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Acid Limes. A Review

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ABSTRACT

For countries with tropical and subtropical climates, like Mexico, the commercialization of fresh horticultural products and their processed by products represent an important economical source. In recent years, Mexico has become one of the main citrus producing countries in the world. At the moment, Mexico is ranked as the main worldwide lime producer. There are two kinds of acid limes, the small-fruited Mexican (*Citrus aurantifolia* Swingle) type, and the large-fruited Persian (*Citrus latifolia* Tanaka) lime, which is triploid and therefore seedless. Extensive research exists on citrus fruits. Nevertheless, there is not compiled information about lime fruits. The purpose of this paper is to review the most recent literature of lime fruits focusing on their main characteristics, chemical composition, nutritional value, maturity indicators, quality indices, main destination markets, pre and postharvest factors that affects the fruit quality, physiological disorders and diseases.

Keywords: *Citrus aurantifolia* Swingle, *Citrus latifolia* Tanaka, citrus fruit, physiological disorders
Abbreviations: COPELP, Council of Producers and Exporters of Persian lime (for its abbreviation in Spanish); **CTV**, citrus tristeza virus; **EUREPGAP** (Euro-Retailer Produce Working Group and Good Agricultural Practices); **GAP**, good agricultural practices; **SEB**, stylar-end breakdown; **SNICS**, National Service for Seed Inspection and Certification (for its abbreviation in Spanish)

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INTRODUCTION

Contrary to what it is thought (due to the place that Mexico holds on world production); acid limes were not originated in Mexico or in the American continent. There are historical reports that consider that lime originated in the Asian continent, in Malaysia, from where it was introduced to North Africa and Europe (mainly to Spain) by the Arabs (Cooper and Chapot 1977; Eckert and Eaks 1989). Acid limes were brought to Mexico during the Spanish colonization acquiring an important place in the national citriculture. The term "citrus" is used to designate several fruits. However, due to the similarities that they present, there is confusion about these fruits classification. It has been suggested that there are six genera that conform the true citrus group: *Citrus*, *Fortunella*, *Poncirus*, *Microcitrus*, *Eremocitrus* and *Clymania*; these genera are characterized by having fruits with a juicy pulp composed by numerous vesicles that fill the space in the fruit segments that is not taken up by the seeds.

From these genera, only three have commercial rele-

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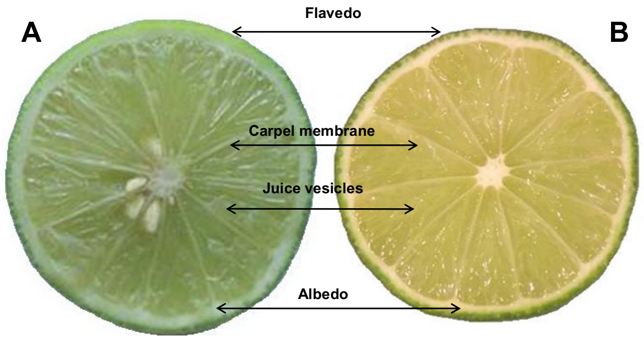

Fig. 1 Cross section of lime fruit. (**A**) 'Mexican' lime and (**B**) Persian lime.

vance all of which belong to the Rutaceae family: *Citrus*, *Fortunella* and *Microcitrus* (Cooper and Chapot 1977; Nagy 1996; Ortiz 2002). Acid limes are classified in the Magnoliophyta division, class Magnoliopsida, order Sapindales, family Rutaceae.

GENERAL MORPHOLOGY

All citrus fruits present the same anatomical structures: flavedo, albedo and carpels segments, although the elements that compose these structures vary according to species and variety (Loussert 1992). The external part of the rind, which consists of several morphologically different tissues, is called the flavedo because of the presence of flavonoid compounds (Ortiz 2002). The outermost layer of the fruit is the epidermis which is formed by a layer of isodiametric, polygonal cells that cover the entire surface of the fruit. The outer cell walls of this layer are heavily cutinized and partly covered with a waxy substance. These cutinized walls and the wax prevent excess loss of water from the fruit. Under the epidermis are layers of collenchyma and parenchyma cells. At different depths of the parenchyma tissue are located numerous oblate, spherical-shape oil glands containing essential oils. Below the layers of collenchyma and parenchyma cells is the white spongy portion of parenchyma called the albedo (Ting and Attaway 1971), name that comes from the Latin (*albus* = white) (Ortiz 2002). The edible part of the fruit is integrated by carpel segments or locules. Within the carpels are many juice vesicles (Ting and Attaway 1971) (**Fig. 1**). The number of carpels varies in acid lime fruits frequently presenting around 8-11 segments or locules (Loussert 1992).

THE PRINCIPAL VARIETIES OF ACID LIMES AND THEIR CHARACTERISTICS

The main cultivated acid limes are 'Mexican' lime (*Citrus aurantifolia* (Christm) Swingle) and the so-called Persian lime (*Citrus latifolia* Tanaka) which it is not currently accepted as a species, but as a natural hybrid of the group formed by citron-lemon-lime (Cooper and Chapot 1977). In Brazil and Florida, USA, it is known as 'Tahiti' lime and in California, USA, as 'Bearss lime' (Roy *et al*. 1996).

