stiff spines (thorns). The leaves are alternate; elliptical to oblong-ovate (4–8 cm × 2–5 cm) in shape and have a crenulated margin. The flower diameter is about 2.5 cm and flower colour is yellow to white with a little purple tinge on the margins. The fruit are globose to ovoid berries of about 3–6 cm in diameter and sometimes have apical

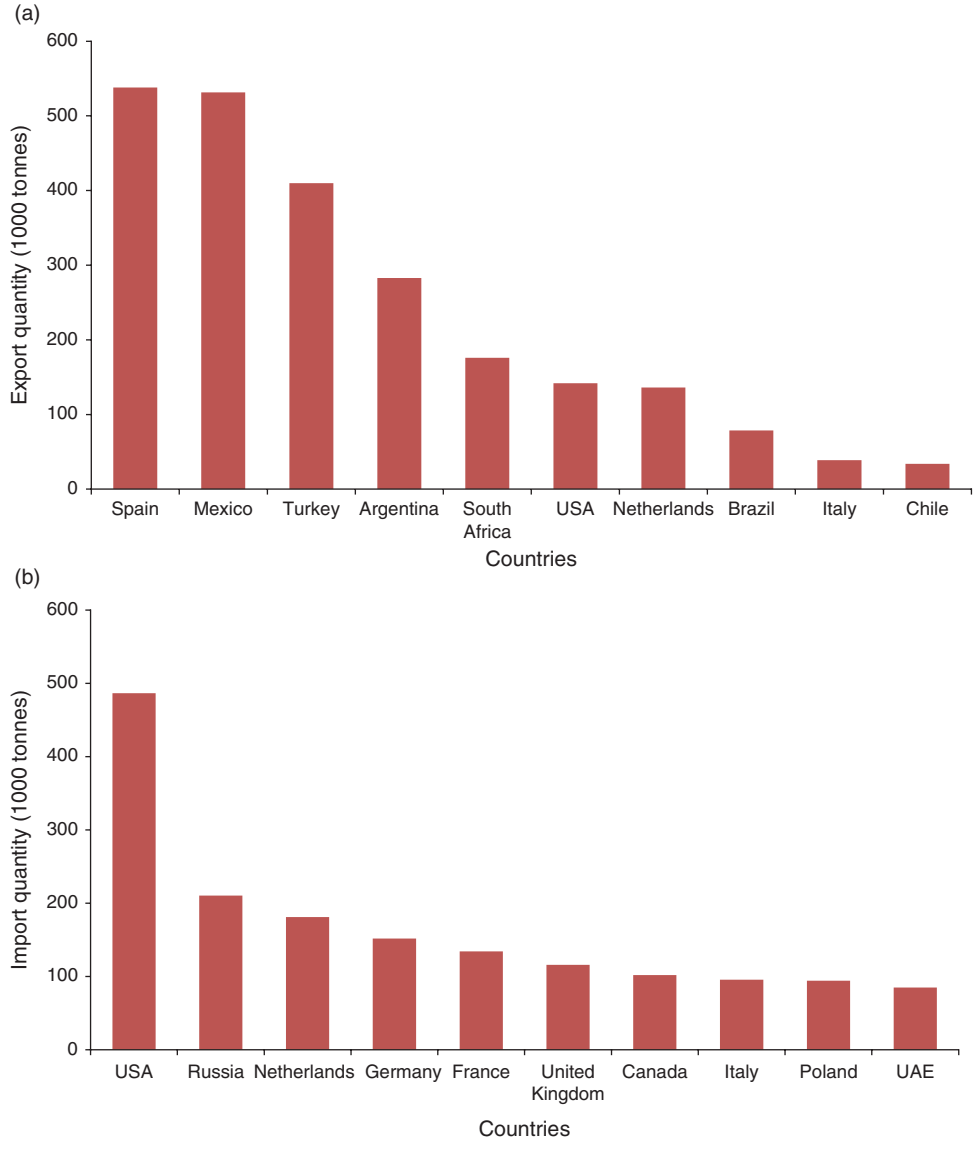

Fig. 1.5. Lime and lemon top ten (a) exporters and (b) importers of the world during 2013. (Source: FAOSTAT, 2016.)

papilla. Limes are usually picked when green for commercial production; however, if kept on the tree longer, the fruit turns yellow at maturity. The lime tree keeps bearing fruit and flowers throughout the year, but blooms most profusely during May–September in the northern hemisphere. The fruit peels are very thin with dense glandular segments with yellow-green pulp vesicles. The fruit juice is acidic and fragrant, as sour as lemon juice but more aromatic. The *C. aurantifolia* limes enjoy high standing due to this exceptional aroma compared with other lime types. The seeds are small, plump, ovoid, pale and smooth with a white embryo.

