

FOOD PRESERVATION TECHNOLOGY SERIES



Advances in Fresh-Cut Fruits and Vegetables Processing

Edited by
Olga Martín-Belloso
Robert Soliva-Fortuny

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Advances in Fresh-Cut Fruits and Vegetables Processing

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1 The Fresh-Cut Fruit and Vegetables Industry

Current Situation and Market Trends

*M. Alejandra Rojas-Graü, Edward Garner,
and Olga Martín-Belloso*

CONTENTS

1.1	Introduction	1
1.2	Global Market Tendencies	3
1.2.1	American Trends	4
1.2.2	European Trends	5
1.2.3	Asiatic Trends	8
1.3	Final Remarks	10
	References	10

1.1 INTRODUCTION

Fresh-cut fruit and vegetables, initially called minimally processed or lightly processed products, can be defined as any fresh fruit or vegetable that has been physically modified from its original form (by peeling, trimming, washing, and cutting) to obtain 100% edible product that is subsequently bagged or prepackaged and kept in refrigerated storage (IFPA, 2005). Fresh-cut produce includes any kind of fresh commodities and their mixtures in different cuts and packaging. Items such as bagged salads, baby carrots, stir-fry vegetable mixes, and fresh-cut apples, pineapple, or melon are only some examples of this type of product.

The production and consumption of fresh-cut commodities is not new. According to the International Fresh-Cut Produce Association (IFPA), fresh-cut products have been available to consumers since the 1930s in retail supermarkets. However, the fresh-cut industry was first developed to supply hotels, restaurants, catering services, and other institutions. For the food service industry and restaurants, fresh-cut produce presents a series of advantages, including a reduction in the need of manpower for food preparation, reduced need of special systems to handle waste, and the possibility to deliver in a short time, specific forms of fresh-cut products (Watada et al., 1996). Yet it has not been until the past two decades that fresh-cut fruit and vegetable

products have gained popularity and penetration in the produce business as a result of a general trend to increase fresh fruit and vegetable consumption (Mayen and Marshall, 2005). The fresh-cut fruit and vegetable industry is constantly growing mainly due to the consumers' tendency to consume healthy and convenient foods and their interest in the role of food in improving human well-being (Gilbert, 2000; Ragaert et al., 2004). In fact, organizations such as the World Health Organization (WHO), Food and Agriculture Organization (FAO), United States Department of Agriculture (USDA), and European Food Safety Authority (EFSA) recommended an increase of fruit and vegetable consumption to decrease the risk of cardiovascular diseases and cancer (Allende et al., 2006). In countries such as the United States, the consumption of fresh whole fruit increased from 282.1 to 284.6 lb/year per capita during the last decade of the 20th century (USDA, 2003), probably as a consequence of an increased public awareness regarding the importance of healthy eating habits.

On the other hand, fresh-cut products are a very convenient way to supply consumers with ready-to-eat foods. Washed, bite-size, and packaged fresh fruit and vegetables allow consumers to eat healthy on the run and to save time on food preparation. For instance, the availability of fresh-cut fruits in vending machines in schools and at workplaces would constitute an excellent strategy to improve the nutritional quality of snacks and convenience foods in a time when obesity and nutrition-related illnesses affect large percentages of the population (Olivas and Barbosa-Cánovas, 2005). In addition to the convenience, there are other reasons for the success of fresh-cut produce, such as the absence of waste material. Waste is generated in peeling and coring fruit. However, when utilizing fresh-cut produce, 100% is consumable, and there is a substantial decrease in labor required for home produce preparation and waste disposal (Garcia and Barrett, 2005).

A study conducted by the IFPA revealed that 76% of surveyed households buy fresh-cut produce at least once a month, and 70% buy fresh-cut fruit every few months (IFPA, 2003). About 30% of consumers prefer fresh-cut fruits and vegetables to their unprocessed equivalents. In addition, Sonti et al. (2003) indicated that women are more likely to buy fresh-cut fruit than men, and as the income level increases, the probability of consuming fresh-cut fruits also increases.

Fresh-cut fruits and vegetables, prepackaged salads, locally grown items, and exotic produce as well as hundreds of new varieties and processed products have been introduced or expanded since the early 1980s. Supermarket produce departments carry over 400 produce items today, up from 150 in the mid-1970s and from 250 in the late 1980s. Also, the number of ethnic, gourmet, and natural food stores that highlight fresh-cut produce continues to rise. Some fresh-cut produce currently available in supermarkets is included in Table 1.1. Because of their convenience and consistent quality, packaged salads continue to be the most popular fresh-cut product. Today, packaged salads account for about 7% of all produce department sales. In fact, in countries such as the United States, consumers have made packaged salads the second-fastest-selling item in grocery stores, trailing only bottled water (Bhagwat, 2006). According to Garrett (2002), organically grown fruits and vegetables are another segment of the fresh produce industry that experienced strong growth in the 1990s, including both whole commodities and fresh-cut products.

TABLE 1.1
Prepared Fruit, Leafy Salad, and Mixed-Tray Salads*

Prepared Fruits	Leafy Salads	Mixed-Tray Salads
Classic salad	Sweet + crunchy salad	Potato + egg salad
Pineapple chunks	Watercress	Sweet + crunchy salad
Luxury fruit salad	Crispy salad	Lettuce + tomato + cucumber + celery
Melon medley	Iceberg lettuce	Mediterranean salad
Melon + grape	Italian salad	Fresh + crispy
Pineapple pieces	Rocket salad	Ribbon salad lettuce + cucumber
Sliced melon selection	Rocket	Mixed pepper salad
Tropical fruit salad	Baby leaf salad	Prawn + pasta salad
Fruit salad	Spinach + watercress + rocket salad	Tuna niçoise
Pineapple slices	Mixed salad	Pasta + cheese salad
Fresh fruit salad	Alfresco salad	Mixed salad white + red cabbage
Mango chunks	Bistro salad	Sweet pepper salad
Grape + kiwi + pineapple	Caesar salad	Oriental edamame soya bean
Apple + grape	Italian leaf salad	Greek salad
Pomegranates	Herb salad	Crunchy lettuce salad + cucumber
Fruit fingers	Ruby salad	Crisp mixed salad
Fruit selection	French style salad	King prawn + pasta salad
Rainbow fruit salad	Crisp mixed salad	Tuna + pasta
Mango + lime wedge	Fine cut salad	Egg salad
Mixed fruit salad	Crispy leaf salad	Poto + peas + bean salad
Fruit cocktail	Leaf salad	Pasta + pepper salad
Seasonal melon medley	Watercress salad	Salmon + potato
Mango pieces	Four leaf salad	Chicken + bacon Caesar salad
Grape + melon	Seasonal baby leaf salad	Avocado spinach + tomato
Apple segments	Mixed leaf salad	King prawn noodle salad
Melon selection	Crunchy mixed salad	Tomato + cheese pasta salad
Summer berry medley	Santa plum tomato salad	
Apple slices + grapes	Tender leaf salad	
Fruit medley	Watercress + spinach + rocket	
Red grape		

Source: Garner, E. 2008. European trends in fresh-cut convenience. Conference presented at the Freshconex, Berlin, Germany

* 52-week ranking ending December 2007.

1.2 GLOBAL MARKET TENDENCIES

Today, there are more fresh-cut fruit and vegetables being consumed as people seek to replace unhealthy snack foods with healthier fruit and vegetable products. This trend has led the fresh-cut industry to increase investment in research and development to address issues regarding raw product supply, packaging technology, processing equipment, and refrigeration. After its popularity in the fast food sector,

fresh-cut produce became available at a retail level. This led the way for expansion in the industry, which continues, including more recent additions of fresh-cut fruits at quick-service restaurants and in retail stores.

The production and commercialization of fresh-cut fruits has grown rapidly in recent years, but fresh-cut vegetables, salad in particular, dominate the production of minimally processed foods. According to Mayen and Marshall (2005), the emerging fresh-cut fruit sector will probably overshadow salad sales in the future, because fresh-cut fruits are more attractive to young consumers and aging baby boomers and in general are more likely to be consumed as snack products. In addition, fresh-cut fruits on average have higher margins than bagged salads from retail, which will result in ample space for display in the stores.

1.2.1 AMERICAN TRENDS

Recently, there has been a boom of fresh-cut produce all over the world, especially in many American countries; however, the main production and consumption are concentrated in North America, with the United States as the leader.

In the United States, fresh-cut produce first appeared in retail markets in the 1940s, but second-quality, misshapen produce was used, quality was unpredictable, and shelf life was limited. In the mid-1970s, fast food chains were using shredded fresh-cut lettuce and chopped onions. In the mid-1980s, salad bars opened, and fresh-cut produce start replacing canned products (Garrett, 2002). In fact, the main expansion of fresh-cut fruits and vegetables in the United States occurred in the food service sector. In the 1980s, fast food restaurants like McDonald's and Burger King were booming in the United States, so fresh-cut products used in their salad bars and ready-to-eat salads, especially fresh-cut lettuce, were the more required items. In effect, in 2006, in the United States alone, McDonald's used 80 million pounds of salad greens (including spring mix), 100 million pounds of leaf lettuce and iceberg lettuce on sandwiches, 30 million pounds of tomatoes, 54 million pounds of apples for apple dippers and fruit and walnut salad, and 6.5 million pounds of grapes (McDonald's, 2006). Nowadays, fresh-cut produce is one of the fastest growing food categories in U.S. supermarkets, with packaged salads the most important item sold (Figure 1.1). Additionally, the most popular Stock Keeping Unit (SKU)—washed, peeled, and packaged—in the United States is mini carrots, available in a number of sizes (USDA, 2003).

Fresh-cut fruit and vegetable sales have grown to approximately \$15 billion per year in the North American food service and retail market and account for nearly 15% of all produce sales. According to the United Fresh Produce Association (2007), the largest portion of U.S. fresh-cut produce sales at retail is fresh-cut salads, with sales of \$2.7 billion per year. However, the fast food sector is increasing the demand for packaged fresh-cut fruits by offering healthier choices on their menus. Scott (2008) reported that the U.S. sales of fresh-cut fruit items increased for every product, ranging from 7% to 54% growth. Melons were the segment with a faster growth. This trend is expected to continue at least during the next few years. A number of consumer market research reports have predicted that the demand for fresh-cut fruit products will continually increase, with food service establishments and school

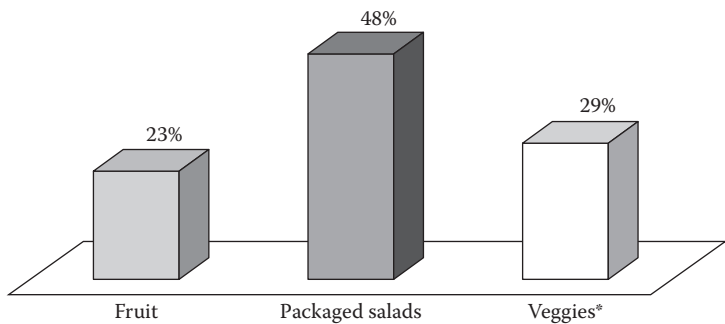


FIGURE 1.1 Fresh-cut produce sales via supermarket channels, 52-week sales ending June 30, 2007, \$6 billion total. *Carrots = 45% of vegetables. (Adapted from Cook, R. 2008. The dynamic U.S. fresh produce industry: an industry in transition. *Fresh Fruit and Vegetable Marketing and Trade Information*, University of California, Davis.)

lunch programs being major customers (Anonymous, 2000; Gorny, 2003). According to a study reported by the Perishables Group in 2008, mixed fruits and vegetables, watermelon, pineapple, carrots, and mushrooms have the most important sales and volume in U.S. fresh-cut items (Figure 1.2).

Currently in the United States, the most important company in fresh-cut fruit sales is Ready Pac, with a market share of 23%, followed by private-label store brands (31%), Del Monte (13%), Country Fresh (7%), Club Fresh (3%), and Fresh Express (1%), according to Information Resources, Inc. (2003). Many of these companies' fresh-cut fruit includes products such as pineapple, melons, grapes, citrus, apples, and kiwi. In the case of fresh-cut vegetables, Fresh Express and Dole reached shares of 42% and 48%, respectively, of retail packaged salad sales in 2005, followed by Ready Pac (8%) and other companies (4%) (PMA, 2006). Many kinds of lettuces, such as radicchio, arugula, and red oak, have gained in popularity in past years because of their inclusion in fresh-cut salad mixes and on upscale restaurant menus. In fact, salad blends reached a share of 37% of the salads market in 2005, followed by iceberg lettuce (13%), romaine lettuce (11%), garden salads (8%), salad kits (6%), organic salad blends (4%), premium garden blends (83%), shredded lettuce (3%), spinach (3%), and other (12%) (PMA, 2006).

1.2.2 EUROPEAN TRENDS

In Europe, fresh-cut products were introduced in France in the early 1980s by Florette Group. It was the first production unit of fresh-cut vegetables in Europe which subsequently started various activities to export to other countries such as the United Kingdom, Italy, and Switzerland. Fresh-cut products have been adapted to each country according to consumer preferences, production, distribution, and legislation. In Spain, for instance, fresh-cut products were introduced by Vega Mayor, which were present on the Spanish and Portuguese markets since 1989. Twenty years later, Vega Mayor was acquired by the Florette Group and at the moment is the Spanish leader in the fresh-cut vegetables market. Currently, the main manufacturers and

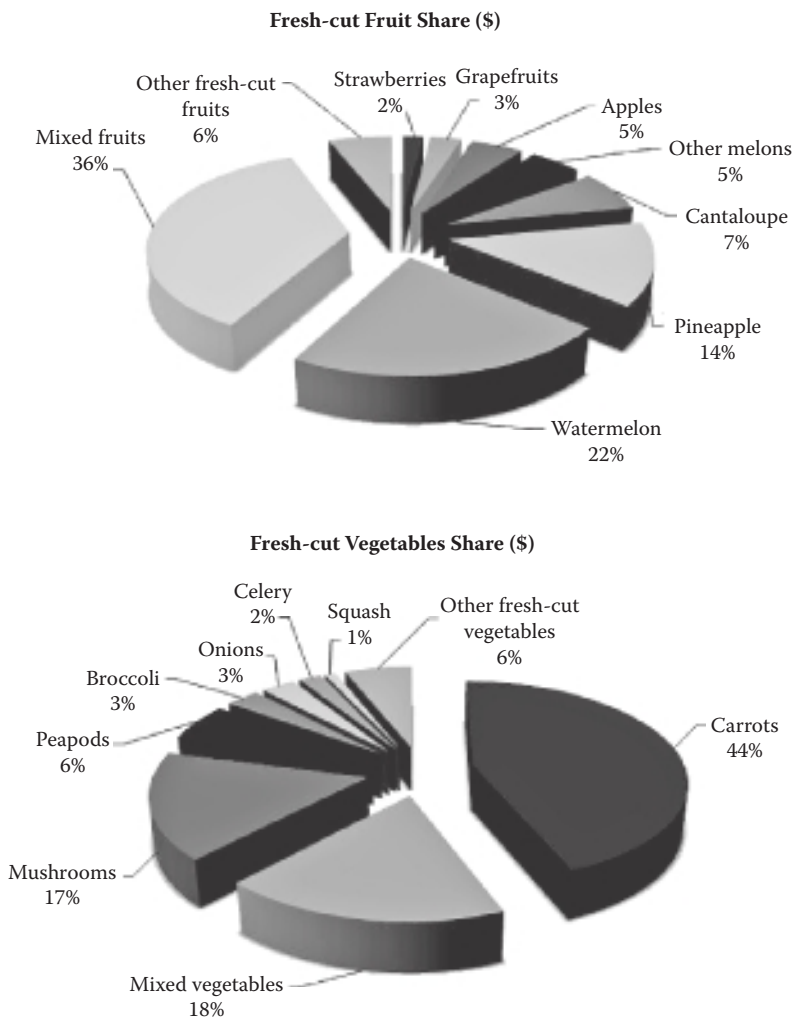


FIGURE 1.2 Fresh-cut vegetables and fruits share in the United States (in dollars). (Adapted from Perishables Group. 2008. U.S. fresh cut produce trends. Conference presented at the Freshconex, Berlin, Germany.)

traders operating in the Spanish market are Vega Mayor, Verdifresh, Kernel, Tallo Verde, Sosegol, and Primaflor (Figure 1.3). However, other producers in the food industry have started to commercialize their new fresh-cut products in the last years. For instance, Vitacress, which is the second firm leading in sales in the English market, after their introduction and success in Portugal, is now beginning their entry into the Spanish market through Vitacress Iberia. Another example is the company Cofrusa, which offers fresher products, such as salads, ready-to-eat vegetables, and, more recently, individual portions of fresh-cut fruits.