'Mexican' lime (*Citrus aurantifolia* Swingle) has small, round, obovate or short-elliptical fruits; which are moderately seedy and highy polyembryonic. They present a very thin rind; smooth surface; and a greenish-yellow color at maturity. Their flesh is juicy and highly acid with a distinctive aroma. On the other hand, Persian lime (*Citrus latifolia* Tanaka) has bigger; oval, obovate, oblong or short-elliptical fruits; with rare or lacking seeds. They present a thin rind, smooth surface; and a pale lemon-yellow color at maturity. Their flesh is juicy, very acid and with the true lime flavor (Hodgson 1967). 'Mexican' acid lime (*Citrus aurantifolia* [Christm.] Swingle) is a hybrid originated in the Archipelago of East India. Its probable ancestors are *C. medica* X *C. micrantha* (Papeda); this is supported by the fact that *C. aurantifolia* has an allele in common with the Papeda specimens, which is not present on the rest of the citrus genera (Torres *et al*. 1978). Since there is little variation between wild and cultivated specimens, there are not recognized varieties of 'Mexican' lime (Morton 1987). However, in Mexico, spineless selections were recognized as a new variety by the National Service for Seed Inspection and Certification (SNICS for its abbreviation in Spanish). According to this organization, there are two varieties of 'Mexican' limes cultivated in Mexico; Colima-01 (with spines) and Colima-02 (spineless), both of them selected in Tecoman, Colima, Mexico (Medina-Urrutia and Robles-González 2004).

Since Persian lime is a triploid (3n=27) hybrid, its pollen and ovules are not viable and for this reason its fruit are parthenocarpic (without seed) (Bacchi 1940; Moore 2001). Persian limes are one of the *Citrus* biotypes that are believed to be apomictically perpetuated. Its probable ancestors are *C. aurantifolia* (Christm.) Swingle and *C. maxima* L. or *C. limon* Burm. Since it does not produce seeds, there are no cultivars (varieties), the more spread clones are AC-5, CNPMF-1, CNPMF-2 and "Quebra galho" in Brazil; IVIA-124 and IVIA-227 in Spain; SRA 58 and SRA 359 in France and Bearss, USDA n° 1 and USDA n° 2 in the United States (Pio *et al*. 2005). The name of the clone cultivated in Mexico is unknown. It might be "Quebra galho" since its stem and branches show typical characteristics from this clone and it also presents cracked trunk and branches when attacked by the exocortis viroid.

ECONOMICAL IMPORTANCE

For countries with tropical and subtropical climates like Mexico, exports of fresh fruits and vegetables as well as its processed products represent an important capital source. In recent years, Mexico has become one of the main citrus-producing countries in the world (FAOSTAT 2008). Currently, acid limes are among the main fruits produced in Mexico both for fresh consumption and for its use in the food industry (Dussel 2002). The main lime- and lemon-producing countries in the period 2001-2007 are presented in **Table 1** (FAOSTAT 2008).

Table 1 Changes in annual production of lemons and limes in major producing countries (unit 10^3 metric tons).

	2001	2002	2003	2004	2005	2006	2007
India	1,377	1,413	1,439	1,493	1,033	1,786	2,060
Mexico	1,594	1,725	1,824	1,927	1,806	1,867	1,880
Argentina	1,217	1,313	1,236	1,340	1,498	1,250	1,260
Brazil	964	984	981	985	1,030	1,031	1,060
spain	1,024	933	1,129	810	944	852	880

*Source FAOSTAT 2008.

Production of acid limes in Mexico

In 2007, the worldwide production of acid lime fruits was of 13'032, 388 thousands of metric tons, of which Mexico contributed 1'880, 000 thousands of metric tons, therefore ranked as the main producer of lime fruits at a world-wide level, contributing 14.5% of the total production.

'Mexican' lime (*Citrus aurantífolia* Swingle) and Persian lime (*Citrus latifolia* Tanaka) are the main acid limes cultivated in Mexico. Both varieties have clearly differentiated production areas and commercialization schemes. 'Mexican' limes are mostly grown in the Pacific coast, with the state of Colima as the leading producer; and Persian limes are typically cultivated along the coast of the Gulf of Mexico with the state of Veracruz as the main producer (Claridades Agropecuarias 2002). Mexico is currently considered the main worldwide producer of 'Mexican' lime fruit and the world's leading Persian lime fruit producer and exporter, and thus, this country sets the quality standards for this species.

CHEMICAL COMPOSITION AND NUTRITIONAL VALUE

Acid limes as all citrus are non-climacteric fruits; hence, they do not show a postharvest organoleptic ripening process (Wills *et al.* 1984). In general, the fruit reaches its physiological and almost its consumption maturity in the tree. It is there, where the pulp becomes juicy and acid (Wardowski *et al*. 2006).

Acid lime fruits are similar to lemon fruits in structure and composition, and juices from the two species have about the same citric acid content (Swisher and Swisher 1980). Also, malic and succinic acids have been reported in lemon and lime juices. Most of the sugars and nearly all the citric acid of acid limes are in the juice which also contains nitrogenous compounds, lipids, phenolic compounds, vitamins such as vitamin C and B and inorganic substances (Ting and Attaway 1971). Even though, both lime and lemon juices are used as an acidulant, the flavor of lime beverages is distinctly different from that of lemon beverages (Nagy 1996). Acid lime fruits are more aromatic in flavor and scent than other citrus fruits especially when used in the green stage. The flavedo of lime fruits contains a lot of oil glands from which essential oils are obtained. The most abundant component of the essential oils in acid limes is d-limonene (Di Giaccomo and Di Giaccomo 2002). The components in lime peel oil and distilled lime oil have been studied extensively (Shaw 1977; Chamblee *et al*. 1985; Lota *et al*. 2002). Lota *et al*. (2002) reported at least 62 volatile compounds in the peel oil and 59 in the leaf oil of several lime species. In the lime fruit peel oils, limonene was the major volatile component, followed by γ-terpinene, β-pinene and/or sabinene. For leaf oils, a higher variability on the volatile composition was observed where the major components were limonene, β-pinene and sabinene, although linalool, geranial, linalyl acetate, citronellal, neral, citronellol, geranyl acetate, neryl acetate, geraniol and nerol were also found in all samples. The flavedo also contains pigments mainly chlorophylls and carotenoids. The albedo generally is rich in cellulose, hemicelluloses, lignin, pectic substances and phenolic compounds. The segment membrane and the juice vesicles membrane have about the same chemical constituents as the albedo.