Propagation

Key lime seeds are poly-embryonic and generally multiplied sexually (seeds). To maintain identical clones in limes asexual propagation is practised. Mature or hardwood cuttings are used for propagation but generally are not able to carry strong root systems. Root sprouts are also used in some areas. Sprouting is stimulated by digging round the parent plant to separate the roots completely or partially. Ground and air layering are also very popular methods of propagation in many regions. For example, in Oman, ground layering is practised, while in Indonesia and Florida, air layering is more common. Using indole butyric acid (IBA) to aid root development, air layering can result in 100% success when propagating the 'Kaghzi' lime in India (Morton, 1987). The improvement of rootstock is highly desirable for obtaining certain benefits for lime cultivars, e.g. biotic and abiotic stress tolerance, enhanced fruit quality, earliness and a better canopy with a robust root system. For example, clones budded onto Rough lemon/sour orange can provide more resistance to strong winds or hurricanes.

Cultivars

There are relatively small differences among wild or cultivated varieties of the Key lime excluding a few thornless cultivars.

'Everglade'

Also known as Philippine Islands 218, this is a seedling of Key lime that was fertilized by grapefruit/pummelo pollen. However, the fruit does not show any dominant feature of grapefruit or pummelo. This fruit was first introduced in Trinidad in 1922, but it showed little or no distinctive characteristics compared with cultivated Key lime when grown in the Citrus Experiment Station collections in Riverside, California. It is similar to lime: the fruit shape is elliptical, having a small nipple at the fruit apex; fruit size is 4–5 cm wide, 4.5–5.4 cm in height; the fruit rind becomes light yellow on ripening; the oil glands in fruit peel are marginally dipped; it has very small size glands about 1.5 mm in length; pulp colour is light greenish; it has eight to ten segments with softer covering walls; scented aroma; and high juice content. The texture and quality are excellent; the aroma lively acidic; the number of seeds may vary from two to ten, with an average number of approximately five. The flowers are perfect and large clusters of fruit are borne on tree branches. The tree is extremely sensitive to lime anthracnose 'wither tip' infection caused by the *Colletotrichum* species of fungus.

'Kaghzi'

This is an acid lime cultivar that is very popular and cultivated on a commercial scale in India. It has several subtypes with varied tree and fruit size, shape and colour. In general, fruit are small to medium; pulp is greenish with a strong aroma; the juice vesicles are heavily adhered to the skin; the skin is green to yellow, thin or papery and shiny. These limes are largely grown for processing purposes.

'Palmetto'

This is a Key lime seedling selection cross-pollinated by the 'Sicily' lemon. Dr H. J. Webber reported this first in the United States Department Yearbook in 1905. Its form is globular to elliptical having a minor nipple on the fruit at the apex. Fruit size is small; peel colour is pale yellow on ripening; the pulp colour is light green to

yellow; and juice vesicles are juicy and enriched with a lively flavour. It has a small number of seeds (three to six).

'Yung'

This is a spineless/thornless Key lime and was introduced from México and into California in 1882 by George Yung.

A thornless bud sport was reported in the Dominican Republic in 1892, and a similar line was introduced from Trinidad to the USA in 1910. Many spineless bud sports were recorded in lime plantations near Weslaco, Texas, after a 1925 freeze. Lime plant seeds found growing in the Yuma desert, Arizona, were introduced to southern Florida in 1967. After germinating about 50 seedlings, there were eight that were virtually spineless. The bud stock from these was selected and grafted onto Rough lemon for dissemination to growers.