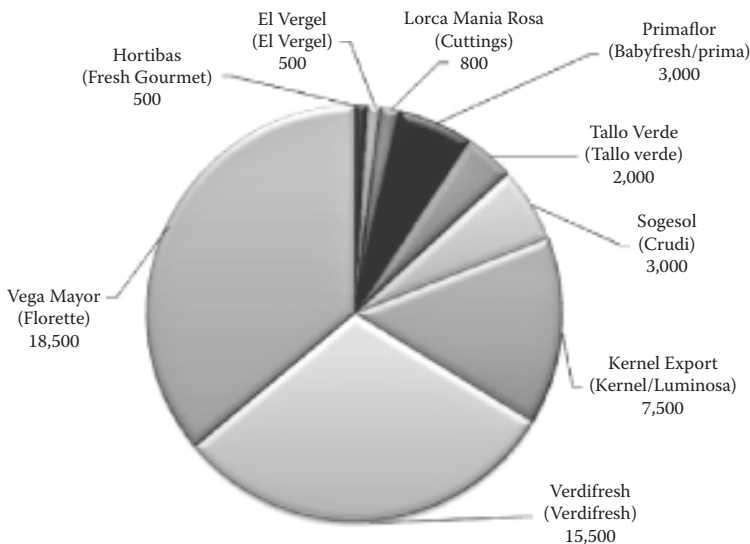


FIGURE 1.3 Ranking of fresh-cut fruits and vegetables manufacturers in Spain. Data correspond to 2004 or estimates for 2005 in tons (t). (Adapted from Alimarket, www.alimarket.es.)

The European markets for fresh-cut fruits and vegetables vary between countries. In some, there is a wide range available in supermarkets, and in others, ready-to-eat food is practically a novelty.

The fresh-cut industry is rising in many European countries with the United Kingdom, France, and Italy as share leaders. Over the last decade, ready-to-eat mixed salad packs have been one of the greatest successes of the UK food industry. The United Kingdom is the leader of the sector, supplying 120,000 tons of fresh-cut salads in 2004, equal to €700 M (\$840 M U.S.); France followed with 77,000 tons considering fresh-cut and grilled/steamed vegetables. In Italy, the sales exceeded 42,000 tons of production, corresponding to €375 M (\$450 M U.S.) in 2004 (Nicola et al., 2006). Currently, the countries with higher growth in the fresh-cut fruits and vegetables market are Germany, The Netherlands, Spain, and United Kingdom (Figure 1.4) (Garner, 2008). According to the latest data released by Afhorla (the Spanish Association of Washed and Ready-to-Use Fruit and Vegetables) between January and April 2006, Spanish sales had reached 14,675 tonnes, 18.5% more than the same months in 2005. Fresh-cut products represent 5% of all fruit and vegetables consumed in Spain. Some studies indicate that this segment could grow by more than 25% annually.

The average European consumes up to 3 kilos of fresh-cut products a year, but the differences are quite substantial within Europe. For instance, in the United Kingdom the rate is 12 kg per capita per year, France comes second consuming half that of its neighbor with 6 kg per capita, and Italians consume around 4 kg. Other countries where fresh-cut foods are well established, although far less than those already mentioned, are Belgium, The Netherlands, and Germany. In the countries

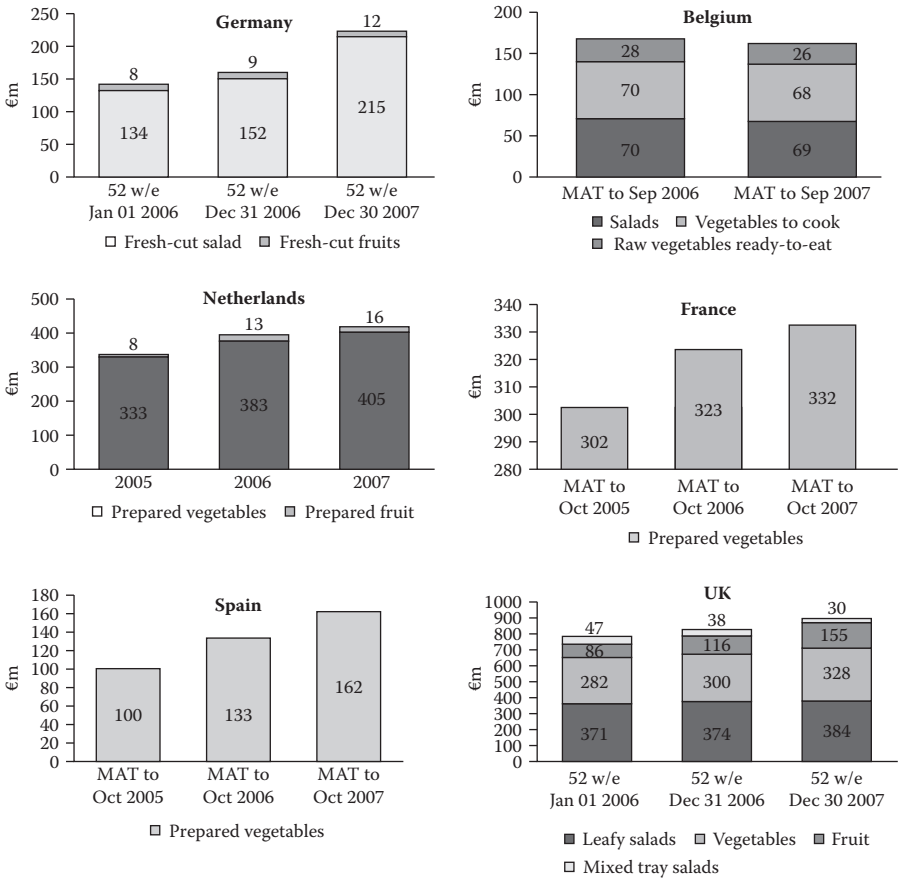


FIGURE 1.4 Fresh-cut fruit and vegetable European market trends. (Garner, 2008.)

of Eastern Europe, with increasingly healthier economies, they are beginning to see great growth in this sector, a development that has not been ignored by the large international holding companies.

1.2.3 ASIATIC TRENDS

Fresh-cut products were introduced in Korea and Japan in the 1990s and 1980s, respectively. Initially, in both countries the main user of fresh-cut products was the food service industry for school meals and restaurants, but in recent years, the consumption has expanded to retail markets (Kim and Jung, 2006). In China, the market for fresh-cut products has been growing since the late 1990s, with more Western fast food industries entering and developing in the Chinese market.

Korea is one of the fastest-growing markets in Asia, with a wide variety of products in the retail segment. In 2006, there were 102 companies producing fresh-cut produce. No fresh-cut fruits were found on supermarkets until the late 1990s

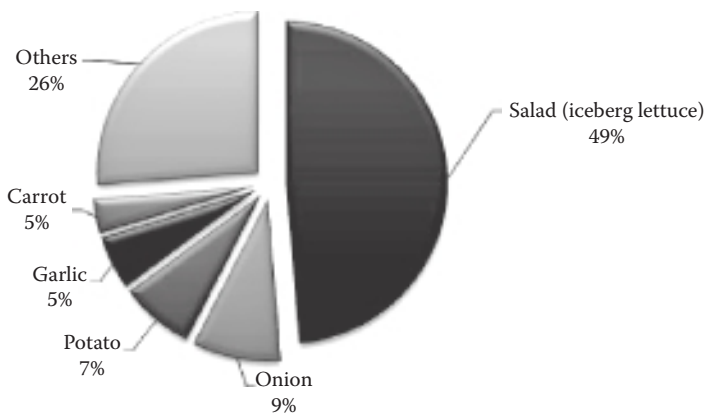


FIGURE 1.5 Proportion of fresh-cut vegetable items based on processing amount in Korea in 2005. (Adapted from Kim, J.G. 2007. Fresh-cut market potential and challenges in Far-East Asia. *Acta Horticulturae* 746: 33–38.)

in Korea. However, the fresh-cut fruits industry has recently enjoyed double-digit growth rates, reaching an estimated \$50 million in 2006 (Kim, 2007). Despite this growth, fresh-cut vegetables continue to dominate the production of fresh-cut items, with salad made from iceberg lettuce the most popular fresh-cut produce, comprising 48.7% of total fresh-cut vegetables (Figure 1.5).

According to the Korean Fresh-cut Produce Association (KFPA), in Korea, the fresh-cut produce market reached approximately \$1.1 billion in 2006, up from \$530 million in 2003. In Japan, the sales of fresh-cut produce have grown from approximately \$1 billion in 1999 to \$2.6 billion in 2005, which is about 10% of total fresh produce sales (Izumi, 2007).

In Japan, the food service sector, which supplies produce to restaurants, fast-food outlets, and school meals, makes up about 66% of the total fresh-cut market. Sales of fresh-cut produce in the retail sector, including supermarkets and convenience stores, are \$0.9 billion, 34% of the total market (Kim, 2007). According to a study published by the Association of Minimally Processed Fruits and Vegetables (AMPFV) in 1999, there are 161 enterprises producing fresh-cut products in Japan (AMPFV, 2000).

Iceberg lettuce, onion, cabbage, Japanese radish, edible burdock, potato, Chinese cabbage, pumpkin, sweet pepper, cucumber, carrot, watermelon, pineapple, and melon are the most popular fresh-cut vegetables and fruits in Japan. In this country, manufacturers such as Dole, for example, offer cut lettuce, cabbage mixes, coleslaw, bean salad, tomato salad, onion salad, corn salad, Caesar salad, and a wide variety of specialty mixes, which make up the bagged category. According to the AMPFV (2004), in Japan, the total input of vegetables to fresh-cut production was reported to be 92,672 tonnes in 2002.

Although no exact data show the scale of the fresh-cut fruits and vegetables market in China, China will become the largest consumer of these products in the future. For example, in Beijing, a new fresh-cut factory was established 3 years ago,

and sales reached 3900 tons by 2006. It is estimated that the fresh-cut fruits and vegetables market in China will increase at a rate of 20% annually (Zhang, 2007).

1.3 FINAL REMARKS

Fresh-cut fruits and vegetables are commodities with a rapidly growing sector in the food industry, with both retail and food service outlets. At the moment, the main factor that has promoted and maintained fresh-cut sales is the technology. However, permanent innovations are necessary to drive new growth in this sector. Use of innovative packaging technology that could improve product quality and shelf life, new fruit mixtures with more variety, incorporation of flavors, or the use of steamer bags for vegetables, are just a few considerations that could expand the markets of fresh-cut products. Worldwide, there is a wide range of vegetables that could be used to broaden and increase the product offerings in the market. However, in many countries, it is necessary to improve preparation and preservation techniques with the purpose of keeping the product safe and of high quality long enough to make the distribution of fresh-cut commodities feasible and achievable.

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4 Physiology of Fresh-Cut Fruits and Vegetables

Elizabeth A. Baldwin and Jinhe Bai

CONTENTS

4.1	Introduction	87
4.2	Plant Stress and Wounding	89
4.3	Ethylene Production	91
4.4	Respiration	96
4.5	Storage Temperature and Modified Atmosphere	97
4.5.1	Atmosphere	97
4.5.2	Storage Temperature	98
4.6	Genetics and Harvest Maturity	99
4.6.1	Genetics	99
4.6.2	Harvest Maturity	99
4.7	Physiological Effects of Sanitizing Treatments	100
4.8	Surface Treatments and Coatings	101
4.8.1	Surface Treatments	102
4.8.2	Coatings	103
4.8.2.1	Firming Agents	104
4.9	Conclusion	104
	References	104

4.1 INTRODUCTION

The idea to preprocess fruits and vegetables in the fresh state started with fresh-cut salads and now has expanded to fresh-cut fruits and other vegetables. The fresh-cut portion of the fresh produce industry includes fruits, vegetables, sprouts, mushrooms, and even herbs that are cut, cored, sliced, peeled, diced, or shredded, but not heated or altered from their fresh state in any way (Shewfelt, 1987). Physiologically this is, in fact, wounding living tissue which starts a cascade of metabolic reactions that can result in texture changes, accelerated ripening and senescence, off flavors, discoloration, and other undesirable events that can render the product unmarketable. Microbiologically, removing the protective peel of fresh produce leaves a cut surface that is awash with cell contents, which makes the surface attractive to plant pathogens (King and Bolin, 1989). The extra handling and processing of the produce result in increased ethylene, a gaseous ripening plant hormone, which results in genetic signals that promote ripening and senescence (Karakurt and Huber, 2007). The

handling and processing also increase the respiration rate, using up sugar and acid substrates and shortening shelf life. Finally, the extra handling, removal of the peel, and altering of the normal microbial ecology of fresh-cut products allow for possible contamination by and growth of human pathogens (Breidt and Fleming, 1997).

Many processing techniques (Artés and Allende, 2005; Palumbo et al., 2007; Reyes et al., 1995) have been developed to counteract the reactions of the cut produce to ethylene production and other wound responses, including use of precooling (Vigneault et al., 2008) to reduce respiration; prequality assessment for microbial stability (Fan and Song, 2008), modified atmosphere packaging (MAP) and other packaging to reduce respiration and ethylene production (Barmore, 1987; Day, 1994; Jaccsens et al., 2000; Myers, 1989; Reyes et al., 1995), 1-methylcyclopropene (1-MCP, marketed commercially as Smartfresh) to minimize ethylene action (Toivonen, 2008a), various sanitation or decontamination procedures (Artés et al., 2007; Gómez-López et al., 2008; Gómez-López et al., 2009), use of antimicrobial agents to reduce spoilage (Ayala-Zavala et al., 2008; Brecht et al., 1993; Breidt and Fleming, 1997; King and Bolin, 1989), use of surface treatments and edible coatings to reduce water loss, dehydration, and browning (Baldwin et al., 1995; King and Bolin, 1989; Olivas et al., 2008; Vargas et al., 2008), use of ethylene absorbents to retard ripening and senescence (Abe and Watada, 1991), and calcium for firmness and preservation (Martín-Diana et al., 2007). All the above have been the subject of numerous reviews, as cited. Other general reviews for extending the shelf life and quality of fresh-cut produce include those by Ahvenainen (1996), Shewfelt (1987), Soliva-Fortuny and Martín-Belloso (2003), and Watada and Qi (1999). Guerzoni et al. (1996) reviewed the topic of modeling for shelf-life prediction. Reviews for Asian fresh-cut fruits have also been published (Rattanapanone et al., 2000).

The consequences of processing fresh produce into fresh-cut products have also been reviewed, including the effect on general quality (Hu and Jiang, 2007; Rico et al., 2007; Shewfelt, 1987), warnings (Brody, 1998), physiology (Parkin, 1987; Rolle and Chism, 1987; Varoquaux et al., 1995), effect on flavor (Forney, 2008), browning (He and Luo, 2007; Salcini and Massantini, 2005), physiological deterioration (Artés et al., 2007; King and Bolin, 1989), microbial deterioration (Artés et al., 2007; Brackett, 1987; King and Bolin, 1989), respiration (Watada et al., 1996), as well as markets and distribution (Huxsoll and Bolin, 1989). Generally, fresh-cut fruit deteriorate much faster than their intact fruit counterpart. In a study where fresh-cut fruit was compared to the intact fruit counterpart, the fruit were stored up to 9 days at 5°C. Of the fruit tested (pineapples, mangoes, cantaloupes, watermelons, strawberries, and kiwifruits), only fresh-cut watermelon and mango pieces were still marketable at the end of the storage period (Gil et al., 2006). Losses of vitamin C and carotenoids was 5 to 25% and 10 to 25%, respectively, in some of the cut fruit products, but negligible in the intact fruit. However, for intact versus fresh-cut spinach during 1 week at 4°C, there were no changes in vitamin C, and flavonoids and color were not altered (Bottino et al., 2009), so the effect of minimal processing depends on the commodity.

In light of the many reviews published to date on fresh-cut products, this chapter will summarize the literature for the past 5 years or so that concerns fresh-cut physiology. Much research continues to be published in this area which relates to quality and microbial stability, although food safety will not be covered here except in cases

TABLE 4.1
Ripening Responses Initiated by Ethylene

Unripe Fruit		Involved Enzymes	Ripe Fruit	
Appearance	Chemical Cause		Chemical Cause	Appearance
Green	Chlorophyll	Hydrolase	Anthocynin, carotenoids	Yellow, blue, red
Firm	Insoluble pectin	Pectinases	Soluble pectin	Soft
Sour	Acid	Kinase	Neutral	Less sour
Dry	Starch	Amylase	Sugar	Sweet + juicy
Odorless	Large organic cpds	Hydrolases and ester synthase	Small organic cpds	Aromatic

Source: Modified from Koning (1994).

where there are reports of impacts on fresh-cut produce physiology. Physiological changes due to wounding, such as occurs with fresh-cut commodities, impact quality and spoilage; thus, this chapter may overlap some other chapters but will focus on the physiological reasons and metabolic mechanisms that cause quality and microbial problems. Plant wound responses fall into several categories: increased ethylene production, increased respiration, increased production of secondary metabolites, accelerated ripening and senescence, cut surface discoloration, texture changes, and off-flavors. To understand the physiology of fresh-cut produce, some basic plant physiological information is first presented, particularly as pertains to ripening (Table 4.1), wounding (Table 4.2), ethylene, and respiration.