In general terms, 'Mexican' lime fruit (*Citrus aurantifolia* S.) and Persian lime fruit (*Citrus latifolia* T.) have a different chemical composition. 'Mexican' lime fruit present higher acidity, higher and better content of essential oils and lower quantities of vitamin C than Persian lime fruit (Dussel 2002).

Antioxidant capacity

The function of natural antioxidants and phenolic content in foods and biological systems has received much attention. Fruits and vegetables play a significant role in the human diet providing protection against cellular damage caused by exposure to high levels of free radicals. Rivera-Cabrera *et al*. (2007b) compared the nutritional composition of citrus fruit grown in Mexico (grapefruit, 'Mexican' lime, Persian lime and orange) in terms of antioxidant activity and total phenolic compounds. The highest antioxidant capacity was observed in grapefruit juice compared to lime and orange juices. A high correlation between phenolic compounds and total antioxidant capacity was observed in different citrus fruits.

Prasad (1996) reported that high temperature conditioning treatments can increase the antioxidant capacity of tissues and prevent the accumulation of reactive oxygen species. Furthermore, several reports have suggested that postharvest stresses enhance the nutraceutical content of fresh fruits and vegetables with a corresponding added value to the produce. Contrary to this idea, Rivera-Cabrera *et al*. (2007a) found that hot dipping (53°C for 3 min) did not have any effect on the total antioxidant capacity in Persian limes during the entire storage period.

HARVEST MATURITY INDICATORS AND QUALITY INDICES FOR ACID LIMES

The main maturity indicators for acid lime fruits are juice content and fruit size. 'Mexican' lime fruits are required to have a minimum of 42% of juice by weight and a size ranging from 32.1 to 40 mm, and Persian limes fruits are required to have a minimum of 45% of juice by weight and a size that goes from 50 to 63 mm. One of the most important quality indices in acid lime fruits is the dark green color, since they are sold while still green. The green color is due to the presence of chlorophylls in mature green fruit. These pigments are located in the flavedo of the peel and the juice vesicles. The maintenance of green peel color is required throughout the postharvest supply chain to attract premium price. Other indices worth mentioning are size, shape, firmness, smoothness, decay-free, and free of defects, such as bruises, oil spotting, dryness, chilling injury and stylar-end breakdown (Rivera 2006b). Acid lime fruits must be harvested, handled, stored and transported gently to assure a very good postharvest quality.

Destination markets

'Mexican' limes *(Cítrus aurantífolia* S.) represent the 70% of the national production, and they are used mainly for the internal market and the extraction of essential oils and pectins (Gómez *et al*. 1994; Bosquez-Molina *et al*. 2004). Persian limes (*Citrus latifolía* T.) contribute to the remaining 30 and 80% of this production is generally for exportation to different countries.

Japan is the most demanding market, followed by Europe and the United States, where more than 95% of the total export is sent. Currently new international markets are being studied to expand exports, especially to Asia and Europe (Rivera 2006b).

EFFECT OF PREHARVEST FACTORS ON QUALITY AND POSTHARVEST BEHAVIOR

In general, the preharvest factors that affect fruit quality are among others, rootstocks, crop management (irrigation or seasonal), nutrition, pruning, harvesting time, presence and management of pests and diseases.

Effect of rootstock

The more common rootstocks used for 'Mexican' lime are *C. volkameriana*, *C. macrophylla* and *C. amblycarpa.* These rootstocks are mainly used to avoid plant death by gummosis since 'Mexican' lime is susceptible to this disease. Mexican lime plants grafted on these three rootstocks are vigorous. Plants grafted in *C. amblicarpa* take longer in producing fruits which are smaller that those obtained from plants grafted in *C. macrophylla and C. volkameriana* (Medina-Urrutia and Robles-Gonzalez 2004). Lallan *et al*. (1999) reported that the use of rootstocks in 'Mexican' lime affects the number of stomas and the leaf nutritional content as it occurs for Persian lime. There is no information on the effect of the use of rootstocks in the 'Mexican' lime fruit quality.

The effect of the use of rootstocks on plant size, yield and disease tolerance of Persian lime has been evaluated by several authors (Jiménez *et al*. 1981; Figueiredo *et al*. 2002; Stenzel and Neves 2004). All reports agree that the rootstock affects plant size and yield. However, regarding the effect on fruit quality (size, juice content, percentage of soluble solids content) results are contradictory. While some authors observed an effect of the rootstock in fruit size (Jiménez *et al*. 1981; Stenzel *et al*. 2004), others reported no significant differences due to the use of the rootstock (Figueiredo *et al*. 2002). Regarding the juice and the soluble solids content, Jiménez *et al.* (1981); and Stenzel *et al.* (2004) reported and increase on these parameters, while Rivera-Cabrera *et al*. (2009) did not observed significant differences attributable to the rootstock. In general, Persian lime fruit grown in volkameriana and rough lemons have a higher juice content than fruit developed in other rootstocks.

A critical but little studied aspect of Persian lime fruit quality for export is the fruit color and the albedo and flavedo thickness. In this regard, Rivera-Cabrera *et al*. (2009) observed that Persian lime fruit grown in plants grafted in 'Flying dragon' developed a darker green, while fruit from Persian lime grafted in *C. volkameriana* presented a higher albedo and flavedo thickness. Therefore, it would be expected that fruit developed in *C. volkameriana* lost less water than those developed in 'Flying dragon'; however, the opposite effect was observed. After 25 days of storage at 25°C, Persian lime fruits grafted in *C. volkameriana* lost 30% of its initial weight and those from 'Flying dragon' only 13%. This is important to be considered for export loadings from Mexico destined to Europe.