During 1925 in Trinidad a hybridization programme was started to develop wither tip (anthracnose) resistant genotypes. Promising selections were made and hybrids with desired traits were given the name 'T-l'. Its fruit was slightly bigger compared with the typical Key lime. The fruit was not juicy at the green stage. However, back crosses were carried out to achieve typical Key lime traits.

Pests and Diseases

Lime is prone to a large number of insects/pests and diseases similar to other citrus species, leading to mild to huge losses. These losses are chiefly dependent on the type of pest, disease, environmental conditions and resistance of the plants. Leaf miners, leafhoppers, scales, mites and psyllids, etc. are considered economically damaging insects of lime. The lime is susceptible to diverse bacterial, fungal and viral diseases (Morton, 1987). The lime anthracnose (wither tip), canker, nematodes and certain *Fusarium* species also result in negative impacts on tree health and productivity. More recently WBDL and Huanglongbing (HLB) or greening have been considered new potential threats to lime plantations in many regions of the world. It has been reported that an important pest elsewhere is the snow scale (*Unaspis citri*), particularly during protracted droughts. It can cause dieback of branches once heavily infested, and it pierces the bark, which encourages other insects and fungi to invade. Ants are also a frequent visitor, moving from plant to plant. Insects cause direct and indirect (vector) threats to the lime industry. Post-harvest decay-related organisms are another dilemma for sustained lime businesses. A chapter in this book is dedicated to lime diseases and pests, and includes a great deal of information regarding infestation control measures.

Uses of Lime

Fruit uses

Lime fruit peel and leaves have been used for culinary and non-culinary purposes around the globe. In addition, lime is known for its juice extract, which is used as a cleansing agent and in cooking (Morton, 1987; Bocco *et al.*, 1998). The use of lime in human history has been documented for centuries, though its usage was mainly limited to folk custom. In general citrus fruits including lime have been reported to have high anti-oxidant properties, e.g. anti-cancer, anti-inflammatory, and anti-fungal and blood clot inhibition (Guimarães *et al.*, 2010; Karoui and Marzouk, 2013). The lime essential oils are used in pharmaceutical forms, fragrances and perfumes, and food flavouring (Dongmo *et al.*, 2013). Lime twigs and leaves are used in the perfume industry and its twigs and the leaves are used to extract petitgrain cedrat oil.

Lime carries a strong aromatic and acidic tang, which makes it valuable in drinks, curries, rice dishes, cakes, desserts, pickles, salads, sauces, jams and jellies (Hardy *et al.*, 2010). Dried lime is abundantly available in Middle Eastern markets, since it is commonly used in Arabian cuisines (Fig. 1.6). Limes contain vitamins, flavonoids, especially ascorbic acid (vitamin C) and citric acid, and provide a potential alternative to synthetic antioxidants (Morton *et al.*, 1994). Although the lime industry is not well developed, increasing health consciousness and industrial usage have increased demand. Limes with special features, for example, finger

Fig. 1.6. Dried lime being sold in Middle East countries. (Source: Courtesy of S.A. Siddiqui.)

lime and coloured flesh lime have high demand in restaurants (Hardy *et al*., 2010; Siebert *et al*., 2010).

Tree uses

Lime seedlings are frequently used as a rootstock for other citrus cultivars. Limes and lemons are generally considered as salt tolerant with vigorous growth and are used as rootstock for other citrus cultivars on a limited scale in Iran, India and other Asian countries (Bitters, 1986). However, lime germplasm is a potential source for crop improvement programmes for the production of new plant materials (scions and rootstocks) with better fruit and plant characteristics (Kahn *et al*., 2001a, b; Krueger and Navarro, 2007; Nawaz *et al*., 2007a, b). Lime trees are used in landscaping and for ornamental use in front yards and backyards. Their flowers and leaves have a specific scent, and the small plants, lush green foliage and small yellow coloured fruit look very attractive. Lime trees carry flower blossoms and young to fully ripened fruit at the same time, which further augments its aesthetic look. A detailed agronomy of 'Tahiti' lime cultivation as a home landscape tree has been explained (Crane and Osborne, 2013). Recently, the Citrus Research and Education Centre in Florida released transgenic Mexican lime plants exhibiting unique pigmented leaf, flower and fruit pulp. These pigmented transgenic materials carry great value for ornamental horticulture and for human health (Dutt *et al*., 2016).