4.2 PLANT STRESS AND WOUNDING

Injured or stressed plants produce signals that induce a wide range of genes whose products are meant to help repair the plant, defend against pathogens (Hillwig et al., 2008), or signal cell death to wall off infection (Dangl and Jones, 2001; Kessler and Baldwin, 2002). Oligogalacturonides (OGAs) (Viña et al., 2007), which come from the cell wall; jasmonic acid (JA) and methyl jasmonate (MeJA) (Howe, 2004), which comes from membranes (plastids, linolenic acid) via lipoxygenase (13-LOX); salicylic acid and methyl salicylate (wintergreen) from benzoic acid (Mur et al., 1997) and abscisic acid (ABA) (Hillwig et al., 2008; Siqueira-Júnior et al., 2008; Wasternack et al., 2006) regulate signaling pathways that induce wound-responsive genes. The wound-induced JA pathway is in turn regulated by other signals including the protein systemin, OGAs, ethylene, and other elicitors (Howe, 2004; Ryan and Moura, 2002). These signals are thought to be transduced to a lipase, which causes the release of linolenic and linoleic acids from membrane lipids. A full-length cDNA clone encoding *Capsicum annum* GDSL-lipase 1 (CaGL1) expression was triggered by MeJA and wound stress, for example (Kim et al., 2008b). These signals also give rise to pathogenesis-related (PR) proteins and proteinase inhibitors (Fallico et al., 1996). Ethylene has been shown to be a signal that mediates wound

TABLE 4.2
Wound Responses

- Increased ethylene production
 - Cell wall degrading enzymes (PG)—softening
 - Chlorophyll degradation (chlorophyllase)—degreening
 - Membrane leakage (lipoxygenase)—water soaking
 - Carotenoid synthesis, anthocyanin synthesis—color development
 - Phenolic metabolism
 - Volatile synthesis (?)
 - Susceptibility to pathogens
 - Reduced shelf life
- Phenolic metabolism (polyphenyloxidase [PPO], peroxidase [POD], and phenylalanine ammonia-lyase [PAL])
 - Browning
 - Secondary metabolites like lignin (toughening of asparagus) or coumarin (bitterness in carrots)
- Increased respiration
 - Use up sugars, acids—poor flavor
 - Use up ascorbic acid—reduced nutrition
 - Generated heat
 - Reduced shelf life

responses (O'Donnell et al., 1996). JA induced by wounding, systemin, and OGAs acts in concert with ethylene (O'Donnell et al., 1996) and hydrogen peroxide (Katsir et al., 2008; Orozco-Cardenas et al., 2001) to positively regulate the expression of downstream target genes (Howe, 2004).

Fresh-cut fruits and vegetables are wounded tissue, so all of the above could be going on in these products. Karakurt and Huber (2003) established that cell walls and membranes played a role in the rapid deterioration of fresh-cut papaya, resulting in softening, breakdown of pectin, increased polygalacturonase (PG, releases OGAs), α - and β -galactosidase, lipoxygenase, and phospholipase D activities (release linolenic and linoleic acids). These likely produce wound signals. They then studied signaling and expression of wound-regulated cDNAs in fresh-cut papaya compared to intact fruit (Karakurt and Huber, 2007). The cDNAs showed homology to signaling pathway genes, membrane proteins, cell-wall enzymes, proteases, ethylene biosynthetic enzymes, and enzymes involved in plant defense responses.

Abiotic stresses and wounding can also result in an increase in antioxidant phytochemicals. Antioxidants scavenge reactive oxygen species (ROS) that can damage plant cells, are generated as part of normal metabolism as by-products, and are involved in the signaling and function of antioxidant systems to detoxify ROS. ROS may be involved as signal messengers after wounding (Orozco-Cardenas et al., 2001) and are involved with synthesis of lignin and suberin that is synthesized during wound healing (Reyes et al., 2007). Phenolic compounds in fruits and vegetables result in elevated antioxidant activity (Mahattanatawee et al., 2006) and their induced accumulation could relate to health benefits. In cut apple, however, the cut

surface browning, due to synthesis of phenolic compounds induced by cutting, is considered undesirable and can be inhibited by surface treatments described later in this chapter. Nevertheless, the stress of cutting may result in increased antioxidants in some fresh-cut products which could translate into health benefits.

The way in which fruit is cut can result in more or less wound responses, which in turn affects shelf life. Generally, respiration rates increase with increased cutting (wounding). In a study on the processing conditions of carrots (Iqbal et al., 2008), the respiration rate was highest for shredded (75 mL O₂/kg h) carrots and lowest for whole carrots (26 mL O₂/kg h) of the various cuts attempted. For fresh-cut papaya fruit, different cut types made a difference in the physiochemical and microbiological properties. Papaya spheres resulted in less color change, firmness loss and higher titratable acidity, maintenance of soluble solids and less weight loss, higher vitamin C content and lower microbial counts compared to papaya cubes (Argañosa et al., 2008). For fresh-cut lemons, wedges, slices, and half and quarter slices were studied while stored at different temperatures. The quarter slice did not maintain its sensory attributes as well as the larger cuts (Artés-Hernández et al., 2007).

4.3 ETHYLENE PRODUCTION

Ethylene is a gaseous plant hormone and biologically active at low concentrations (parts per billion to parts per million) (Abeles et al., 1992; Saltveit, 1999). Ethylene production occurs in all plant tissues at some minimal level. It is necessary for growth (usually thickening or lateral growth such as with etiolated pea seedlings), inhibits longitudinal growth, and promotes seed germination, degreening, adventitious root formation, abscission, ripening, and senescence (Baldwin, 2004; Reid, 1985). Ethylene is considered autocatalytic when ethylene stimulates its own synthesis and autoinhibitory when it turns off continued synthesis (Mattoo and White, 1991). System-I ethylene, engaged during vegetative growth, is thought to be autoinhibitory, and system-II ethylene, engaged during ripening of climacteric fruits and senescence of some flowers, is generally autocatalytic. Each seems to be regulated in a unique way (Barry et al., 2000). System-II ethylene coincides with increased respiration and induces activity of PG (DellaPenna et al., 1986), cellulase, chlorophyllase (Baremore, 1975), polyphenyloxidase (PPO), peroxidase (POD), and phenylalanine ammonia-lyase (PAL) (Kader, 1985; Watada, 1986) which promote softening, color changes, and browning, respectively. Ethylene initiates ripening in fruits (Koning, 1994). It is used commercially to ripen fruits like bananas, mangoes, melons, and tomatoes (100 to 1,000 µL/L) and to degreen citrus (Watada, 1986). Generally, rates of ethylene production are highest when associated with meristematic, stressed, or ripening tissues. For example, ethylene production is high in young fruit or tissues during the period of rapid cell division, declines during cell expansion, and increases again during ripening (fruits) or senescence (flowers) (Abeles et al., 1992; McGlasson, 1985). Climacteric fruit can ripen off the mother plant in response to ethylene (Baldwin, 2004). They can respond either to their own ethylene synthesis, which becomes autocatalytic, or to exogenously applied ethylene, or to both. Ethylene is associated with ripening-related color and flavor development as well as softening in many fruits and vegetables (Kader, 1985; Watada, 1986). Ethylene is

also produced at elevated levels in response to plant stress or wounding (Baldwin, 2004; Hyodo, 1991; Morgan and Drew, 1997) as occurs with fresh-cut products. This elevated ethylene, either due to ripening for climacteric fruit or to wounding for both climacteric and nonclimacteric fruit representing system-I and -II ethylene, can be active in fresh-cut products. Ripening or wound response ethylene triggers via signaling and subsequent gene expression many ripening and stress and wound responses (Bailey et al., 2005). These, as mentioned above, include production of browning enzymes, secondary metabolites, chlorophyllase, cell wall degrading enzymes, secondary metabolites, lignin and more ethylene (if autocatalytic), or a reduction of ethylene synthesis (if autoinhibitory). This can result in yellowing of broccoli florets, softening of fruit tissue, abscission of cabbage leaves, pinkening and browning of lettuce, browning of cut apple, sprouting of potato, toughening of asparagus stems, and bitterness (isocoumarin) in carrots. For intact fruit, ethylene promotes color changes, softening, and general ripening and senescence. For fresh-cut fruit, ethylene promotes discoloration, off-flavor, softening, ripening, and senescence. Ethylene generally shortens the shelf life of whole or fresh-cut products. Some techniques to prolong the shelf life of intact or fresh-cut produce are targeted at inhibiting or retarding ripening and wound response ethylene production or action.

Ethylene is thought to be synthesized from the amino acid L-methionine, which is converted to S-adenosylmethionine (SAM or adomet) by the enzyme methionine S-adenosyltransferase, which is converted to 1-aminocyclopropane-1-carboxylic acid (ACC) by ACC synthase (ACS), which, in turn, is converted to ethylene by ethylene-forming enzyme (Podoski et al., 1997) now called ACC oxidase (ACO) (Adams and Yang, 1979; Imaseki, 1991; Yang and Hoffman, 1984) (Figure 4.1). The key regulatory enzymes in the pathway are ACS and ACO. Ripening positively modulates ACS and ACO; however, wounding and water stress only positively modulate ACS. 1-MCP negatively modulates ACS and ACO, but aminoethoxyvinylglycine (AVG) and aminooxyacetic acid (AOA) only negatively modulate ACS, and high temperature ($>35^{\circ}\text{C}$) and anaerobiosis only negatively modulate ACO. The enzyme malonyltransferase can catalyze the conjugation of ACC into malonyl ACC (Fallico et al., 1996). Ethylene can turn on or off genes that encode some portion of its biosynthetic pathway (autocatalytic or autoinhibitory, respectively). As mentioned above, it is often autoinhibitory in vegetative and immature reproductive tissues and autocatalytic in mature reproductive tissues like flowers and fruit (Baldwin, 2004; Lelièvre et al., 1997; Saltveit, 1999). Therefore, fresh-cut products may behave differently if made from vegetative, reproductive, climacteric, or nonclimacteric tissue.

A diverse multigene family encodes ACS (Zarembinski and Theologis, 1994), which is the rate-limiting step in ethylene biosynthesis. Ethylene can increase levels of malonyltransferase in various tissues which may account for the autoinhibition that is sometimes observed (Vangronsveld et al., 1988). Synthesis of ethylene requires O_2 and is inhibited by high levels of CO_2 , especially if the response is autocatalytic as with climacteric fruits (Abeles et al., 1992; Sisler and Wood, 1988). Thus, MAP is used with fresh-cut products to control ethylene and respiration and thereby extend shelf life. Wound-response ethylene is thought to enhance activity of ACS (Apelbaum and Yang, 1981; Boller and Kende, 1980). To have a biological effect, ethylene must bind to a receptor that is thought to reside in a membrane. If the

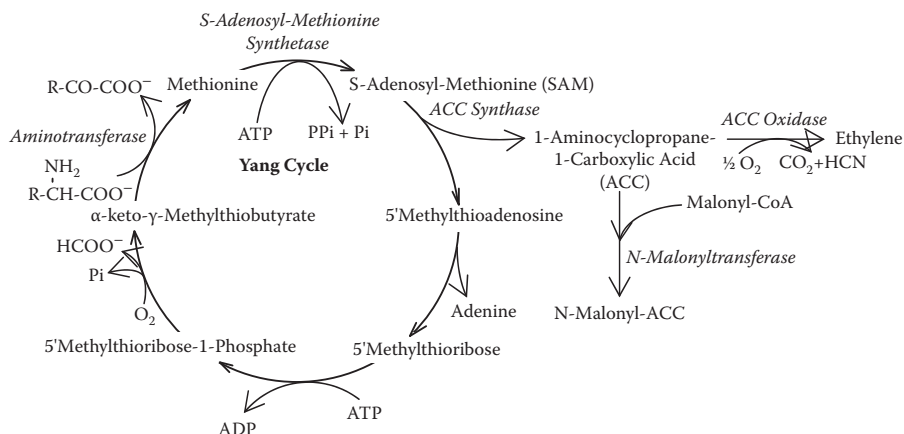


FIGURE 4.1 The ethylene synthesis pathway and Yang cycle. (Adapted from Adams, D.O., and S.F. Yang. 1979. Ethylene biosynthesis: Identification of methionine to ethylene. *Proc. Natl. Acad. Sci. U.S.A.* 76: 170–174; Imaseki, H. 1991. The biochemistry of ethylene biosynthesis, pp. 1–20. In: A.K. Mattoo and J.C. Suttle (eds.). *The Plant Hormone Ethylene*. CRC Press, Boca Raton, FL; and Yang, S.F., and N.E. Hoffman. 1984. Ethylene biosynthesis and its regulation in higher plants. *Ann. Rev. Plant Physiol.* 35: 155–189.)

receptor is blocked, then ethylene will have no effect (inhibition of ethylene action). Silver ions, CO₂, 2,5-norbornadiene and 1-MCP can block the ethylene receptor, and therefore inhibit ethylene-induced effects, including its own synthesis in cases where ethylene is autocatalytic or promote its synthesis where ethylene is autoinhibitory (Abeles et al., 1992; Saltveit, 1999; Sisler et al., 1986). Of these compounds, only 1-MCP is approved for food and thus has been used to control ethylene responses and production in fresh-cut products (Toivonen, 2008a).

Suppression of the ethylene receptor (LeETR4) resulted in early ripening of tomato but did not affect fruit size, yield, or flavor composition, demonstrating that ethylene receptors may act as biological clocks that regulate onset of fruit ripening (Kevany et al., 2008). Ethylene receptors are degraded in the presence of ethylene, likely through a proteasome-dependent pathway; therefore, immature fruits exposed to ethylene undergo a reduction in the amount of receptor protein and earlier ripening (Kevany et al., 2007). In other words, the receptor acts as a negative regulator of ethylene responses, and this suppression is removed when ethylene binds the receptor. Figure 4.2 (Ecker, 2004; Li and Guo, 2007; Schweighofer and Meskienne, 2008) shows that after wounding or other stress perception, plant cells activate protein phosphorylation cascades mediated by kinases. Mitogen-activated protein (MAP) kinases, MKK4, MKK5, and MPK6 phosphorylate target proteins, leading to cell responses. One of the targets is the enzyme responsible for ethylene production, ACC synthase (ACS). Members in the two major subgroups of the ACS family, represented by ACS5 and ACS6, are regulated by different kinase pathways. Phosphorylation stabilizes ACS6 (and possibly ACS5), and interaction of ACS5 with unknown components targets ACS5 for degradation by the proteasome. Fine-tuning

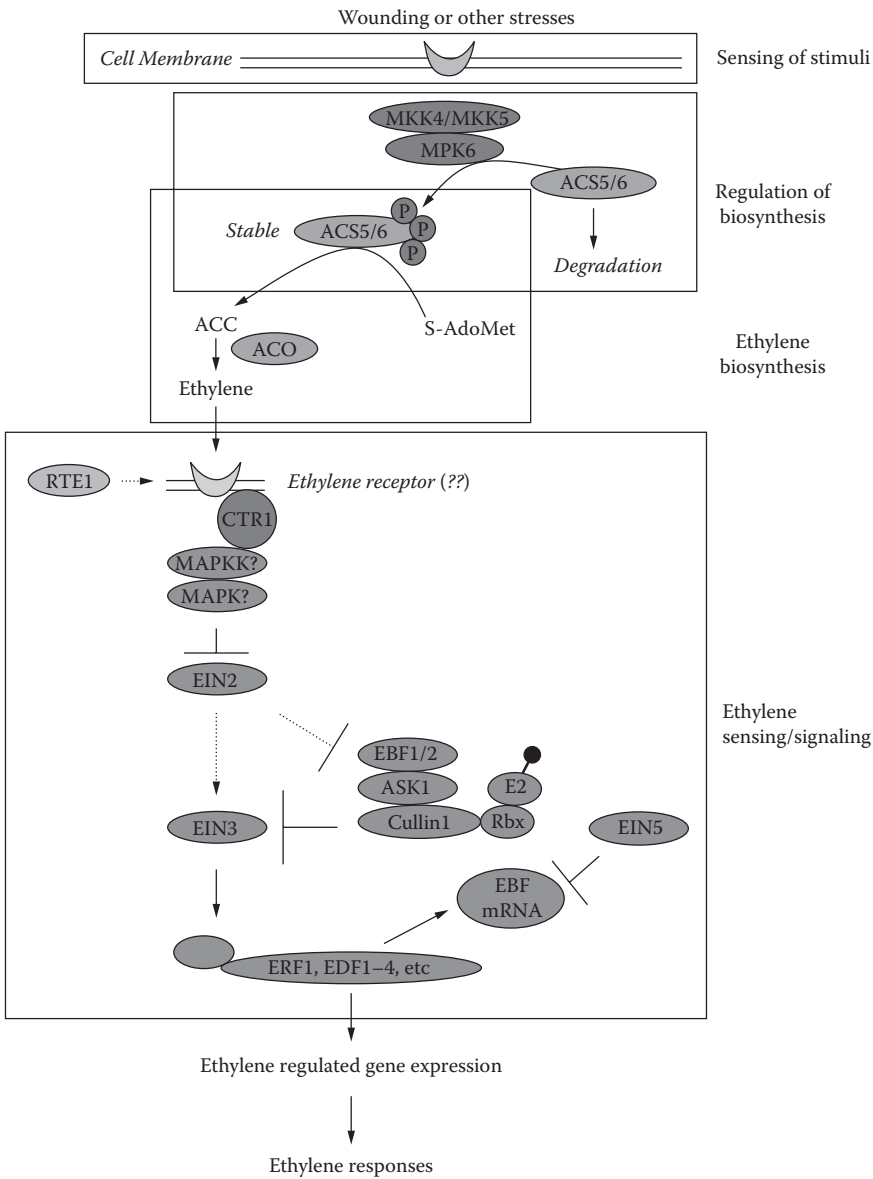


FIGURE 4.2 A simplified model depicting the induction of ethylene biosynthesis and their sensing and signaling pathway in *Arabidopsis*. Arrows and t-bars represent positive and negative regulations, respectively. Solid arrows and t-bars correspond to direct interactions, and dotted lines indicate the likely existence of unidentified elements between upstream and downstream components. (Adapted from Ecker, J.R. 2004. Reentry of the ethylene MPK6 module. *Plant Cell*. 16: 3169–3173; Li, H., and H. Guo. 2007. Molecular basis of the ethylene signaling and response pathway in *Arabidopsis*. *J. PlantGrowth Regul.* 26: 106–117; and Schweighofer, A., and I. Meskiene. 2008. Regulation of stress hormones jasmonates and ethylene by MAPK pathways in plants. *Molecul. BioSyst.* 4: 799–803.)

of ethylene induction is achieved by tissue-specific expression, gene activation, and the formation of heterodimers between different ACS members. ACC oxidase (ACO) activity can also affect levels of ethylene induction. Ethylene binding leads to the inactivation of ER-localized receptors (ETR1, ETR2, ERS1, ERS2, and EIN4) by an unknown mechanism. A novel membrane protein, RTE1, might specifically enhance the function of the ETR1 receptor. An inactive receptor is incapable of recruiting the negative regulator CTR1 to the ER membrane, which in turn shuts off its activity. EIN2 is then free from inhibition by CTR1 and increases the nuclear accumulation of EIN3 protein by repressing its turnover, which is mediated by SCF complexes containing the F-box proteins EBF1/2. There are two possibilities for how EIN2 stabilizes EIN3: EIN2-derived signal modulates EIN3 directly or inhibits the SCFEBF complex. One of the *EBF* genes, *EBF2*, is induced by ethylene in an EIN3-dependent manner. Thus a negative feedback loop is formed between EIN3 and EBF. EIN5, an exoribonuclease, seems to downregulate the level of *EBF1* and *EBF2* mRNAs without affecting their half-life. The nuclear accumulation of EIN3 induces a large amount of gene expression and ultimately triggers various ethylene responses.