A high degree of roughness of the peel (surface slightly pitted or rough) is another important but little studied factor for lime export, mainly to Europe and Japan. This characteristic is affected by rootstock and nutrition; the peel of fruits developed in plants of Persian lime grafted in *Citrus volkameriana* and *citrange* C 35 is rougher than that from those obtained from plants grafted in 'Flying dragon' and sour orange. Nitrogen, magnesium and manganese concentrations are the most important factors of nutrition to be considered for this characteristic expression and they should be determined depending on soil type and rootstock.

Effect of pruning

Persian lime produces independent fruits and fruit clusters. Fruits obtained from clusters are smaller and regularly they present a shaded area that can limit exportation. Individual fruits which are bigger and with a homogeneous green color in their entire surface are exported to Europe and Japan, the most demanding markets regarding fruit size, color and the absence of mechanical damage. Pruning is an important factor for obtaining individual fruits and favors a better color (dark green) development by increasing sun exposure. In recent years, most lime producers in Martínez de la Torre, Veracruz, Mexico, prune their trees "hedge type" and maintain the height of the plants below 2 m; this, besides making harvesting easier, allows more sun exposure. Even though more studies are needed, field observations show that Persian lime plants grafted in *citrumelo swingle* and 'Flying dragon' produce individual fruits, while for those grafted in *C. volkameriana*, most of the fruits are produced in clusters, in which case thinning is recommended.

GOOD AGRICULTURAL PRACTICES (GAP) AND SAFETY

Companies which want to export Persian lime need to fulfill a set of national and international regulations. According to the Council of Producers and Exporters of Persian lime (COPELP, A.C. for its abbreviation in Spanish) in Martinez de la Torre, Veracruz, Mexico, there are 38 Persian lime packing houses, from which 32 are part of this organization and only six are certified for good agricultural practices (GAP). From the six GAP certified packing houses, two are not part of COPELP, which means that only 25% of those that form part of this organization are certified. Most of these packing houses own Persian lime orchards and therefore can guarantee a determined exportation volume. Even when all these 38 companies export Persian lime, the destination of their fruit varies, some (3-4 packing houses) export mainly to Europe and Japan, while most of them export to the United States. The destination market establishes the differences between the fruit from different companies; fruit destined to Europe and Japan is bigger, with a more intense green color, a rougher surface and less that 5% of damaged area (including the shaded area of the fruit).

It is important to mention that the orchards from the certified packing houses are also certified by the Mexican Department of Agriculture, Farming Rural Development, Fishing and Food (SAGARPA for its abbreviation in Spanish) in Good Agricultural Practices and in the Management in the production of fresh fruits and vegetables. They also comply with what is stipulated in the Codex Alimentarius and EUREPGAP (Euro-Retailer Produce Working Group and Good Agricultural Practices) to ensure harmlessness of fresh fruits and vegetables.

Another important certification is "Mexico Selected Quality of Persian Lime". According to this regulation the fruit color should be dark green. For fruits destined to the American market it is required that the fruit have this color in at least 70% of its total surface area, 80% for the European market and 90% for the Asian market. Other characteristics such as size, juice content, form, texture, firmness, mechanical damage or plagues are indicated in the conditions for the use of the official trademark "Mexico Selected Quality of Persian Lime".

PHYSIOLOGICAL DISORDERS AND DISEASES IN ACID LIMES

Physiological disorders significantly influence the quality of lime fruits. Preharvest and postharvest factors affect the occurrence of physiological disorders in lime fruits (Grierson 1981). Physiological disorders could be caused by preharvest factors such as nitrogen, boron and copper deficiency, water spotting, sunburn, wind scar and freezing.

On the other hand, postharvest factors such as temperature, humidity, mechanical stress and ageing also have an impact on the development of physiological disorders.

Typical lime fruit physiological disorders are chilling injury, oil spotting (oleocellosis) and stylar-end breakdown. It is also important to point out that 95% of losses are due to mechanical damage during postharvest operation.

Chilling injury

Among postharvest disinfestations' procedures to certify citrus free from fruit fly, cold quarantine treatments are accepted by regulatory agencies of several countries and are commercially applied. In addition, cold storage allows an extended marketing period and long distance transport. However, long- term storage at low, non-freezing temperatures induces chilling injury, especially in horticultural products growing in tropical and subtropical regions, such as citrus fruit.

Chilling injury symptoms in citrus are pitting of the flavedo and brown depressed areas, necrosis and eventually cell death. The size of the affected areas depends on the damage extent. This disorder affects consumer acceptability and may result in commercial losses. Chilling injury symptoms are often accompanied by an increase in susceptibility to decay and in extreme cases by the appearance of off-flavors (Cohen *et al*. 1990). Symptoms of chilling injury may not be apparent during cold treatment but may be fully expressed when fruit are transferred to warmer conditions. Susceptibility to chilling injury depends on several factors such as climate, cultural practices, fruit position in the canopy, exposure to the sun and picking date. Oxidative stress has been associated with chilling damage in plants (Hariyadi and Parkin 1991).

Treatments to ameliorate chilling injury

Fruit temperature previous to cold storage affects susceptibility to chilling injury. Several authors reported that prestorage hot water dips reduced significantly citrus fruit sensitivity to chilling injury and alleviated the severity of the damage.