Challenges and Future Perspectives

Although the documented history of limes is more than 700 years old, the parentage and origin of limes is not clear. Advancement of biotechnological and molecular tools can aid in resolving these issues. A recent report revealed the phylogenetic origin of lemons and limes by using cytoplasmic and nuclear markers (Curk *et al*., 2016). These studies are helpful in understanding the history of limes and will open up new avenues for research and development work on limes.

Lime plants are facing a number of problems across the world, including excessive attacks from insect pests (citrus psyllids, leaf miners, mealy bugs, citrus canker, bacterial diseases, fungal disease, viral and viroid-related diseases and some physiological problems). The emerging threats to the lime industry are climate change impact and new diseases like WBDL and HLB. These natural calamities have drastically reduced lime plantations in many regions of the globe. Substantial work on rootstock intervention on other closely related citrus fruits (e.g. oranges, mandarins and grapefruit) has led to remarkable achievements. However, very little work has been reported on rootstock scion interaction on lime, and it is hard to find standard rootstocks being used for limes. The role of rootstocks in other fruits has been well documented; lime needs further attention from plant breeders to develop resistant genotypes with the best traits to help in promoting lime cultivation across the world. Lime genetic resources are eroding and face serious threats and losses. These valuable resources need to be preserved and broadened for future crop improvement programmes by the breeders and geneticists.

Despite lime cultivation having faced numerous setbacks in the past, there is massive potential as the demand from both the domestic and industrial consumer grows. It has been reported that the consumption and trading of limes between countries has been on an upward trend in recent years (Plattner, 2014). Keeping in view the customer and industry demands, new lime cultivars/hybrids are expected to emerge to meet the demands of different countries across the world. Recently, seedless lime hybrids including C4-5-27 (a cross of 'Key lime' and tetraploid lemon) with superior fruit and

plant characteristics have been released (Grosser *et al.*, 2015). Similarly, the development of pigmented Key lime has been described through the introduction of transcription factor Ruby (blood orange) and VvmybA1 (grapes). This has opened up new opportunities for the development of lime cultivars with different colours for ornamental and nutraceutical values (Dutt *et al.*, 2016). These conventional and emerging biotechnological tools are creating interesting new lime genotypes, which will include biotic/abiotic resistance as well as possessing health/ornamental values.

About this Book

A survey of the current literature indicates the limited availability of authoritative reference material on limes. Current books on citrus cover mainly oranges, grapefruits and mandarins. There is little exclusive literature available on lime cultivation worldwide, despite lime being ranked third in global citrus production and having a significant share of the citrus trade. Citrus species including lime are grown throughout the globe and particularly in the northern to southern hemisphere and Mediterranean regions. Detailed research-based information presented by dedicated academicians with in-depth knowledge will greatly enhance the understanding of lime cultivation. The diversity of the subjects covered in an array of chapters brings an opportunity to citrus students, amateurs, agriculture extension workers, researchers, growers and fruit industry experts to comprehend the advances and deficits in lime culture. A reader interested in lime can find much information related to his/her subject in a single book.

The book covers an assorted collection of subjects. For example, in Chapter 1, lime importance and global production are emphasized; in Chapter 2, its comprehensive systematic classification and distribution is covered; in Chapter 3, lime breeding, genetics and biodiversity are discussed; and in Chapter 4, lime tree growth, development and reproductive physiology are elaborated. In Chapter 5, propagation techniques, nursery production and certification are explained; in Chapter 6, schematic planning for lime orchard establishment is discussed; in Chapter 7, crop water requirements, irrigation systems and fertigation are highlighted; and in Chapter 8, cultural practices, e.g. tree pruning, thinning, weeding, planting density and intercropping, are covered. In Chapter 9, precision agriculture in lime is elaborated; in Chapter 10, insect pests and diseases and their control measures are covered; in Chapter 11, innovative production technologies, e.g. the use of plant growth regulators, remote sensing and organic production systems, are highlighted. In Chapter 12, harvesting and post-harvest management of lime fruit are emphasized; and in Chapter 13, uses (folk to modern) and future dynamics are discussed in depth.

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