Therefore, inhibition or reduction of ethylene synthesis or action can help to extend the shelf life of fresh-cut products but again may differ depending on the type of product (vegetative, reproductive, harvest maturity, etc.). There are numerous techniques to reduce ethylene production or effects which can be applied to the intact fruit prior to processing or to the processed product directly. Such treatments include genetics (Klee and Clark, 2002), storage temperature, MAP packaging, coatings, ethanol, ethylene absorbents, and 1-MCP. Ethylene synthesis inhibitors such as AVG can be used preharvest to inhibit ethylene production (Schupp and Greene, 2004; Yang, 1985), which can affect postharvest shelf life. Genetic engineering can also be used to reduce fruit ethylene production as has been shown in tomato by downregulating ACS (Oeller et al., 1991), ACO (Hamilton et al., 1990), or enhancing expression of ACC deaminase (Klee et al., 1991). Antisense molecular techniques have also been used to knock out the ethylene receptor (Klee and Clark, 2002), making the tissue nonresponsive to ethylene. For example, tomatoes with downregulated ACS or ACO do not produce much ethylene and do not ripen, and tomatoes with inserted ACC deaminase do not make much ethylene either, because this enzyme degrades ACC to α -ketobutyric acid. If ever approved, these transgenic fruits would be useful as fresh-cut products.

Temperatures above 35°C can cause injury to the ethylene biosynthetic pathway, disrupting ethylene synthesis (Antunes and Sfakiotakis, 2000; Lurie, 1998). Cold temperatures below 2.5°C slow metabolism, including ethylene synthesis (Wang and Adams, 1982) due to reduced ACO activity. The relatively low oxygen (O₂) and high carbon dioxide (CO₂) in MAP or the internal atmosphere of coated fruit (Bai et al., 2001; Bai et al., 2002) inhibit ethylene production because the ethylene biosynthetic pathway requires O₂ and is inhibited by CO₂ (Figure 4.1). Anaerobic conditions inhibit ACO. Ethanol has been shown to inhibit ethylene production in intact tomato fruits (Kelly and Saltveit, 1988; Saltveit and Mencarelli, 1988; Saltveit and Sharaf, 1992) and ethanol vapor was used to inhibit ethylene production in cut apple and mango (Bai et al., 2004; Plotto et al., 2006). Ethanol vapor treatment can be problematic because it sometimes results in altered or off-flavors, but at lower levels

this was minimized, and the ethanol treatment of intact mango fruit had the added benefit of reducing the microbial population on the surface of the cut mango (Plotto et al., 2006).

The ethylene action inhibitor, 1-MCP, also reduced ethylene effects by inhibiting ethylene action in cut fruit (Bai et al., 2004; Ergun et al., 2007; Perera et al., 2003; Saftner et al., 2007). This included, in some cases, ethylene synthesis, if it was autocatalytic (Baldwin, 2004). For fresh-cut apple, treatment of intact apple with 1-MCP resulted in reduced ethylene production, respiration for 'Braeburn,' 'Pacific Rose,' and 'Gala' subsequent sliced products and reduced browning for 'Braeburn' cut apple (Bai et al., 2004; Perera et al., 2003). For 'Galia' melon, treatment of intact fruit resulted in reduced softening and watersoaking of the subsequent fresh-cut fruit (Ergun et al., 2007). Treatment of intact pineapple resulted in inhibition of respiration and ethylene production and delayed softening in combination with MAP (Rocculi et al., 2009). Treatment of fresh cut cilantro resulted in reduced respiration (Kim et al., 2007). Low dosage 1-MCP treatments prior to ethylene exposure of intact watermelon prevented ethylene-mediated quality deterioration in subsequent fresh-cut slices under MAP (Saftner et al., 2007). Application of 1-MCP before or after processing of kiwifruit reduced ethylene and softening which was enhanced by a dip of calcium chloride (CaCl_2). 1-MCP also reduced softening and browning when applied directly on fresh-cut mango slices. For fresh-cut persimmons, direct application of 1-MCP after processing resulted in higher ethylene production, slower softening, and darkening of color with no effect on respiration (Vilas-Boas and Kader, 2007).

4.4 RESPIRATION

Fruit ripening, senescence, and the wound response are energy-consuming processes. The respiratory quotient of a fruit or vegetable is the ratio of the CO_2 evolved to O_2 consumed. Novel proteins, messenger ribonucleic acids (mRNAs), pigments, and flavor compounds are synthesized in fresh produce, requiring energy and carbon that are supplied by the fruit as with other tissues. Once harvested, however, the fruit has limited resources, which is even more pronounced in fresh-cut products. For example, fresh-cut lemon had two to five times the respiration of whole lemons when stored below 5°C and 12-fold higher respiration if stored at 10°C (Artés-Hernández et al., 2007). Ripening of climacteric fruit and wounding of all fruit produce a characteristic peak of respiratory activity. In general, the higher the respiratory rate, the shorter the shelf life, as respiratory substrates, generally sugars and acids, are consumed (Tucker, 1983). Usually, sugars and acids of fruits are sequestered in the vacuole but are released periodically or maintained in a separate pool for use in respiration (Tucker, 1983; Tucker and Grierson, 1987). Respiratory pathways by which fruit oxidize sugars are glycolysis, oxidative pentose phosphate (OPP) pathway (less important, but may operate in climacteric respiration), and the tricarboxylic acid (TCA) pathway. In glycolysis, glucose-6-phosphate (P) is converted to fructose 6-P which is converted to fructose-1, 6-bisphosphate, and phosphoenol pyruvate to pyruvate. Pyruvate feeds into the the TCA cycle. Malic acid appears to be used as a respiratory substrate via malic enzyme which decarboxylates malate to pyruvate, with the extra carbon being fed into the TCA cycle, while citrate can feed directly into

the TCA cycle (Goodenough et al., 1985; Tucker, 1993). The NAD(P)H produced by glycolysis, TCA, or malic enzyme activity is oxidized by plant mitochondria and the energy used for adenosine triphosphate (ATP) synthesis via oxidative phosphorylation, and mediated by membrane-bound dehydrogenases in the mitochondria (Palmer and Moller, 1982; Tucker, 1993).

Through the engulfing of a α -proteobacterium, the mitochondrion, the ancestral eukaryotic cell gained many metabolic capabilities (Sweetlove et al., 2007). The mitochondrion is uniquely sensitive to ATP demands in the cell. The mitochondria also produces ROS, which as mentioned before, are potent intracellular signals for, among other things, abiotic stress and oxidative damage of proteins, so that it acts as an early warning sensor of altered cellular redox balance. ROS are generated in the mitochondrion when overreduction of the respiratory complexes occurs, causing leakage of electrons to molecular oxygen causing superoxide formation (Moller, 2001). This is a result of an imbalance between electrons entering the respiratory chain and the dissipation of the proton gradient by ATP synthesis, or by reactions of electron transport due to altered physiological state (low temperature) (Sweetlove et al., 2007) or wounding, as with fresh-cut produce. What is important is the balance between ROS production and antioxidant capacity. The alternative oxidase (AOX) responds to redox signals, which bypass much of the respiratory chain and significantly reduce proton pumping and ROS production (Maxwell et al., 1999). AOX expression is linked to the TCA cycle, and the TCA cycle intermediates may act as signals for gene expression (Sweetlove et al., 2007).

As for the connection between climacteric ethylene and respiration, a developmental factor seems to be involved in the activation of the respiratory climacteric. For example, honeydew melon needs to achieve a certain maturity for low levels of exogenous ethylene to stimulate climacteric ethylene and respiration. In an experiment using antisense ACO cantaloupe harvested at 20 to 35 days past pollination compared to wild-type fruit, it seemed there was an interaction between developmental factors and ethylene levels in the induction of the respiratory upsurge (Flores et al., 2008).

4.5 STORAGE TEMPERATURE AND MODIFIED ATMOSPHERE

4.5.1 ATMOSPHERE

Storage temperature of fresh-cut commodities affects their respiration rate, which increases with increasing temperature. This effect is exacerbated if the commodity is in a modified atmosphere (MAP package, coating or CA storage) of relatively low O_2 and high CO_2 , likely designed for low-temperature (therefore, low respiration) storage (2 to 10°C). If the cold chain is broken, then the respiration rate/ O_2 demand increases, and the O_2 level may fall below the extinction point for that particular commodity, and the anaerobic pathway is engaged, producing ethanol and off-flavors. Sometimes the product has acceptable appearance but not acceptable flavor. The product can then quickly deteriorate. The Q_{10} of respiration rates of fresh-cut vegetables ranged from 2 to 7.5 when the temperature was increased from 0 to 10°C

(Watada et al., 1996). High O_2 MAP (70% + O_2) has also been used to inhibit enzymatic discoloration, prevent anaerobic fermentation, and inhibit aerobic and anaerobic microbial growth. Argon and nitrous oxide have also been shown to reduce respiration rates (Day, 1994).

4.5.2 STORAGE TEMPERATURE

The temperature at which products are stored can also affect the nutritional shelf life of a fresh-cut product. In a study of the antioxidant potential of fresh-cut strawberries, temperature affected the anthocyanins and vitamin C content as well as antioxidant capacity of the cut strawberry stored 21 days under 80% O_2 , which reduced wounding stress (Odriozola-Serrano et al., 2009). Vitamin C degradation was more susceptible to small temperature increments than the other antioxidant compounds, and a storage temperature of 5°C was most effective in keeping the antioxidant properties of cut strawberry under the high O_2 atmosphere. For fresh-cut tomato, lycopene, vitamin C, and phenolic contents as well as other physiochemical parameters were maintained for 14 days at 5°C in MAP (5% O_2 + 5% CO_2). Raising the storage temperature enhanced lycopene and total phenolics but decreased vitamin C, and shelf life was reduced due to microbial growth at storage temperatures above 10°C (Odriozola-Serrano et al., 2008). One advantage of fresh-cut produce from chilling-sensitive fruits is that the cut product often does not manifest chilling injury, symptoms of which are often exhibited in the intact fruit peel.

Films available for fresh-cut produce often do not have sufficient O_2 and CO_2 transmission rates to reach steady-state gas concentrations before reaching O_2 and CO_2 levels that are too low or too high, respectively (Oms-Oliu et al., 2007). This promotes anaerobic respiration or CO_2 injury that results in fermentive off-flavor and odor, excess CO_2 production, as well as visual defects. In a survey of bagged salads from major supermarket chains, the mean headspace was 1.2% O_2 and 12% CO_2 , and the mean ethanol content was 700 parts per million (ppm) (Hagenmaier and Baker, 1998). Fresh-cut sweet potato in medium- or high-permeability film bags stored at 2 or 8°C resulted in anaerobiosis at 2°C and especially 8°C for the low-permeability bags and at 8°C for the medium-permeability bags (Erturk and Picha, 2008). Nevertheless, MA is used to reduce respiration and ethylene production of fresh-cut produce to extend shelf life, generally in the range of 1 to 5% O_2 and 5 to 10% CO_2 (Gorny et al., 2002). This was successfully used for Kohlrabi sticks (2.5% O_2 and 9% CO_2) (Escalona et al., 2007), broccoli and cauliflower florets (1% O_2 and 21% CO_2) (Schreiner et al., 2007), minimally processed bok choy (5% O_2 and 2% CO_2) (Lu, 2007) and fresh-cut pineapple (2% O_2 and 12% CO_2) (Montero-Calderón et al., 2008), while low O_2 reduced browning of cut carambola (Teixeira et al., 2007) in vacuum-sealed bags. MAP and osmotic dehydration worked well for minimally processed guava (Pereira et al., 2004). Studies on the use of superatmospheric O_2 (>70%) were done to prevent anaerobic conditions, although this technique reduced the quality of fresh-cut pears (Oms-Oliu et al., 2007) by promoting oxidative processes (reduced vitamin C, solids, and acids). The high oxygen active packages, however, reduced accumulation of fermentative metabolites compared to typical MAP (relatively low O_2 and high CO_2) and inhibited some spoilage microorganisms

(Oms-Oliu et al., 2007). For cut peppers, 50% to 80% O₂ with less than 20% CO₂ was found to maintain good visual appearance without fermentation or off-odors. Higher levels of CO₂ promoted respiration (Conesa et al., 2007). Coating cut pears with antioxidant compounds (N-acetylcysteine and glutathione at 75%) in high O₂ (70%) atmosphere, low O₂ atmosphere (2.5% O₂ and 7% CO₂ active flush), or passively modified atmosphere showed that the low O₂ with the antioxidant treatments best maintained vitamin C, chlorogenic acid, and antioxidant capacity and reduced browning and ethylene production compared with the high O₂ treatment (Oms-Oliu et al., 2008a). However, Chinese bayberry fruits treated with air or 80% to 100% O₂ exhibited less decay and high levels of total soluble solids, titratable acidity and ascorbic acid contents, and reduced pH compared to air. The high O₂ treatment was less stressful as demonstrated by lower malonaldehyde content and higher catalase, ascorbic acid peroxidase, and peroxidase activities during storage. Elevated O₂ levels may improve the antioxidative defense mechanism and decay resistance (Yang et al., 2009).

4.6 GENETICS AND HARVEST MATURITY

4.6.1 GENETICS

Breeders are beginning to look for ways to breed varieties with characteristics tailored to a fresh-cut product. For example, lettuce breeders are seeking to develop multiuse cultivars. To this end, breeding lines were screened for increased cut lettuce shelf life in modified atmosphere (MA) environments such as encountered with MAP (Hayes and Liu, 2008). Genetic variation was thus determined for cut lettuce shelf life in low O₂ MA environments of 0.2% to 5% O₂ with the balance of N₂ in bags or in CA, to which cultivars could avoid damage from self-generated CO₂ injury or fermentation from low O₂. A novel hybrid muskmelon bred from an ultrafirm parent resulted in a fruit that was larger and had high external and internal firmness, ideal for long-distance shipping (Lester and Saftner, 2008). This hybrid also had high concentrations of sugar, β -carotene, and folic acid.

4.6.2 HARVEST MATURITY

When a product is harvested can affect the shelf life and quality of a fresh-cut product in that the fruit may or may not continue to ripen and soften after cutting. In some studies, relationships between harvest maturity and shelf life have been found (Chiesa et al., 2003; Couture et al., 1993; Watada and Qi, 1999), but this has not been found in others (Hayes and Liu, 2008). For cantaloupe, the length of storage duration decreased as harvest maturity increased for fresh-cut cantaloupe. Vitamin C losses were greater in fresh-cut cubes from more mature harvested fruit (full slip), and firmness losses were faster in more mature fruit (Beaulieu and Lea, 2007). Volatiles were reduced in more immature harvested cantaloupe (1/4 slip) (Beaulieu, 2006). It was therefore recommended to harvest at moderate maturity (1/2 slip) (Beaulieu and Lea, 2007) for a fresh-cut cantaloupe product. On the other hand, pear destined

for a fresh-cut product was more acceptable if harvested 1 month later than normal commercial harvest due to less browning potential (lower levels of phenolic compounds in the pulp) and better flavor (sweeter due to lower titratable acidity, higher levels of total aroma volatiles) (Bai et al., 2009). For mango also, later harvest maturity resulted in generally higher levels of desirable aromatic compounds (Beaulieu and Lancaster, 2008). Cut apple prepared from partially ripe intact 'Fuji' apples was most suitable for a fresh-cut product (Rojas-Graü et al., 2007b). However, for 'Granny Smith' apples, fruit harvested 2 weeks or more before induction of climacteric ethylene production (starch index <2.5) had more cut edge browning, despite use of anti-browning dip (Toivonen, 2008b).