Active oxygen species scavenging enzymes such as superoxide dismutase, catalase, ascorbate and guaiacol peroxidases and glutathione reductase have been implicated in postharvest heat-conditioning treatments protecting citrus fruit against chilling. Rivera *et al*. (2004) evaluated the effectiveness of a hot water dip conditioning (53°C for 3 min) to prevent chilling injury in Persian limes fruits (*Citrus latifolia* Tanaka). However, heat treatment did not protect the fruit against chilling injury and oxidative stress. Even when heat treatment caused a transitory increase in peroxidase and superoxide dismutase activities it also produced a significant increase in lipoperoxidation. These results suggest that in order to make heat treatment effective against chilling injury, it is necessary to induce antioxidant enzymes during the entire storage period.

Conditioning temperatures above the critical chilling temperature have also been used to reduce chilling injury symptoms in citrus fruits. Lemon fruits conditioned at 5°C or 15°C for 1 week before quarantine treatment (0-2.2°C for 10-22 days) showed less chilling injury than non conditioned fruits (Huock *et al*. 1990). A cold conditioning treatment (13°C for 48 h) reduced 1.6 fold chilling injury symptoms in 'Mexican' lime fruits (*Citrus aurantifolia* S.). Conditioning induced a significant increase of peroxidase activity and maintained the activity of superoxide dismutase in limes. These results support the suggestion that the effectiveness of the cold conditioning treatment in increasing chilling tolerance in 'Mexican' limes depends on the induction and maintenance of antioxidant enzymatic systems during the entire storage period (Rivera *et al*. 2007).

Molecular basis of chilling injury and chilling tolerance

In order to understand the mechanisms involved in the acquisition of chilling tolerance, molecular studies of gene expression has been performed in citrus fruits. Overall, exposure to chilling led to a general arrest of the expression of genes involved in cellular metabolic activity (photosynthesis, respiration, protein, nucleic acid and secondary metabolism). Among the putative genes associated to chilling tolerance, transcription factors, proteins involved in membrane, lipid, cell wall and carbohydrate metabolism, proteins with scavenging and repair function that prevents oxidative damage, stress related proteins such as heat shock proteins, dehydrins and proteins involved in hormone biosynthesis (jasmonic acid) have been detected. These studies suggest that heat treatment and conditioning at low temperatures activate different chilling stress defensive pathways (Sánchez-Ballesta *et al*. 2003; Sapitnitskaya *et al*. 2006; Maul *et al*. 2008).

Oil spotting (oleocellosis)

Oil spotting (oleocellosis) is a physiological rind disorder of citrus fruit caused by the action of phytotoxic rind oils. These oils are released from glands located in the rind (Knight *et al*. 2002) when the fruit suffers mechanical damage by inadequate potsharvest handling (Eaks 1968). Oil spotting can result from various types of damage, including insect attack, hail damage or wind rub and can also develop in undamaged fruit that comes in contact with damaged fruit (Murata 1997).

The oils (mainly terpenes) released from glands are toxic to the surrounding living cells and result in necrosis of the adjacent epidermis, presented as the formation of irregularly shape brown spots in which the oil glands stand out prominently due to a slight sinking of the tissues between them. The nature of the reaction between the phytotoxic oils and the rind tissue is ill-defined in the literature. Oil spotting is found in all kind of citrus fruit but especially in limes, lemons and oranges harvested early before they have lost their green color (Eaks 1968; Shomer and Erner 1989; Murata 1997; Knight *et al*. 2002; Bakkali *et al*. 2008).

Rivera-Cabrera *et al*. (2006a) tested the effect of two different cutting procedures (traditional or underwater) on the postharvest behavior in fresh-cut lime and observed that oil spotting was the main restriction of fresh-cut process in Persian lime fruits. These results contrast with those reported by Artés-Hernández *et al.* (2007) in fresh cut lemons where oil spotting was not observed and suggest that acid limes are more susceptible to this disorder than lemon fruits.

Stylar-end breakdown

Persian limes (*Citrus latifolia* T) are susceptible to collapse of the rind at the stylar end of the fruit. A water-soaked, grayish or tan-colored patch, especially near of the nipple at the stylar end of seedlees limes, appears as an initial symptom of stylar-end breakdown (SEB). Usually SEB is initiated by rough handling. Different factors affect the susceptibility of limes to SEB. Davenport and Campbell (1977) reported that the fruit size, turgor, high temperature and humidity are directly correlated with susceptibility to this disorder.

Diseases of acid limes

The main diseases of acid limes cultivated in Mexico are exocortis and cachexia and Citrus tristeza virus (CTV) that is a general problem for citrus fruits worldwide. In the case of 'Mexican' and Persian limes CTV represents a serious threat, due to the use of sour orange rootstock in more than 90% of the orchards, being that sour orange is susceptible to CTV (Rivera-Cabrera *et al* 2006b).

'Mexican' and Persian lime fruits are susceptible to invasion by fungi at bruises and skin breaks. Clipper cut, fingernail scratches, injuries caused by harvesting or packhouse machinery, packing bruises, damage caused by rough handling in transit or storage are all sources of danger. In particular *Penicillum* spp, which causes a typical fungus wound infection such as green-mould (*Penicillum digitatum*) and blue-mould rot (*Penicillum italicum*) are common posharvest diseases of lime fruits in storage. *Penicillum digitatum* and *P. italicum* attack fruits on the tree or in the packing house, transit, storage and market. Early symptoms are similar in both rots; diseased tissue in the rind becomes soft, watery and decolorized. Ocurrence of green and blue-mould root can be reduced by spraying with fungicide such as benomyl, which can be applied as an orchard spray up to 3 weeks before harvest or as postharvest treatment in the packinghouse. However, carefully handling in harvesting, packing, transit, storage, and marketing is essential to avoid wound infection in lime fruits by *Penicillum* spp (Brown and Eckert 1993; Murata 1997).