4.7 PHYSIOLOGICAL EFFECTS OF SANITIZING TREATMENTS

Some sanitizers have physiological effects on the treated fresh-cut products. Sodium hypochlorite (NaOCl) has been shown to reduce browning of apple and potato, although CaCl_2 was found to be more effective (Brecht et al., 1993). Cut tomato treated with hydrogen peroxide (H_2O_2) exhibited reduced microbial populations when stored at 10°C ; however, they also had reduced phenolic and antioxidant levels after 7 days of storage and exhibited reduced color and levels of carotenoids. On fresh-cut Chinese water chestnuts, use of H_2O_2 reduced surface discoloration as well as decay. The H_2O_2 also delayed increases in total phenolic contents and reduced PPO, PAL, and POD activities (Peng et al., 2008; Podoski et al., 1997). Heat treatments for sanitation purposes can also cause heat shock and denaturation of metabolic enzymes that result in physiological effects. Hot water treatment of cantalopes to "pasteurize" the surface prior to cutting resulted in reduced microbial populations on the rind and of the subsequent cut melon pieces without affecting the quality of the fresh-cut product (Fan et al., 2008). A mild heat treatment of fresh-cut table grapes (45°C hot water or 55°C hot air for 8 or 5 minutes, respectively) followed by storage at 5°C resulted in reduced O_2 consumption, ethylene production, and decay (Kou et al., 2007).

Irradiation doses of 0.2 to 0.8 kGy can result in a 1 log reduction of bacterial pathogens, while 1 to 3 kGy is necessary to achieve a 1-log reduction of pathogenic viruses and fungi but can impact quality. Doses of 1 kGy or less are tolerated by most fresh-cut fruits and vegetables with little change in appearance, flavor, color, or texture. In some cases, there is loss of firmness and wilting due to an effect on permeability and functionality of cell membranes resulting in electrolyte leakage and loss of tissue integrity, especially at doses above 1 kGy (Fan and Sokorai, 2008). Low-dose irradiation (1 kGy) that can potentially inactivate *Escherichia coli* O157:H7 by 5 logs was tested on 13 common fresh-cut vegetables and was found not to result in significant losses of quality attributes (appearance, texture, flavor, and nutritional composition), with the exception of irradiated green and red leaf lettuce having reduced vitamin C values (Fan and Sokorai, 2008). Low-dose electron beam irradiation on fresh-cut cantalope lowered and stabilized respiration compared to nonirradiated samples while lowering microbial populations (Boynton et al., 2006).

Heat is also used to reduce ripening, senescence, and wound responses of fresh-cut produce (respiration, ethylene, softening, browning). Treatment of fresh-cut

peach with hot water at 50°C for 10 minutes followed by MAP storage at 5°C controlled browning and retained firmness during storage, with lower concentrations of CO₂ and ethylene in the package atmosphere (Koukounaras et al., 2008). However, the heat treatment increased total carotenoid loss and reduced chroma color values on the slices compared to nonheated controls, but PPO activity was not affected. Hot dips in CaCl₂ or other calcium salts (60°C) helped maintain firmness (increased bound Ca levels in the cell wall), reduced microbial growth, and improved sensory quality compared to unheated controls (Aguayo et al., 2008). Other calcium salts were evaluated with varying amounts of success. Heat-treated cut apple (4 days at 38°C hot air) reduced ethylene synthesis, respiration, and softening, but also reduced aroma volatiles (Bai et al., 2004). Mild heat shock of lettuce leaves had mixed results, reducing browning but causing deleterious surface color and texture effects (Moreira et al., 2006).

UV light can also be used to sanitize fresh-cut produce, but it can also affect quality. Fresh-cut tomatoes, grown hydroponically, when exposed to UV-C light exhibited reduced microbial populations, increased phenolic content, and delayed degradation of vitamin C after 7 days storage at 4 to 6°C. The UV light treatment did not affect appearance, color, or lycopene content when the tomatoes were grown in lower salt concentrations. When the tomatoes were grown at higher salt concentrations and exposed to UV treatment, lycopene and vitamin C contents were increased likely due to stress; however, the UV-C treatment accelerated the decline of phenolic compounds and vitamin C in the subsequent fresh-cut product of these fruit (Kim et al., 2008a). Use of higher UV-C doses (up to 11.35 kJm⁻²) on fresh-cut spinach resulted in a loss of lightness likely due to superficial tissue damage and an accelerated decrease in total antioxidant activity and polyphenol content during storage, although microbial growth was reduced (Artés-Hernández et al., 2009). UV irradiation of cut cantaloupe enhanced terpenoid production accompanied by some ester losses, which were cultivar and maturity dependent (Beaulieu and Lea, 2007).

Ozonated water is also used as a sanitizer, but it can have physiological effects. Use of ozonated water on the shelf life of fresh-cut lettuce antioxidants, including polyphenols and vitamin C, did not affect these compounds and did not increase respiration. The ozone treatment reduced browning and improved appearance compared to water and chlorine rinses (Beltran et al., 2005). In a comparison of sanitizing methods including sodium hypochlorite, electrolyzed water, and peroxyacetic acid for effect on respiration rates of fresh-cut vegetables stored at 7°C with 3% O₂, sodium hypochlorite increased respiration of iceberg lettuce but not carrot, leek, or cabbage. Peroxyacetic acid did not affect respiration of leek and iceberg lettuce, but it decreased respiration of carrot and cabbage. Electrolyzed water, however, reduced respiration of leek and cabbage (Vandekinderen et al., 2008).

4.8 SURFACE TREATMENTS AND COATINGS

Often, fresh-cut fruit are treated to combat derivative physiological changes such as browning, softening, flavor changes, and losses of nutrients or other healthful compounds and dehydration.

4.8.1 SURFACE TREATMENTS

Browning of cut tissue is generally due to the action of PPO with some involvement in some cases of POD and PAL. POD is a heme-containing enzyme that can perform single-electron oxidation of phenolic compounds in the presence of H_2O_2 . Generation of H_2O_2 by PPO when oxidizing some phenolics can induce synergistic action between PPO and POD (He and Luo, 2007). Ascorbic acid or its derivatives can be used as an antioxidant to reduce browning and as an acidulant. Citric, malic, tartaric, oxalic, and succinic acids can also be used to acidify the surface and to act as chelator of browning compounds. Calcium or its derivatives can be used to reduce browning and to increase firmness (He and Luo, 2007). Acidifying the surface helps to inhibit PPO activity due to its pH optimum being quite sensitive (Chisari et al., 2008). PPO isoenzymes have two copper ions at the active site. This enzyme can catalyze the hydroxylation of monophenols and the oxidation of diphenols to quinones, using oxygen as a cosubstrate. The quinones polymerize into brown pigments (Arias et al., 2007; He and Luo, 2007; McEvily et al., 1991; Taylor and Clydesdale, 1987). Other antibrowning agents include thiol-containing compounds cysteine, glutathione, and acetylcysteine, which are thought to form colorless thiol-conjugated o-quinones (He and Luo, 2007). Calcium ascorbate is also effective (adapted by the fresh-cut industry in the commercial form of Nature Seal), as are sulfates (banned by the U.S. Food and Drug Administration [FDA] due to allergenic reactions). The effect of calcium ascorbate was demonstrated on cut apple (Wang et al., 2007). 4-Hexylresorcinol and ascorbic acid were investigated in pear. It was found that ascorbic acid did not interact directly with PPO but prevented browning by reducing oxidized substrates. 4-Hexylresorcinol, however, interacted with the deoxy form of PPO, thus inactivating the enzyme in the absence of substrates, or competed with substrates for the catalytic site (Arias et al., 2007). POD activity, however, was more associated with browning of cut melon than PPO (Chisari et al., 2008). Oxyresveratrol and an extract from mulberry twigs (mulberroside) in combination with isoascorbic acid, calcium chloride, and acetylcysteine delayed browning of cut apple (Li et al., 2007). Ascorbic acid, citric acid, and calcium chloride were used on cut mango to retain color and antioxidant activity (Robles-Sánchez et al., 2009). In cut apple, antibrowning agents ascorbic acid, 4-hexylresorcinol, N-acetylcysteine, and glutathione were tested. N-acetylcysteine and glutathione inhibited PPO activity. Ascorbic acid in combination with 4-hexylresorcinol, N-acetylcysteine, or glutathione inhibited POD activity. Generally, 4-hexylresorcinol and ascorbic acid individually were not very effective at levels tested for browning of cut apple (Rojas-Graü et al., 2008) compared to the sulfur compounds N-acetylcysteine and glutathione. Other inhibitors of PPO and browning from natural sources include kojic acid, arbutin, and glabridin, as well as an extract from the wood of *Artocarpus heterophyllus*, which was effective on cut apple (Zheng et al., 2008). Lychee fruit have a bright red pericarp that browns after harvest due to dehydration, breakdown of anthocyanins, and action of PPO. Therefore, a lychee fresh-cut product was developed where the edible aril was removed from the peel and treated with cysteine, ascorbic acid, and 4-hexylresorcinol along with osmotic vacuum dehydration, which maintained color and sensory characteristics (Shah and Nath, 2008).

4.8.2 COATINGS

One problem of minimal processing of fruits and vegetables is water loss and dehydration. Use of edible coatings can reduce water loss by acting as a barrier to water vapor transfer, or by acting as a sacrificing agent, losing water from the coating before losing water from the product tissue, and thus delaying water loss by the cut product. Coatings can also be used as carriers of the above antioxidants, sanitizers, acidulents, chelators, firming agents, and probiotics. The problem is that fresh-cut products often have high water vapor activity on the cut surface, making use of hydrophobic coatings difficult, although they are best at preventing water loss. Gellan-based films containing antioxidants and viable probiotic bifidobacteria on cut papaya and apple exhibited good water vapor properties (Tapia et al., 2007). Although hydrophilic protein and polysaccharide films are more compatible with a cut surface, an antioxidant candelilla wax carrying *Aloe vera* reduced weight loss, changes in pH, and firmness when tested on fresh-cut avocados, bananas, and apples (Saucedo-Pompa et al., 2007). Algenate and gellan-based edible coatings on fresh-cut 'Fuji' apples delayed ethylene production, reduced microbial growth, and maintained firmness and color when N-acetylcysteine was added (Rojas-Graü et al., 2007b). Alginate coating with acetylated monoglyceride minimized weight loss of cut 'Gala' apple (Olivas et al., 2007). Apple puree-alginate coatings with antimicrobial essential oils (lemongrass, oregano, and vanillin) and antioxidants reduced respiration, ethylene production, and microbial growth when applied to fresh-cut apples but exhibited some ethanol and acetaldehyde formation in the first week of storage (Rojas-Graü et al., 2007a). Candelilla wax with ellagic acid-reduced color changes. Generally, these films reduced softening of cut avocado, banana, and apple (Saucedo-Pompa et al., 2007). Coatings of sour whey powder, soy protein isolate, and calcium caseinate on cut apple, carrots, and potato resulted in reduced color changes and weight loss (Shon and Haque, 2007). Application of chitosan coatings on fresh-cut mushroom delayed discoloration and reduced enzyme activities of PPO, POD, catalase, PAL, and laccase as well as resulted in lower phenolic content. A chitosan coating also maintained color and reduced microbial growth on cut papaya (González-Aguilar et al., 2009). The coatings also reduced activities of cellulose, total amylase, and α -amylase and inhibited microbial populations (Eissa, 2007). Edible coatings have also been used to reduce dehydration of the surface of peeled carrots, which takes on an undesirable white coloration (white blush) using cellulose (Mei et al., 2002; Sargent et al., 1994), sodium caseinate/stearic acid (Avena-Bustillos et al., 1994), whey protein, or xanthan gum (Mei et al., 2002). Vacuum impregnation of chitosan-based films reduced peeled carrot whitening and resistance to water vapor transmission (Vargas et al., 2008). Application of a chitosan/methyl cellulose film on fresh-cut cantaloupe and pineapple reduced microbial growth when vanillin was added and helped maintain moisture content (Sangsuwan et al., 2008). Alginate, pectin, and gellan-based coatings prevented dehydration of cut melon and inhibited ethylene production (Oms-Oliu et al., 2008b).

4.8.2.1 Firming Agents

Calcium can interlink pectin chains in cell walls and thus improve firmness. Calcium lactate strengthened the structure of fresh-cut ‘Fuji’ apples stored for 3 weeks at 4°C (Alandes et al., 2006) and counteracted activity of both pectinmethylesterase (PME) and PG. Addition of calcium chloride as a cross-linking agent helped maintain firmness of fresh-cut melon (Oms-Oliu et al., 2008b).

4.9 CONCLUSION

Fresh-cut fruits and vegetables present unique physiological challenges to postharvest physiologists and food scientists. The products are living tissues that have the outer protective peel breached in some way, allowing water loss and providing an entrance for microbes. The processing also induces a range of wound responses, including ethylene production and increased respiration, which in turn induce undesirable color, texture, and flavor changes. Many methods have been developed and continue to be tested to counteract the physiology, including MAP packaging, edible coatings, antioxidants, acidulants, antimicrobial agents, and firming agents. Anti-ethylene production and action agents have also been employed, including 1-MCP, ethanol, and use of temperature. In the end, successful marketing of fresh-cut products is evident judging by the rapidly growing fresh-cut segment of the fresh produce industry.

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7 Fruits and Vegetables for the Fresh-Cut Processing Industry

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CONTENTS

7.1	Introduction	186
7.2	Quality of Intact Fresh Fruits and Vegetables	186
7.3	Dynamic Behavior of Fresh Fruits and Vegetables	187
7.3.1	Respiration Rate	188
7.3.2	Ethylene Production.....	188
7.3.3	Water Loss	189
7.3.4	Internal and External Color	189
7.3.5	Texture	192
7.3.6	Compositional Changes	193
7.3.7	Growth and Development	193
7.3.8	Microbial Spoilage.....	194
7.4	Technological Tools to Preserve Fresh Produce for Processing.....	194
7.4.1	Cultivar Evaluation and Selection	195
7.4.2	Preharvest Practices to Improve Intact Produce Quality	196
7.4.3	Harvest and Maturity Indices	198
7.4.4	Postharvest Strategies to Reduce Undesirable Changes.....	201
7.4.4.1	Use Optimum Storage Temperatures to Reduce Metabolic Activity	201
7.4.4.2	Relative Humidity and Water Loss Control	202
7.4.4.3	Air Movement	203
7.4.4.4	Light.....	203
7.4.4.5	Atmosphere Composition	203
7.4.4.6	Ethylene	203
7.4.4.7	Handling and Processing	203
7.4.4.8	Field and Storage Packages.....	204
7.4.5	Conditioning and Storage Before Processing	204
7.5	Conclusions	205
	References.....	205

7.1 INTRODUCTION

Fruits and vegetables are a gift of nature and delight people of all ages. They provide a wide range of flavors and textures and are loaded with most of the nutrients required for good health and wellness.

Their consumption as fresh produce is largely recommended all over the world; however, nowadays, consumers have limited time for food preparation. This has led the fresh-cut fruits and vegetables market to grow, as they offer good and convenient produce, ready to eat, with the attributes of fresh produce.

Fresh-cut fruits and vegetables are composed of living cells that naturally spoil and deteriorate over time and are affected by all preparation operations and surrounding conditions during pre- and postharvest handling, processing operations, and storage. Respiration and ethylene production rates, color, aroma, and texture change as a response to physical damages produced during cutting operations, as well as to the activity of undesirable microorganisms (Wiley 1994; Aguayo et al. 2004; Artés-Hernández et al. 2007; Artes-Calero et al. 2009).

Quality attributes of the fruit and vegetables used as raw materials for processing have a great influence on the final quality and shelf-life of fresh-cut products; hence it is very important to identify and understand relevant changes for specific products and how they are affected by handling, processing, and storage.

Produce to be used for the fresh-cut industry should resist processing and maintain their attributes with minimum variations for as long as possible. This chapter focuses on the fruits and vegetables requirements for handling and conditioning for fresh-cut produce processing.

7.2 QUALITY OF INTACT FRESH FRUITS AND VEGETABLES

Fresh fruits and vegetables are expected to preserve quality during handling, storage, processing, and distribution. Even though quality criteria vary among products, it is generally associated with intrinsic properties of the food, such as visual appearance, texture, flavor, nutritive value, and safety issues during field production, handling, and processing. Appearance has a great influence on product selection for processing; shape, size, color, gloss, uniformity, and lack of wilting, browning, and decay symptoms give clues about stage of maturity, freshness, and expected process yield.

Texture attributes gather structural properties of the product and related sensorial attributes perceived as the product is bitten. Structures of fresh fruits and vegetables cells and tissues are complex in shape, chemical composition, adhesive and cohesive forces between cells, and how they are affected by turgidity, maturity stage, and other variables, resulting in a wide range of responses to force stresses during handling and processing (Schouten and Kooten 2004). Texture can be described by a series of parameters for specific characteristics, such as firmness or hardness, fracturability, adhesiveness, gumminess, crispiness, fibrousness, juiciness, flexibility, and others, with their relative importance dependent on the product and its final use. Mechanical response of intact produce is affected when fresh-cut products are prepared, because of injured cells and tissues, size reduction, elimination of protective skin, increased water losses, and wilt and decay.

Flavor embraces taste and aroma attributes, with a very wide range of combinations of sweetness, sourness, bitterness, and astringency, along with the characteristic aromas of each product, and the absence of undesirable off-flavors and off-odors. Kader (2008) highlights the importance of nutritive and better-flavored fruits and vegetables as a key factor in selecting cultivars, as a key to increase sales and consumption.

Nutrient content and biochemical composition vary with the products as they might come from different parts of the plant. Storage organs such as roots and tubers have high starch content; stems are rich in fibers and skeleton-type tissues with high lignin and cellulose content; and fruits are rich in sugars, organic acids, mineral salts, pectic substances, and enzymes (Maestrelli and Chourot 2002). Soluble solids content, total or titratable acidity, pH, water content, density, and the ratio of soluble solids content to acidity are commonly used as quality attributes. Fruits and vegetables are very good sources of vitamins A and C, minerals, carbohydrates, dietetic fiber, proteins, and antioxidant compounds such as carotenoids, flavonoids, and other phenolic compounds (Kader and Barret 2004); their composition and concentration vary among cultivars and are affected by pre- and postharvest practices.

Safety requirements related to fresh-cut produce include good agricultural practices (GAP) and good processing practices (GMF), freedom of plagues, mycotoxins, pesticide residues, and any other chemical or physical contamination that might risk consumer health.

Finally, it is important to consider that required quality attributes of fruits and vegetables for the fresh-cut industry may differ from those for the intact fruit market, because no alterations are done to the products in the latter case. Processors need intact fruits and vegetables that can withstand processing and maintain quality attributes of the fresh-cut product as long as possible, with high production yields, with very good and consistent quality, free from defects, with the right maturation stage; thus, the use of grocery store surplus or low quality and unmarketable products for processing should be avoided. The right intact fruits and vegetables used as raw matter must allow for the preparation of high-quality fresh-cut products, with uniform and consistent quality, suitable postcutting shelf-life, and consumer satisfaction.

7.3 DYNAMIC BEHAVIOR OF FRESH FRUITS AND VEGETABLES

Fruits and vegetables are composed of living tissues and have to withstand two major hurdles: harvest and processing. When they are harvested, water and nutrient supply from the mother plant ends, and tissues are injured at the incision point. Processing causes further physical damages as the products are cut, and the product skin is removed, causing an increase in the respiration and other metabolic activities continue all the way up to the consumer table.

For such a dynamic system, changes are continually occurring, even though they may not be obvious for the first hours or days after harvesting or cutting. Appearance and texture alterations are the first to be noticed, although many more physical, physiological, and biochemical changes are ongoing at the same time at different rates, and are influenced by internal and external factors.

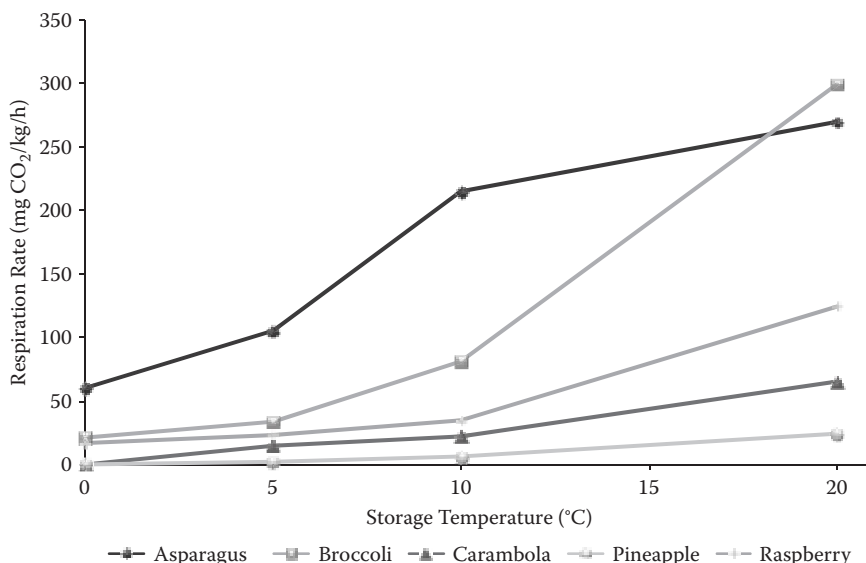


FIGURE 7.1 Effect of storage temperature on respiration rate of several intact fruits and vegetables. (From Barth, M.M., Zhuang, H., and Saltveit, M.E. 2004. Fresh-cut vegetables. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*. USDA-ARS. Agriculture Handbook Number 66 (draft-revised 2004). Ed. K. Gross. <http://www.ba.ars.usda.gov/hb66/147freshcutvegetables.pdf> (accessed August 25, 2009); Beaulieu, J.C. and Gorny, J.R. 2004; Fresh-cut fruits. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*. USDA-ARS. Agriculture Handbook Number 66 (draft-revised 2004). Ed. K. Gross. <http://www.ba.ars.usda.gov/hb66/146freshcutfruits.pdf> (accessed August 25, 2009); Gross, K. 2004. Summary of respiration and ethylene production rates. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*. USDA-ARS. Agriculture Handbook Number 66 (draft-revised 2004). Ed. K. Gross. <http://www.ba.ars.usda.gov/hb66/010respiration.pdf> (accessed August 25, 2009).)

The main intrinsic changes of fruits and vegetables are directly related to external factors, such as temperature, relative humidity, handling, microbiological, and other stresses occurring during pre- and postharvest operations.

7.3.1 RESPIRATION RATE

The rate of respiration is sensible to internal factors, such as product type and maturity stage, and also to external factors like temperature (Figure 7.1), ethylene concentration, stress caused during harvest, postharvest, and processing operations, pathogens, and physical injuries (Fonseca et al. 2002; Kader et al. 2002a; Varoquaux 2002). The faster the respiration rate is, the shorter will be the shelf life of the intact and fresh-cut products. Respiration rate is a good indicator of ongoing processes inside a product and how fast they are happening; products harvested during active growth (vegetables and immature fruits) usually have high respiration rates, while mature fruits and storage organs have relatively low rates (Saltveit 2004a).

7.3.2 ETHYLENE PRODUCTION

Ethylene has an active participation in growth, development, maturation, healing, and senescence of fresh produce (Kader 2002a; Saltveit 2004b). Its production rate varies

among products; it increases with temperature, disease incidence, mechanical injuries, water stress, and maturity stage at harvest; and it can be partially controlled by low temperature storage, reduced oxygen composition, or elevated carbon dioxide levels surrounding the commodity. Very small concentrations of ethylene can damage sensible products (Table 7.1); hence, they should be handled separately from those that produce it.

7.3.3 WATER LOSS

Fruit and vegetable water content is very high and can be easily lost through the skin lenticels, stomatas, cuticle, and other structures when the surrounding atmosphere has low relative humidity. The skin of fruits and vegetables acts as a natural barrier that helps to partially control water loss, but its effectiveness depends on product morphology, surface characteristics, size, ratio of product surface area to weight and volume, maturity stage, physical injuries, as well as environmental temperature, relative humidity, and air movement around the product. Some products are more susceptible to lose water, such as lettuce and other leafy vegetables, which wilt and shrivel and generally deteriorate rapidly; others are more resistant to water loss, like apples and pears. The water loss for other products increases for those with rough, uneven, or extended surface area or with high stomata or lenticels density, like rambutan, with hair-like structures that favor water loss and desiccation, with the consequent external darkening occurring in a few days at 25°C and 60% relative humidity (Yingsanga et al. 2006), with losses of 7% to 11% weight during the first storage day.

On the other hand, fresh-cut products can lose water even more rapidly than whole products because of their increased surface area to volume ratio, as skin removal and damaged tissues resulting from cutting operations favor cellular content leakage. For such products, the use of sharp knives and proper packaging materials are key elements to reduce water migration.

7.3.4 INTERNAL AND EXTERNAL COLOR

Color is one of the main quality attributes of fresh commodities commonly used as selection criterion by the consumers and the fresh-cut industry, as well as an indicator of the overall quality and maturity stage of the product. Color varies among products, cultivars, and stages of maturity or development; it can be affected by preharvest factors such as plant nutrition, seasonality, climate conditions, production lot, temperature, relative humidity, storage time, and postharvest handling conditions. Color changes can result from the degradation or formation of pigment compounds such as chlorophylls (green), anthocyanins (red, blue, and purple), and carotenoids and flavonoids (yellow and orange) (Maestrelli and Chourot 2002; Kader and Barrett 2005). They can occur as part of the ripening process, but they also can be caused by mechanical stresses on cell wall, membranes, and tissues during produce handling and fresh-cut processing. Such damages favor fluids leakage, tissue softening, and enzymatic browning reactions, as enzymes and their substrates come into contact (Singh and Cadwallier 2004). Enzymatic activity of PPO (polyphenol oxidase) and POD (peroxidase) is also associated with color changes in fruits and vegetables. Mangoes, avocados, peaches, apples, pears, bananas, olives, potatoes, mushrooms, lettuce, grapes, and other fruits and vegetables are very sensitive to enzymatic browning due to PPO activity.

TABLE 7.1
Optimum Storage Temperature and Relative Humidity for Selected Fruits and Vegetables

Product	Storage Temperature °C	Relative Humidity %	Sensitivity to Chilling ^a	Freezing Temperature °C	Sensitivity to Ethylene ^b	Product	Storage Temperature °C	Relative Humidity %	Sensitivity to Chilling ^a	Freezing Temperature °C	Sensitivity to Ethylene ^b
Apple (summer)	0–2	85–95				Lettuce head					
Fuji, Gala	0	90–95	✓	–1.5	H	Butterhead	0	98–100	✓	–0.2	H
Golden, McIntosh	4	90–95	✓	–1.5	H	Iceberg	0	98–100	✓	–0.2	H
Asparagus	2,5	95–100	✓	–0.6	M	Lime	9–10	85–90	✓	–1.6	
Avocado (ripe)	0–2	85–95	✓	–1.6	H	Mango	13	85–90	✓	–1.4	M
Avocado (unripe cv. Fuerte, Hass)	3–7	85–90	✓	–1.6	H	Mushrooms	0	90	✓	–0.9	M
Banana	13–18	85–90	✓	–0.8	H	Nectarine	–0.5–0.0	90–95	✓	–0.9	M
Beets (topped)	0–2	98–100	✓	–0.9	L	Onion (mature bulbs, dried)	0	65–70	✓	–0.8	L
Blackberry	–0.5–0.0	90–95		–1.3	L	Orange	7–10	85–90	✓	–0.8	M
Broccoli	0	95–100	✓	–0.6	H	Oregano	0–5	90–95	✓		M
Brussels sprouts	0	95–100	✓	–0.8	H	Papaya (ripe)	13–18	85–90	✓	–0.9	M
Cabbage	0	98–100	✓	–0.9	H	Passion fruit	7–10	85–90	✓		M
Cantaloupe	2–5	95	✓	–1.2	M	Peach (ripe)	–0.5–0.0	90–95	✓	–0.9	M
Carambola	7–10	85–90	✓	–1.2		Pear	–1.5–0.5	90–95	✓	–1.7	H
Carrots	0	98–100	✓	–1.4	H	Pepper (Bell)	7–10	95–98	✓	–0.7	L

Cassava	13–18	85–90	✓	L	Pineapple	7–13	85–90	✓	–1.1	L
Cauliflower	0	95–98	✓	H	Plantain	13–15	90–95	✓	–0.8	H
Celery	0	98–100	✓	M	Pomegranate (arils)	5–7	90–95	✓	–3.0	L
Chayote	7	85–90	✓		Potato (cured)	13–18	85–90	✓	–0.8	M
Cherimoya (custard apple)	13–18	85–90	✓	H	Rambutan	12	90–95	✓		H
Coconut	0–2	85–95	✓		Raspberry	–0.5–0.0	90–95	✓	–0.9	L
Cucumber	10–12	85–90	✓	H	Rhubarb	0	95–100	✓	–0.9	L
Eggplant	10–12	90–95	✓		Soursop	13	85–90	✓		
Garlic	0	65–70	✓	L	Spinach	0	95–100	✓	–0.3	M
Granadilla	7–10	85–90	✓		Summer squash	7–10	95	✓	–0.5	L
Guava	7–10	85–90	✓		Sweet potato	13–18	85–90	✓	–1.3	L
Honeydew melon	13–18	85–90	✓	H	Strawberry	0	90–95	✓	–0.8	L
Kiwifruit (ripe)	0	90–95	✓	H	Tomato (mature green)	10–13	90–95	✓	–0.5	H
Lemon	10–13	85–90	✓		Tomato (firm ripe)	8–10	85–90	✓	–0.5	L
					Watermelon	10–15	90	✓	–0.4	H

^a o, no; ✓, yes.

^b L, low; M, medium; H, high.

Sources: Beaulieu, J.C., and Gorny, J.R. 2004. Fresh-cut fruits. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*. USDA-ARS. Agriculture Handbook Number 66 (draft-revised 2004). Ed. K. Gross. <http://www.ba.ars.usda.gov/hb66/146freshcutfruits.pdf> (accessed August 25, 2009) Thompson, J.F., and Kader, A.A. 2004. Wholesale distribution center storage. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*. USDA-ARS. Agriculture Handbook Number 66 (draft-revised 2004). Ed. K. Gross. <http://www.ba.ars.usda.gov/hb66/016wholesale.pdf> (accessed August 25, 2009); Cantwell, M. 2002. Optimal handling conditions for fresh produce. In *Postharvest Technology of Horticultural Crops*. Ed. A.A. Kader. University of California Agriculture and Natural Resources. Publication 3311, pp. 511–518.

Color changes can be accelerated by external factors such as high temperature, low relative humidity environment, physical damages, and other stress conditions. Odriozola-Serrano et al. (2009) found that the degradation of anthocyanins responsible for the appealing bright red color of strawberries was significantly larger as the temperature rises and storage time increases.

Color requirements for fresh intact product consumption varies with those for fresh-cut processing. For the whole produce market, external color is one of the main quality attributes, while for the industry, both external and internal colors are important. In general, color should be bright, even, and preserve the natural appearance of the fresh product. Care must be taken with new cultivars with improved processing characteristics but with major differences in color, because they could be rejected by the consumer.

7.3.5 TEXTURE

Texture attributes vary during pre- and postharvest handling, as they are affected by stage of maturity, plant nutrition, water stress, storage temperature and relative humidity, rough handling, and ripening processes. Product softening, loss of turgidity, and increased elasticity or toughness are some of the changes occurring during product handling, which may reduce the product's value and utility for the fresh-cut industry. Changes can be due to water losses, as mentioned earlier, or to the activity of several enzymes or pathological breakdown in combination with handling conditions. Enzymes such as β -galactosidase, polygalacturonase, pectin methyl esterase, cellulose, phenylalanine ammonia lyase, peroxidase, and cellulase participate in cell-wall modification; degradation of pectin compounds in tomatoes, melons, avocados, and peaches; pectin solubilization in strawberries; ripening initiation processes; tissue weakening and softening in raspberries, avocado, blackberries, mangoes, cherimoya, and tomatoes; and toughness development in asparagus (Bhowmik and Dris 2004).

Physical damages of fresh fruits and vegetables should be minimized throughout harvest, transportation, and postharvest and processing operations, because they have a negative effect on quality attributes and shelf life. Symptoms could show immediately, during processing, or after several days or weeks of storage; they are generally described as tissue darkening, loss of firmness, bruises, cracks, cuts, and perforations which lead to faster deterioration reactions than with intact products. Damaged tissues increase respiration rates, water loss, and other metabolic reactions; allow better contact between enzymes and their substrates; and favor microbial spoilage and other undesirable reactions (Singh and Anderson 2004).

Maestrelli and Chourot (2002) classified fruits as very fragile, fragile, resistant, or very resistant to handling. They found cultivar, stage of maturity, and handling practices influenced the response to mechanical injuries of peaches, pears, prunes, and apricots. Damages are caused by impact, compression, penetration, vibration, and shear forces against the product; hence, they can be controlled by protecting

and immobilizing the product, which can be achieved by careful handling, reducing unnecessary movements, drop heights, and any cut edges or rough surfaces that could threaten product integrity.

Bruising response to processing varies among apple and peach cultivars, but the fruit susceptibility can also be influenced by preharvest practices, weather conditions, maturity stage, and other factors that might affect phenolic compound content and enzymatic activity (Varoquaux, 2002).

Impact bruising damages susceptibility is larger for sweet cherries handled below 10°C as compared with temperatures up to 20°C. Mechanical damages due to vibration are not affected by temperature (Crisosto et al. 1993). On the other hand, physiological disorders such as chilling and freezing injuries also contribute to tissue softening, water-soaked areas, ripening problems, surface and flesh discoloration, off-flavors and off-odors production, and increased susceptibility to microbial spoilage and breakdown (Kader 2002a; Kader and Barret 2004; Wang 2004).

7.3.6 COMPOSITIONAL CHANGES

Internal composition of fruits and vegetables keeps changing during growth and development and after harvest. Changes could be desirable or not, depending on the product and how and when it is going to be processed. Soluble solids content and acidity are two important parameters for fruits, frequently related to stage of maturity, flavor, and consumer preferences, and used as quality parameters for product selection for processing. Little changes occur in nonclimacteric fruits after harvest (pineapple, citrus fruits), while climacteric fruits suffer important changes as they continue to ripen.

Aroma compounds losses or the production of off-flavors and off-odors directly affect fruit and vegetable flavor. They can be associated to maturity stage, unfavorable storage conditions, or enzymatic activity of peroxidases and lipoxygenases in chile peppers, broccoli, asparagus, carrots, and green beans.

Antioxidant and other nutritional attributes can be lost during handling and processing. Kader and Barret (2004) pointed out the high sensibility of ascorbic acid to high temperatures, light, low humidity environments, physical damages, and chilling injuries.