Another important postharvest disease in warm and humid regions is stem-end rot (*Lasiodiplodia theobromae*, and *Phomopsis citri*). Diplodia stem-end rot is rarely observed on fruit attached to the tree, even when they are mature. After harvest, symptoms appear within 2 weeks when the temperatures are above 21°C. Phompsis stem-end rot occurs after harvest during transit or storage. Stem-end rot appears as water-soaked spots near the stem end of the lime fruit, which turn tan to blackish-brown. A fungicidal treatment with imazalil or benomyl either at the orchard within 3 weeks of harvest or during the postharvest operation is effective to control occurrence of stem-end rot. Low temperature (5-7°C) and low humidity (80-88% RH) during storage help to reduce the occurrence of the stem-end rot in lime fruits (Brown and Eckert 1993).

HARVESTING, FIELD HANDLING AND PACKING HOUSE OPERATIONS

To ensure and excellent Persian lime fruit quality during the packing process, harvesting should take place when fruits are totally dry; depending on the time of the year, in Martinez de la Torre, Veracruz, this takes place between 9 and 10 am. Manual harvesting is performed by trained personnel instructed in the minimum size required depending on the destination market. Fruits are placed in plastic buckets and then transferred to washed and disinfected with a solution of 30% hypochlorite plastic boxes to be transported to the packing house.

In the packing house, the receptionist performs a visual

Fig. 2 Persian lime fruit export quality.

inspection of the fruit to obtain samples of uniform colour, size and quality (dark green, 3.4 to 3.9 cm in diameter and free of defects and if it fulfills the intended characteristics (**Fig. 2**), it is weighted and each box is labeled wit the name of the producing orchard and the harvesting date. If the fruit does not fulfill the required size and color it is rejected and sent to the national market. Accepted fruit is placed in hoppers covered with sponge (to avoid mechanical damage) located at 1.5-2.0 m from the transport band, where fruits are deposited and manually selected. At this stage, yellow fruits, fruits with mechanical damage, plagues or diseases are eliminated. Afterwards, fruits are washed by immersion for 3 to 5 min. Later, fruits are brushed with rollers to eliminate dust residues and the excess of water. Then, fruits are waxed (WATERWAX, FOMESA, Spain). The wax may be applied by hand or mechanically as a spray. Spray application is most commonly used in larger scale operations, using a pair of traveling spray nozzles over a bed of slowly rotating (not more than 100 rpm) horsehair-type brush rollers. A fungicide (thiabendazole or imazalil 2000 mg L^{-1} or benomyl 1000 mg L^{-1}) can be incorporated in the wax (WATERWAX-21 UK/UE, FOMESA, Spain) to prevent postharvest decay. Then, fruits are transported to a tunnel for drying with hot air at 40°C for 30-40 seconds. After this process, fruits are selected again by trained personnel to eliminate fruits with physical and mechanical damages and then, passed to a "sizer" that selects fruit by its diameter, separating the following classifications: 250, 230, 200, 175, 150 and 110 (referring to the number of fruits that fit in a 18.12 kg box), presentations used in the US market.

Fruit that will be exported to Europe and Asia are selected again by personnel with a higher degree of training. Fruits from each classification are selected again by color (depending on the destination market, eliminating those which have more that 5% of shaded area) and damage absence and place in 4.53 kg cardboard boxes covered with waxed paper. Fruits are arranged in lines of 4 or 5 fruits in two layers for a total of 44 fruits per box (**Fig. 2**). Each fruit from the upper layer is labeled and waxed. Boxes are labeled with all the specifications (variety, size, and packing date) to comply with traceability, placed in pelts and sealed with mesh to avoid entrance or exit of pathogens. Finally, fruits are introduced in refrigerated trucks at 12°C and transported to the shipping port at the airport or the United States border (pers. obs.).

CONCLUSIONS

Acid limes represent a commercially important tropical crop, distributed in subtropical, tropical and temperate regions of the world. Lime fruits have a complicated structure formed by the rind, consisting of flavedo, albedo and oil glands, and the segmental flesh.

This review highlights the most important factors to obtain high quality lime fruits, as well as the postharvest management that this fruit receive in Mexican packing houses, its main producer. Currently, there are numerous research reports concerning the postharvest physiology and biochemistry of citrus fruit; however, there is still very little information in this sense for acid limes.

Therefore, it is important to go deeper in the study of the molecular and biochemical mechanisms of the development of the physical and chemical quality characteristic of acid lime fruits, such as the regulation of their chemical composition and the essential oil biosynthesis as well as the oil spotting (oleocellosis) development mechanism.

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REFERENCES

Artés-Hernández F, Rivera-Cabrera F, Kader AA (2007) Quality retention and potential shelf-life of fresh-cut lemons as affected by cut type and temperature. *Postharvest Biology and Technology* **43**, 245-254

Bacchi O (1940). Observacoes citológicas em *Citrus*. I. Número de cromossômios de algumas espécies e variedades. *Jornal de Agronomia Piracicaba* **3**, 249-258

Bakkali F, Averbeck S, Averbeck D, Idaomar M (2008) Biological effects of essential oils; A review. *Food and Chemical Toxicology* **46**, 446-475

Bosquez-Molina E, Domínguez-Soberanes J, Pérez-Flores LJ, Díaz-de-León-Sánchez F, Vernon-Carter J (2004) Effect of edible coatings on storage life of 'Mexican' limes (*Citrus aurantifolia* Swingle) harvested in two different periods. *Acta Horticulturae* **632**, 329-335

Brown GE, Eckert JW (1993) Postharvest fungal diseases. In: Whiteside JO, Garnsey SM, Timmer LW (Eds) *Compendium of Citrus Diseases* (2nd Edn), APS Press, The American Phytopathological Society, St. Paul, Minnesota, USA, pp 30-38

Chamblee TS, Clark BCJr., Radford T, Jacobucci GA (1985) Identification of new constituents in cold-pressed lime oil. *Journal of Chromatography* **330**, 141-151