7.3.7 GROWTH AND DEVELOPMENT

Some fresh produce continues to grow and develop after harvest. Rooting can occur on root crops and onions, seed germination on tomatoes and peppers, and elongation in asparagus (Kader 2002a). Proper selection of the harvesting index, handling and storage conditions, and special treatments are necessary to diminish these undesirable changes. Most of these changes are undesirable for fresh-cut processing, because metabolic activity increases and product appearance may rapidly deteriorate.

7.3.8 MICROBIAL SPOILAGE

Fruits and vegetables are good sources of nutrients and water for humans, but also for microorganisms, which can grow easily under ambient conditions. Microorganisms can get into the fruits at different stages of their field production, at the earlier stages of development, or during postharvest handling and processing operations. Some microbes can rapidly deteriorate fruit and vegetables' appearance and other quality attributes, but do not represent a risk for consumers (phytopathogens), while others can be harmful for consumer health (food safety related microorganisms). They can be separated into two different groups:

- Fruit and vegetables microorganisms: Include molds, yeast, bacteria and viruses which affect product quality, but do not represent a risk for consumer health.
- Harmful microorganisms: They can cause illness and even death to consumers, but in general they affect neither the product appearance nor other quality attributes of the fruit or vegetable. Since no deterioration symptoms are observed in the product, care must be taken to avoid product contamination. Sanitation programs in the fields and processing area and good hygienic practices of the operators are needed to avoid product contamination.

7.4 TECHNOLOGICAL TOOLS TO PRESERVE FRESH PRODUCE FOR PROCESSING

Quality is a key factor for processed foods, but it is particularly true and important for fresh-cut fruits and vegetables, which must preserve the quality attributes of the intact produce after cutting stresses, without being subjected to any strong temperature-stabilizing treatment. Hodges and Toivonen (2008) highlighted the importance of recognizing that all processes applied to a fruit or vegetable cause stress-induced changes in the tissue physiology and metabolism. They also pointed out the need to understand how these changes occur to set effective strategies to preserve the product quality and extend its shelf life.

The fresh-cut processing industry requires high-grade fruits and vegetables as raw materials. They should have good appearance, texture, taste, odor, and nutritive attributes, and they must be safe for the consumer. They should be free from mechanical injuries, decay, insects, and other damages, and they must resist process operations and further handling and storage procedures.

In addition, effective technological tools must be used in each of the slabs of the chain, from the production fields to the processing industry, to assure proper quality produce supply and minimize product losses.

The success of a fresh-cut product will depend on the fulfillment of the target consumer needs and expectations, the use of the right fruits and vegetables at their optimum maturity stage for processing, and the application of the right operation procedures and packages, as well as the utilization of appropriate market tactics.

Strategies for better intact fruits and vegetables for processing involving preharvest, harvest, and postharvest handling will be discussed later in this chapter.

7.4.1 CULTIVAR EVALUATION AND SELECTION

For each type of produce, there could be a few or many cultivars in the market, each with particular benefits and limitations for processing. Studies comparing cultivars usually show considerable variation in respiration rates, color, texture, bruising susceptibility, size, shape, appearance, nutritional value, sensory, and other characteristics of many fruits and vegetables (Crisosto et al. 1993; Gorny et al. 2000; Crisosto and Mitchell 2002; Maestrelli and Chourot 2002; Schouten and Kooten 2004; Deepa et al. 2007).

Cultivar selection for the fresh-cut industry looks for intact fresh fruits or vegetables that can meet the desired quality attributes preestablished for their fresh-cut product, resist transportation and handling before processing, tolerate processing operations with minor quality alterations, and have a prolonged after-cutting shelf life. These four elements are interrelated because of the dynamic behavior of intact fresh fruits and vegetables, because their characteristics and quality are continually changing and influenced by environmental conditions, production technology during preharvest and postharvest handling, fresh-cut processing and packaging, and distribution to the final market.

Industry needs reliable agricultural products with high quality throughout the year, when possible, in order to produce uniform fresh-cut products without interruption. Cultivar selection is the first step, and it has to be followed by proper preharvest practices, harvesting indicators, postharvest handling operations and storage before processing, and food safety programs to avoid consumer risks (Chiesa et al. 2003).

Ideal fruits and vegetables for fresh-cut processing are those with the best and homogeneous quality attributes: right stage of development or maturity; high field production and processing yields; availability year-round; free from physical, physiological, or pathological disorders; easy to handle; highly resistant to handling and all processing operations and stabilizing treatments; little susceptible to external conditions; with a prolonged shelf life after processing to maintain quality attributes all the way to the consumer and safe consumption. It should also meet consumer likes and preferences and market requirements.

For specific products, particular requirements are needed. Processors need to clearly define the attributes of their final products to evaluate cultivar response to handling, processing, and after-cutting handling and to determine limiting factors, such as juice leaking, discoloration, browning, wilting, microbial spoilage, or others that might restrict fresh-cut product shelf life. The effects of harvesting indicators, handling, and preparation for processing practices on final product quality should also be evaluated.

Some examples of studies conducted to select the best cultivars for fresh-cut processing include one of Gorny et al. (1999), who found that the critical factors that impact fresh-cut peach and nectarine slice quality were ruled by product response to cutting, which was better when the flesh firmness was between 13 and 27 N, and the fruits were stored at 0°C and 90% to 95% relative humidity. In another study, the same authors (2000) compared the suitability of Anjou, Bartlett, Bosc, and Red Anjou pear cultivars for fresh-cut slices production and found significant differences in respiration and ethylene production rates, flesh firmness, color, and susceptibility

to cut-surface browning, which was very intense for Anjou and Red Anjou cultivars. Apple sensibility to browning of five apple cultivars was also studied by Milani and Hamed (2005), who found differences in browning rate; the Red Delicious cultivar exhibited the highest browning rate, followed by Golden Delicious with a medium rate, and Granny Smith and Golden Smoty had a weak browning rate. Sweet cherry cultivars were evaluated for fresh-cut processing by Toivonen et al. (2006), who concluded that most of them were adequate for fresh-cut processing, as they maintain firmness, even though they showed differences in postcutting bleed, weight loss, and decay throughout storage.

Following are some hints for fruits and vegetables cultivar selection for fresh-cut processed products:

- Define desirable quality parameters and tolerance ranges for the fresh-cut product (color, shape, size, flavor, soluble solids content, acidity, texture, juiciness, nutritional content, other).
- Identify available cultivars with consistent and reliable quality that can meet product concept.
- Look for limiting factors to fresh-cut product quality and shelf life, based on visual and eating quality and microbial safety; consider deteriorative changes that reduce their marketability, such as browning, water-soaked tissues, translucency, softening, composition changes, microbial growth, decay, or others.
- Evaluate cultivar aptitude for processing by studying product response to handling and processing, and susceptibility to deteriorative changes before, during, and after cutting.
- Determine required harvest maturity stage and ripening treatments when needed.
- Evaluate processing yields (usable product per kilogram of intact fruit or vegetable, processing time per kilogram of prepared fresh-cut product, etc.).
- For those cases in which a cultivar is preferred though it may have some limitations, evaluate alternative treatments to control undesired browning, softening, or other changes on the fresh-cut product.
- Determine expected postcutting shelf life of the final product at handling temperatures.
- Study product compatibility among products for mixed fresh-cut fruits or vegetables.
- Seek possible suppliers, production sites, agricultural practices, traceability possibility, product quality, and availability throughout the year.
- When possible and convenient, evaluate product response to mechanization to reduce processing time, reduce contamination risks, and improve yields.

7.4.2 PREHARVEST PRACTICES TO IMPROVE INTACT PRODUCE QUALITY

Genetic material, sowing, growing conditions, light intensity along production period, pruning, product thinning, harvest maturity, nutrients and water supply, soil quality, fertilization, weeds control, and pest management affect product quality together

with climate conditions (Hodges and Toivonen 2008; Kader 2008). Thus, careful production plans must be implemented, looking to strengthen the preferred characteristic of a particular crop and, consequently, the final quality and shelf life of fresh-cut products. The effects of some preharvest practices are provided in advance.

Crop rotation is recommended for its positive effect on product quality contrast with the decay inoculum of soilborne fungi, bacteria, and nematodes which would build up with repeated cropping of the same vegetable in the production fields (Crisosto and Mitchell 2002). Fruit size and yield are affected by fruitlet thinning, position inside the tree, pruning, and other cultural practices according to the same authors.

Irrigation is very important for all crops, because plants tissues need water to live. Low water supply might stress product and increase its sensibility to sunburns, alter maturation processes in pears, and provoke a leather-like texture on peaches, while moderate water stress can reduce fruit size and increase soluble solids content, acidity, and ascorbic acid content (Kader 2002a). Gelly et al. (2003) also reported that deficit irrigation on peaches (*Prunus pérsica* L.) increased soluble solids content and helped to maintain fruit color longer. On the other hand, excess water stress could lead to cracking failures in cherries, apricots, tomatoes, and other products; reduce firmness and soluble solids content; and cause an increased susceptibility to mechanical injuries due to an excess of turgidity (Kader 2002b). Plants can also be stressed because of salt presence in irrigation water. Kim et al. (2008b) evaluated stress due to water salinity on romaine lettuce (*Lactuca sativa* cultivar Clemente). Sodium chloride concentrations above 100 mM resulted in 1.5- to 3-fold reduction of lettuce height and weight, as compared with control treatment without salt. Color losses increased with sodium chloride concentrations.

Carotenoids and phenolic compounds contents are also affected by irrigation with salt water. The number of days before harvest at which irrigation is stopped also influenced product quality in Iceberg lettuce, as observed by Fonseca (2006), who found out that when irrigation was stopped 4 days before harvesting instead of 16 days, the product weight and diameter were larger, but the aerobic bacteria counts increased, resulting in faster deterioration of the quality of the product. For intact tomatoes, Kim et al. (2008a) found a 30% increase in lycopene and vitamin C content when they were irrigated with salt water, though phenolic compounds content was not affected. Type of substrate also affects quality attributes.

Fertilization affects both quality at harvest and postharvest shelf life of fruits and vegetables. Nutrients should be balanced, because deficiencies or excesses can favor physiological disorders and reduce product quality and shelf life. High nitrogen fertilization is used to increase product size, but it can reduce volatile compounds production and promote changes in product flavor; other elements also show opposite response, such as high levels of potassium, which can reduce color disorders, while high levels of magnesium can increase them (Crisosto and Mitchell 2002). Plant nutrition differences can affect product size, firmness, and weight loss susceptibility. Calcium has been associated with a reduction of respiration rate and ethylene production, firmness increase, and ripening and deteriorative reactions slowdown (Kader 2002b).

Hodges and Toivonen (2008) compared quality attributes of tomato slices grown in hairy vetch and black polyethylene mulch and found that those grown in the hairy vetch mulch were firmer and had less water-soaked areas and less increase in electrical conductivity, stresses associated with chilling injuries and membrane damages, respectively.

Calcium chloride sprays have been successfully used to reduce browning core, cork spots, superficial scalds disorders, and external and internal rots on Anjou pears, with an overall enhancement of fruit appearance and an improvement of fruit juiciness and fruit color (Alcaarez-Lopez et al. 2009; Raese and Drake 2000).

Climatic conditions (temperature, rain, wind, light) affect internal quality attributes of the products as well as their susceptibility to handling and processing. The effect of climatic conditions can be partially controlled in the growing areas by shades, drainage, and wind stoppers; they can also be precisely controlled in greenhouse plantations. Jolliffe (1996) found an important reduction on skin chlorophyll content and shelf life for low light intensity on greenhouse-grown English cucumbers; such a reduction can be avoided by the use of supplemental light during growing which increases product yields, external and internal quality of many vegetables, including dry matter content and skin chlorophyll content on cucumber, higher ascorbic acid and sugar content in tomato, and better head firmness on lettuce (Hovi-Pekkanen and Tahvonon 2008).

There is a trend in Europe and Latin America to start moving from traditional growing to protected areas cultivation for better control during produce growing. A wide range of simple and complex technologies are used to control temperature, relative humidity, and irrigation control, and more recently, floating trays with a nutrients solution supply were incorporated, and small leaves grow with a significant reduction in nitrates accumulation and microbial load, two characteristics appreciated for fresh-cut processing (Rodríguez-Hidalgo et al. 2006).

7.4.3 HARVEST AND MATURITY INDICES

Stage of maturity at harvest is critical not only to assure product quality and shelf life of intact fruits and vegetables for the fresh market but also for the fresh-cut industry; it affects product composition, postharvest tolerance to handling and processing operations, and their postcutting life (Kader 2002b; Toivonen and DeEll 2002; Kader and Barret 2004; Martín-Belloso and Rojas-Graü 2005; Kader 2008).

Maturity at harvest influences fruits and vegetables response to processing and deterioration reactions. Toivonen (2008) studied the effect of maturity at harvest on the susceptibility of antibrowning treated apple slices to cut-edge browning. He found that the cutting surface of slices from Granny Smith apples picked prior to proper harvest maturity are more susceptible to browning even after commercial antibrowning treatments. Fruit ripeness of pear slices at cutting affected their shelf life (Gorny et al. 2000); it varied from 2 days at 0°C for ripe fruit to more than 8 days for partially ripe and mature-green pears; and it also affected surface darkening at 0°C, which was significantly reduced for partially ripe and mature-green fruit. However, the eating quality of mature-green pear slices exhibited lack of juiciness and aroma.

Harvesting criteria vary among products: how they are to be consumed or processed, distance to marketplaces, intended storage time and temperature, industry

requirements, consumer preferences, and many other parameters. Some produce may be consumed in several stages of maturity, such as mangoes, papayas, and plantains, which have different uses for green-mature and fully ripe products; vegetables are obtained from different parts of the plant, such as leaves, flowers, sprouts, roots, and tubers that reach their best quality attributes at various stages of growth and development of the plant, so there is a wide range of possibilities for harvesting, depending on the final destination of the produce, the desired quality attributes, and their resistance or tolerance to withstand handling and processing.

Maturation or harvesting indices have been set to describe the right time to harvest for better quality and shelf life. Harvest indices must be simple, easy to understand and apply, reliable, the product of an objective measurement, and nondestructive if possible (Reid 2002). Table 7.2 shows maturity indices commonly used for fruits and vegetables harvesting. Production yields and quality parameters of the product are

TABLE 7.2
Maturity Indices Commonly Used for Fruits and Vegetables

Index	Examples
Elapsed days from full bloom to harvest	Apples, pears
Mean heat units during development	Peas, apples, sweet corn
Development of abscission layer	Some melons, apples, feijoas
Surface morphology and structure	Cuticle formation on grapes, tomatoes; netting of some melons; gloss of some fruits (development of wax)
Size	All fruits and many vegetables
Specific gravity	Cherries, watermelons, potatoes
Shape	Angularity of banana fingers; full cheeks of mangoes; compactnes of broccoli and cauliflower
Solidity	Lettuce, cabbage, Brussels sprouts
Textural properties:	
Firmness	Apples, pears, stone fruits
Tenderness	Peas, apples, sweet corn
External color	All fruits and most vegetables
Internal color and structure	Formation of jellylike material in tomato fruits; flesh color of some fruits
Compositional factors:	
Starch content	Apples, pears
Sugar content	Apples, pears, stone fruits, grapes
Acid content, sugar:acid ratio	Pomegranates, citrus, papaya, melons, kiwifruit
Juice content	Citrus fruits
Oil content	Avocados
Astringency (tannin content)	Persimmons, dates
Internal ethylene concentration	Apples, pears

Source: Reid, M.S. 2002. Maturation and maturity indices. In *Postharvest Technology of Horticultural Crops*. Ed. A.A. Kader. University of California. Agriculture and Natural Resources Publication 3311, pp. 55–62. With permission.

taken into consideration, as well as market prices and buyers' requirements. Early harvesting results in low production yields and underdeveloped quality attributes, whereas late harvesting leads to overmature products and excessive postharvest losses.

To develop a maturity index, Reid (2002) suggested the following steps:

1. Determine changes in the commodity throughout its development.
2. Look for features whose changes correlate well with the stages of the commodity's development.
3. Carry out storage trials and taste panels to determine maturity indices that fulfill minimum acceptability and required shelf life.
4. Select maturity indices and assigned minimally acceptable values.
5. Test harvesting indices over several years in several growing locations to ensure that they reflect the quality of the harvested product.

The chosen index or indices should be adjusted for fruits and vegetables to be used for fresh-cut processing, after evaluating their response to process, handling, and storage operations.

Nonfruit vegetables generally include diameter, length, shape, color, firmness and compactness, and other appearance parameters as the main harvesting indices; some examples are asparagus, celery, rhubarb, and okra length; bud size of artichokes; compactness of broccoli, cauliflower, Brussels sprouts, cabbage, and some lettuce cultivars; and color in lima beans, broccoli, collards, and peas.

Color, size, firmness, appearance, and internal quality attributes are used for fruit vegetables harvested, along with observations about natural incision of the fruit to the plant. For instance, for cantaloupes and other melons, stem appearance and how the stem naturally breaks are good indicators for harvesting, together with soluble solids content, aroma, fruit and rind color changes, or even days from bloom. Tomato harvesting indices selection will depend on the use given to the product: They can be harvested mature-green, which are very firm tomatoes, with color changing from green to light green; ripe with full red color and soft, but still firm; or in the middle, known as breaker tomatoes, which are firmer than ripe tomatoes but softer than mature-green and exhibit a pink to red color on the blossom end. Color and firmness are very important parameters for cucumber, eggplant, bell pepper, watermelon, and other fruit vegetables. Asghary et al. (2005) found 'Sensory' muskmelon (*Cucumis melo* L. var. *reticulatus*) harvested at the first stages of yellow color development had higher sugar content, better color, taste, aroma, and market value than those harvested at the mature green stage.