Claridades Agropecuarias (2002) La competitividad de la cadena productiva del limón Mexicano. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentos (SAGARPA), Mexico, DF, pp 3-33

Cohen E, Shalom Y, Rosemberg I (1990) Postharvest ethanol build up and off-flavor in 'Murcott' tangerine fruits. *Journal of the American Society for Horticultural Science* **115**, 775-778

Cooper WC, Chapot H (1977) Fruit production with special emphasis on fruit for processing. In: Nagy S, Shaw PE, Veldhuis MK (Eds) *Citrus Science and Technology* (1st Edn, Vol 2), AVI Publishing Co., Westport, CT, USA, pp 1-127

Davenport TL, Campbell CW (1977) Stylar-end breakdown in 'Tahiti' limes: aggravating effects of field heat and fruit maturity. *Journal of the American Society for Horticultural Science* **102**, 484-486

Di Giacomo A, Di Giacomo, D (2002) Essential oil production. In: Dugo G, Di Giacomo A (Eds) *Citrus: The Genus Citrus* (1st Edn), CRC Press, Taylor and Francis group, Boca Raton, FL, USA, pp 114-147

Dussel PE (2002) *Territorio y competitividad en la agroindustria en México: Condiciones y propuestas de política para los clusters del limón Mexicanoen Colima y la piña en Veracruz* (1st Edn), Plaza y Valdez-CEPAL-INIFAP-Universidad de Colima-Ayuntamiento de Isla, 270 pp

Eaks IL (1968) Rind disorders of oranges and lemons in California. In: 1st *International Citrus Symposium*. 16-26 March, 1968 UC Riverside CA, USA, pp 1343-1354

Eckert JW, Eask IL (1989) Posharvest disorders and diseases of citrus fruit. In: Reuther WE, Calavan EC, Carman GE (Eds) *The Citrus Industry* (Vol V), University of California, Division of Agriculture and Natural Resources, CA, USA. pp 174-260

FAOSTAT (2008) The FAO Statistical Database on-line. Available online: http://faostat.fao.org/site/567/default.aspx#ancor

Figueiredo JO, Stuchi ES, Donadio LC, Sobrinho JT, Laranjeira FF, Pio RM, Sempionato OR (2002) Porta-enxertos para a lima ácida 'Tahiti' na região de Bebedouro, SP. *Revista Brasileira de Fruticultura* **24**, 155-159

Gómez CMA, Rindermann SR, Barrera GA (1994) El limón persa en México: Una opción para el trópico. Universidad Autónoma de Chapingo, Texcoco, Mexico, pp 50-52

Grierson W (1981) Physiological disorders of citrus fruits. In: *4th International Citrus Congress*, *International Society of Citriculture*, 9-13 November, 1981, Tokyo, Japan **2**, 764-767

Hariyadi P, Parkin KI (1991) Chilling induced oxidative stress in cucumber fruits. *Postharvest Biology and Technology* **33**, 45-49

Hodgson R (1967) Horticultural varieties of citrus. In: Reuther W, Batchelor LD, Webber HJ (Eds) *The Citrus Industry* (1st Edn, Vol I) Division of agricultural Sciences, University of California, California, USA, pp 496-533

Huock LG, Jenner JF, Bianchi J (1990) Holding lemon fruit at 5°C or 15°C before cold treatment reduces chilling injury. *HortScience* **25**, 1174

Jiménez VR, García BG, Santos MM (1981) Influencia de cinco patrones sobre la calidad de la lima Persa SRA-58 (*Citrus latifolia*) en el sur de la Habana. *Agrotecnia de Cuba* **13**, 21-29

Knight TG, Klieber A, Sedgley M (2002) Structural basis of the rind disorder Oleocellosis in Washington navel orange (*Citrus sinensis* L. Osbeck). *Annals of Botany* **90**, 765-773

Lallan R, Singh S, Marathe RA (1999) Preformance of pre-bearing acid lime on various rootstocks strains. *India Agricultural Science* **69**, 193-197

Lota ML, de Rocca Serra D, Tomi F, Jacquemond C, Casanova J (2002) Volatile components of peel and leaf oils of lemon and lime species. *Journal of Agricultural and Food Chemistry* **50**, 796-805

Loussert R (1992) *Los Agrios* (1st Edn), Mundi-Prensa, Madrid, España, 319 pp

Maul P, McCollum GT, Popp M, Guy CL, Porat R (2008) Transcriptome profiling of grapefruit flavedo following exposure to low temperature and conditioning treatments uncovers principal molecular components involved in chilling tolerance and susceptibility. *Plant Cell and Environment* **31**, 752-768

Medina-Urrutia VM, Robles-Gonzalez MM (2004) Situacion actual y perspectivas del limón Mexicano. In: *2do Simposium Internacional de Citricultura*, 26-28 Agosto, 2004, Puerto Escondido, Oaxaca, Mexico, pp 1-10

Moore GA (2001) Oranges and lemons: clues to the taxonomy of *Citrus* from molecular markers. *Trends in Genetics* **17**, 536-540

Morton, J (1987) Mexican lime. In: Morton J (Ed) *Fruits of Warm Climates* (1th Edn) Creative Resource Systems, Inc. Winterville, NC, USA, pp 168-172

Murata T (1997) Citrus. In: Mitra SK (Ed) *Postharvest Physiology and Storage of Tropical and Subtropical Fruits* (1st Edn), CAB International, Wallingford UK, pp 21-46

Nagy S (1996) Factor affecting the flavor of citrus fruits and their juice products. In: Nagy S, Shaw PE, Chen CS (Eds) *Quality Control Manual for Citrus Processing Plants* (1st Edn, Vol III), Agscience., Inc., Auburndale, FL, pp 102-133

Ortiz JM (2002) Botany: Taxonomy, morphology and physiology of fruits, leaves and flowers. In: Dugo G, Di Giacomo A (Eds) *Citrus: The Genus Citrus* (1st Edn), CRC Press, Taylor and Francis group, Boca Raton, FL, USA, pp 114-147

Pio RM, Figueiredo JO, Stuchi ES, Barros SA (2005) Variedades copas. In: Mattos D, Negri JD, Pio RM, Pompeu J (Eds) *Citrus*, Instituto Agronómico e Fundog, Campinas, Cordeiropolis, SP, Brazil, pp 37-60

Prasad TK (1996) Mechanisms of chilling-induced oxidative stress injury and tolerance in developing maize seedlings: changes in antioxidant system, oxidation of proteins and lipids, and protease activities. *Plant Journal* **10**, 1017-1026

Rivera C F, Rodríguez SZ, Díaz de León SF, Bósquez ME, Domínguez SJ, Chávez FS, Cajustes BJ, Pérez FL (2004) Lipoperoxidation and antioxidant enzymes of refrigerated Persian limes (*Citrus latifolia* Tanaka) as influenced by a pre-storage hot treatment. *Journal of Food Biochemistry* **28**, 305-317

Rivera-Cabrera F, Díaz de León-Sánchez F, Pelayo-Zaldívar C, Pérez-Flores LJ, Ebeler SE, Kader AA (2006a) Postharvest behavior of fresh-cut limes (*Citrus latifolia* t.) under two different cutting procedures. In: *27th International Horticultural Congress*, 13-19 August, 2006, Seoul, Korea, p 442 (Abstract)

Rivera-Cabrera F, Jacuinde JK, Diaz de Leon F, Perez-Flores LJ (2006b) Trends in citrus industry and research in Mexico. In: *International Seminar Trends in Citrus Industry and Research*, 21 August, 2006, Jeju, Korea, pp 33-50

Rivera-Cabrera F, Jacuinde J, Diaz de Leon F, Pelayo-Zaldívar C, Perez-Flores LJ (2007a) Influence of pre-storage hot treatment on lipid peroxidetion, antioxidant enzymes and antioxidant capacity of Persian limes (*Citrus latifolia* tanaka). *2nd International Symposium on Human Health Effects of Fruits and Vegetables*, 9-13 October, 2007, Houston, TX, USA, p 115 (Abstract)

Rivera-Cabrera F, Jacuinde JK, Diaz de Leon F, Perez-Flores LJ (2007b) Total antioxidant activity of citrus fruits and their phenolic composition. *3rd Workshop on comparative aspects of oxidative stress in biological systems*, 17-19 October, 2007, Cuautla, Morelos, Mexico, p 13 (Abstract)

Rivera F, Pelayo C, Díaz de León F, Buentello B, Castillo M, Pérez FLJ (2007) Cold-conditioning treatment reduces chilling injury in Mexican limes (*Citrus aurantifolia* S.) stored at different temperatures. *Journal of Food Quality* **30**, 121-134

Rivera-Cabrera F, Raddatz-Mota D, Villegas-Monter A y Curtí-Díaz S (2009) Efecto de dos portainjertos tolerantes al VTC en la calidad postcosecha de lima Persa (*Citrus Latifolia* T.). In: *Proceedings of 54th Meeting of the InterAmerican Society for Tropical Horticulture*, 12-17 October, 2008, Vitória, Brazil, **52**, 131-133

Roy M, Andrew CO, Spreen TH (1996) World markets for U.S and Mexican limes. In: Persian limes in North America. An economic analysis of production and marketing channels. Florida Science. Source, Inc. Lake Alfred, FL, USA, pp 27-43

Sánchez-Ballesta MT, Lluch Y, Gosalbes MJ, Zacarias L, Granell A, Lafuente MT (2003) A survey of genes differentially expressed during long-term heat-induced chilling tolerance in citrus fruit. *Planta* **218**, 65-70

Sapitnitskaya M, Maul P, McCollum GT, Guy CL, Weiss B, Samach A, Porat R (2006) Postharvest heat and conditioning treatments activate different molecular responses and reduce chilling injuries in grapefruit. *Journal of Experimental Botany* **57**, 2943-2953

Shaw PE (1977) Essential oils. In: Nagy S, Shaw PE, Veldhius MK (Eds) C*itrus Science and Technology* (1st Edn, Vol I), AVI publishing Co., Inc., Westport, CT, USA, pp 427-462

Shomer I, Erner Y (1989) The nature oleocellosis in citrus fruits. *Botanical Gazette* **150**, 281-288

Stenzel MNM, Neves J CSV (2004) Rootstocks for 'Tahiti' lime. *Scientia Agricola* **61**, 151-155

Swisher HE, Swisher LH (1980) Lemon and lime juices. In: Nelson PE, Tressler DK (Eds) *Fruit and Vegetable Juice Processing Technology* (3rd Edn), AVI Publishing Co., Inc., Westport, CT, pp 125-128

Ting SV, Attaway JA (1971) Citrus fruit. In: Hulme AC (Ed) *The Biochemistry of Fruit and their Products* (Vol I), Academic Press, London, pp 107-369

Torres AM, Soost RK, Diedenhofen U (1978) Leaf isozymes as genetic markers in *Citrus*. *American Journal of Botany* **65**, 869-881

Wardowski WM, Hall DJ, Grierson W (2006) *Fresh Citrus Fruits* (2nd Edn), Florida Science Source, Inc., Florida, USA, 571 pp

Wills RH, Lee TH, McGlasson WB, Hall EG, Graham D (1984) *Fisiología y Manipulación de Frutas y Hortalizas Post Recolección*, Editorial Acribia, Zaragoza, Span, 195 pp