Beaulieu et al. (2004) highlighted tissue softening as a serious problem and limiting factor for fresh-cut products, and listed softening enzymes, decreased turgidity due to water loss, and stage of maturity as the main causes of texture changes. They studied the effect of product firmness on the postcutting sensory attributes of fresh-cut cantaloupe stored at 4°C, prepared from melons harvested at four distinct maturity stages (one-quarter to full-slip), and found that those from three-quarters mature cantaloupes exhibit less firmness loss than those from full-slip maturity fruits. Antioxidant characteristics also vary with cultivars and maturity stage; total

and individual phenolic content, antioxidant capacity, carotenoids, ascorbic acid, and capsaicin content varied among sweet pepper genotypes and maturity stage (Marin et al. 2004; Deepa et al. 2007). Kader (2008) pointed out that nonfruit vegetables have better quality taste when they are harvested immature, while fruit vegetables and fruits get better when they are harvested fully ripe.

Harvesting criteria for fruits also include shape, size, and appearance parameters, but flavor and aroma take an important role. They have great influence on product quality, because aroma-related volatile and nonvolatile compound synthesis increases as the product matures and ripens (Kader 2008). Optimum levels of such compounds do not always match the harvesting criteria, because other parameters have to be considered, such as the type of product, resistance to handling and processing, time required to reach the final market, produce prices, how it is processed or consumed, and others. For apples, harvest date is determined by several parameters, including days from the full bloom as a rough idea of fruit maturity, background color, ease of separation of the fruit from the spur, soluble solids content, starch conversion into sugars, flesh firmness, and internal ethylene concentration (Gast 1994; Toivonen 2008).

For climacteric fruits, proper selection of harvesting indicators is very important, because if fruits are picked prior to physiological maturation, in an early period of preclimacteric stage, fruits quality attributes would not reach desired levels. Robles et al. (2006) studied changes in Ataulfo mangoes as the fruit ripened and found an important increase in total soluble solids and ethylene production rate, accompanied by a gradual reduction of the respiration rate, acidity, and firmness. Maradol papaya, Keitt mangoes, and Red Spanish pineapple give better results for fresh-cut processing, when processed before the full ripeness stage (Hernández et al. 2007), explained by less firmness and color alterations during postcutting storage.

In summary, maturity at harvest affects quality attributes and after-cutting shelf life of intact and fresh-cut produce, and harvesting indices should be adjusted to produce response to handling and processing. Under- or overmature produce results in deficient quality attributes and low yields, while overmature products diminish postcutting shelf life of fresh-cut products and increase susceptibility to deterioration, mechanical damages, microbial spoilage, and other damages.

7.4.4 POSTHARVEST STRATEGIES TO REDUCE UNDESIRABLE CHANGES

7.4.4.1 Use Optimum Storage Temperatures to Reduce Metabolic Activity

Temperature is the most important external factor to control during postharvest handling and storage previous to processing, because it rules most of the changes occurring inside an intact or fresh-cut fruit or vegetable. As the temperature drops, most reactions slow down; hence quality attributes can withstand for longer periods. Optimum storage temperature should always be chosen for intact and fresh-cut fruit and vegetables (Table 7.1). As a general rule, fresh-cut products should be stored at 5°C or below, but the optimum temperature for the intact products could be higher for chilling sensitive fruits and vegetables, and it must be considered for produce storage before processing. Some produce can withstand temperatures near freezing (0°C and below), some need temperatures near 0°C, and those sensitive to chilling

injury disorders cannot be stored at temperatures below 7 to 13°C, depending on the product. Storage at lower temperatures than those tolerated by the intact produce will result in uneven ripening, flavor, and color, and aroma losses, texture changes, and other undesirable changes.

For every 10°C rise on the produce handling temperature in the range from 0 to 30°C, the rates of respiration and deterioration increase two to three times for non-chilling-sensitive commodities (Kader 2002a; Saltveit 2004a). Crisosto et al. (1993) observed that sweet cherry respiration rates of four cultivars rapidly increased from nearly 10 mg CO₂/kg/h at 0°C to 45 to 50 mg CO₂/kg/h at 20°C, though response to temperature varied among cultivars exhibiting differences in fruit sensibility to temperature changes (Crisosto et al. 1993).

Exposure to high temperatures is also detrimental, though some product tissues can tolerate them for short periods; it causes phytotoxic symptoms that lead to accelerated deterioration (Saltveit 2004a). Prolonged exposure to sun in the fields, transportation trucks, or during storage should be avoided to reduce quality losses.

Once the produces are processed, temperature must be held at 5°C to minimize changes on the quality attributes of the fresh-cut products as well as microbial spoilage.

7.4.4.2 Relative Humidity and Water Loss Control

Following temperature, relative humidity is the second factor in importance for quality maintenance. Shelf life and value of fruits and vegetables decreases with water loss because it causes appearance deterioration, tissue softening, wilting, shriveling, and weight loss. Such changes also affect product suitability for the fresh market and the fresh-cut industry, because commodity resistance and yield during processing and handling deteriorate, and it is more sensible to have a shorter shelf life for the product.

Fresh produce are not solid-pack but porous materials filled with their own internal atmosphere, which has a high relative humidity. They lose water through the skin or abscission cuts, because of relative humidity differences between the internal atmosphere and that surrounding the product. Because of this, fresh produce should be stored under high relative humidity environments, as a complement to optimum storage temperature. However, storage requirements vary because water losses also depend on skin and other product characteristics, which make some products more susceptible to losses than others (Table 7.2). Díaz-Pérez et al. (2007) determined water loss relations with intrinsic characteristics of bell pepper, such as fruit size, maturity stage, cuticle thickness, natural wax over the product surface, and reported larger water loss through the calyx or stem scar than from the product skin, as previously reported for eggplants and tomato.

Water loss cannot be completely stopped, but it can be reduced by careful handling and proper storage temperature and relative humidity conditions. Temperature should be as low as the product can tolerate without chilling injury symptoms (Table 7.1), and relative humidity should be higher than 80% for most products, and up to 95% to 100% for products very sensitive to water loss, such as leafy vegetables and strawberries. Packaging materials, produce waxing, and reduced exposure to air movement could also help reduce water losses.

7.4.4.3 Air Movement

Cold air is normally used for produce cooling and storage; it removes heat from the produce and delivers it to the evaporator of the refrigeration system. The faster the air passes through the produce, the quicker the product cools. However, once the product is cold, excess air movement favors water losses, and thus, it should be kept as low as possible to allow proper ventilation without major losses. Adequate package sizes and ventilations and design proper product layout in the storage rooms can help to control excessive exposure to air.

7.4.4.4 Light

Exposure of potatoes to light favors greening during storage because of the production of solanine and chlorophyll. Such changes are undesirable and can be avoided by storing in darkness. Prolonged storage of green vegetables without light could also discolor them. The light effect starts at the fields or greenhouses; light intensity also affects flavonoids, thiamine, riboflavin, carotenoids, ascorbic acid, and other compounds found in fruits and vegetables during growing, thus affecting their composition and nutritional quality (Kader 2002b).

7.4.4.5 Atmosphere Composition

Cells and tissues require oxygen and produce carbon dioxide during respiration. Low oxygen and high carbon dioxide concentration in the atmosphere surrounding the fruit or vegetable can be used to delay deterioration and extend shelf life. Table 7.1 shows recommended atmosphere composition for several commodities; however, product benefits and shelf-life extension can significantly vary among products and cultivars.

7.4.4.6 Ethylene

Ethylene is a plant regulator that affects growth, development, ripening, and senescence processes and postharvest quality (Watkins 2006). Very low concentrations of ethylene in the atmosphere surrounding the product can trigger ripening processes of climacteric fruits and undesirable reactions on some fruits and vegetables, such as color loss and senescence reactions. Sensibility to ethylene varies among products, and changes can be desirable or not, but as a general rule, very low concentrations of ethylene are needed to affect product quality. Controlled application of ethylene can be used for uniform maturation and degreening but should be avoided for long-term storage. As a general rule, ethylene producers must always be separated from ethylene-sensitive products.

7.4.4.7 Handling and Processing

Mechanical damages on fruits and vegetables are caused by impact, compression, and shear and puncture forces applied to the product while harvesting and handling it all the way to the consumer or processing industry. Such damages accelerate metabolic processes and favor microbiological spoilage. Some of these damages symptoms can be detected only after several days of storage, during processing, or during subsequent storage, but they greatly affect product quality, stability, and shelf life. Stress caused by physical efforts during handling should be minimized in order

to supply raw materials suitable to resist further stress processes during fresh-cut processing.

Varoquaux (2002) suggested that peeling and cutting damage product cells and cause an increase of the membrane permeability and, probably, a reduction of phospholipids biosynthesis. These events trigger the reactions of restoration of cellular microstructures and membrane integrity, entail the production of aldehydes of long carbonated chains, cause an increase in respiration rate, and lead to rapid consumption of cellular metabolites and consequent deterioration. However, produce response to stress also depends on the type of fruit or vegetable, its stage of development or maturity, and environmental conditions, and thus, it can vary for a single product, such as kiwi for which ethylene production rise due to cutting stress can be very rapid, or it might take several hours (Varoquaux et al. 2002).

7.4.4.8 Field and Storage Packages

The main function of packaging is to protect fresh fruits and vegetables against mechanical injuries, contamination, or any other damages throughout postharvest handling. Packages should have smooth surfaces and edges, be resistant to staking, have a suitable size and shape for the product, be easy to handle, allow proper ventilation for cooling, and be readily available. Some packages should have water loss barriers or some other special requirement. Packages for fresh fruits and vegetables used for fresh-cut processing are used only to protect the product as it is carried from the fields to the processing plant, and for short-term storage prior to processing.

7.4.5 CONDITIONING AND STORAGE BEFORE PROCESSING

Fresh-cut products quality starts with fresh fruits and vegetables, properly handled during preharvest, harvest, and postharvest. The fresher the prime matter, the better is the final product.

Temporary storage between harvesting and processing also affects the quality and shelf life of fresh-cut products; in general, the longer the delay before processing, the shorter the shelf life is going to be. However, because fresh-cut products are very perishable, lasting between 1 and 2 weeks, temporary storage of intact fruits and vegetables will be convenient. Tropical or template fruits, roots, or tubers, or other vegetables brought from distant markets could be processed at the final market, though some quality attributes could be partially compromised.

As for the cultivar selection, the effect of storage prior to processing should be studied for specific intact fruits and vegetables and their fresh-cut products.

Products to be stored prior to processing should be conditioned before storage or transportation to the market where they are going to be prepared, as a means to preserve their quality. Some common preparation operations include product selection (separation of culls), washing, classification based on quality criteria, stabilizing treatments such as application of growth regulators, antifungal treatments, curing, packaging, and cooling.

Induced fruit ripening could be useful to obtain uniform product characteristics prior to processing. It is generally carried out under controlled conditions of tem-

perature, humidity, and air circulation. Ethylene generator devices yield very good results with banana, tomato, avocado, plantain, and other fruits.

In contrast, application of 1-methylcyclopropene (1-MCP) has been widely used to reduce the action of ethylene in fruits and vegetables. Several authors reported that color changes, tissue softening, and other changes occurring during ripening are substantially delayed (Schouten and Kooten 2004). 1-MCP (1-methylcyclopropene) inhibits ethylene action and ripening reactions. It is applied at 20 to 25°C in low concentrations (2.5 nL/L to 1 µL/L) for 12 to 24 hours, but results depend on cultivar, development stage, time from harvest to treatment, and multiple applications. Effects vary among fruits and vegetables, including delay in respiration rate, ethylene production, volatile production, color changes, chlorophyll degradation, membrane changes, softening, acidity and sugars variation, and development of disorders and diseases. It protects products from endogenous and exogenous sources of ethylene. Chlorophyll degradation and color changes are prevented or delayed in oranges, broccoli, tomato, avocado, and other green vegetables, and volatile development is inhibited in several apple cultivars, apricots, melons, bananas, and other fruits. Product softening is also delayed in fruits such as avocado, custard apple, mango, papaya, apple, apricots, pears, mature plums, peaches, nectarines, and tomato (Blankenship and Dole 2004; Watkins 2006; Manganaris et al. 2008). As product ripening and senescence processes are delayed or inhibited, the product shelf life is increased.

McArtney et al. (2008) studied preharvest applications of 1-MCP in Golden Delicious apples, and they were able to reduce the rate of softening of the fruit during storage.

Storage of intact fruits and vegetables should be carried out at their optimal temperature and relative humidity levels.

7.5 CONCLUSIONS

Intact and fresh-cut fruits and vegetable characteristics have an intrinsic dynamic behavior because they are composed of living tissues that keep changing over time and are influenced by environmental conditions and handling practices.

Initial quality of the intact fruits and vegetables used for fresh-cut processing will fix the maximum attainable quality and after-cutting shelf life of the processed product.

Temperature control and reduction of mechanical injuries of the intact produce before processing are key factors in maintaining their quality and suitability for processing.

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15 Future Trends in Fresh-Cut Fruit and Vegetable Processing

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CONTENTS

15.1 Consumer Demands and Market Development	377
15.2 New Approaches toward the Control of Quality and Safety of Fresh-Cut Fruits and Vegetables.....	379
15.2.1 Disinfection Technologies	379
15.2.2 Packaging Technologies	380
15.2.3 Biotechnological Approaches	383
15.3 Summary	384
References.....	384

15.1 CONSUMER DEMANDS AND MARKET DEVELOPMENT

In the last few decades, a tremendous revolution has occurred within the family structure. The inclusion of women in the labor force has caused a radical change in lifestyles, characterized by a dramatic reduction in the times for meal preparation. An increasing number of people have at least one meal away from home, making use of public or private food services. In this context, industrial kitchens need to prepare and cook large numbers of meals in short periods of time, often with limited staff and equipment. At the same time, consumers have become more health conscious about food choices and have developed interest in both fresh and convenience products (Rocha and Morais, 2007).

European nutrition experts agree that consumption of sufficient amounts of fruits and vegetables is key to a healthy diet and can play an integral role in reducing cardiovascular diseases, certain types of cancer, obesity, and diabetes. They are low-caloric food items, but at the same time, they contain remarkable amounts of some minor functional constituents in foods, such as fiber, vitamins, and minerals. They also contain phytonutrients that offer protection against degenerative diseases, leading to lower mortality and increased life expectancy and quality. Encouraging consumers to increase their intake of fruits and vegetables is a

worldwide issue. Nutrition experts have proposed lowering the price of healthy foods to increase consumption. However, increased health information may be a more efficient policy tool than price decrease to increase the consumption of fruit and vegetables. In this regard, the international movement of “five a day” promotes the consumption of fruits and vegetables worldwide and is present in over 40 countries on five continents. The claim for five servings of fruits and vegetables is based on the daily minimum consumption recommended by the scientific and medical community in a healthy diet. Great importance is being placed on consuming fresh products as part of a broader emphasis on health. Despite increasing knowledge about the health benefits of diets high in fruits and vegetables, many consumers’ diets are still deficient in the recommended intake. Americans consume only half as much as recommended by the Food Guide Pyramid. In Southern European countries, trends show that diets are moving away from the traditional “Mediterranean diet” based on fruit and vegetables, bread and other cereals, olive oil, and fish consumption (Rodrigues and de Almeida, 2001).

This scenario created the challenge, and also the opportunity, for the introduction to the markets of new products like fresh-cut fruits and vegetables as a way to increase the consumption of fruits and vegetables to the recommended levels for a healthy diet. Fresh-cut produce meets the expressed consumer desire for convenience, quality of appearance, and healthy nutrition. A considerable number of fresh-cut commodities are already available in the markets of many developed countries, thus becoming a useful tool for attracting consumers and boosting the intake of fruit and vegetables servings. Minimally processed products are one of the major growing segments in food retail establishments (Soliva-Fortuny and Martín-Belloso, 2003). At the top of the freshness tree, products labeled as “organic” stand out from the rest, corresponding to produce that has been grown without the aid of chemicals and delivered free from preservatives, with emphasis on the purity of the product and the effectiveness of the packaging that protects it. Once sold in specialty stores, organic products now rate special sections in a growing number of retail stores. Sales of organic packaged salad mixes, one of the fastest-growing categories, have grown at a rate of 200% over the past three years and show no sign of slowing down.

The market for fresh-cut fruits and vegetables is consolidated in the United States, as well as in some European countries such as the United Kingdom, France, or The Netherlands, whereas in countries such as Spain and Italy, its development is still moderate. The evolution of the North American market is due to the wide array of products and presentations offered, the increase in exhibition space, and the increase in shelf-life of up to 10–16 days for fresh salads. Such a reality differs from that of Spain or Italy, where the shelf-life of fresh-cut salads is around a week. This time difference may be related to technology issues, but especially to the logistic development that allows maintenance of the cold chain. The marketing of fresh-cut fruits and vegetables requires the appropriate combination of technologies for extending the shelf-life of the products, maintaining the sensory and organoleptic characteristics of the original fresh product.

15.2 NEW APPROACHES TOWARD THE CONTROL OF QUALITY AND SAFETY OF FRESH-CUT FRUITS AND VEGETABLES

Much research is still to be done in order to develop technologies that render fresh-cut fruits and vegetables products with high sensory quality, microbiological safety, and nutritional value. In general, it is currently possible to reach a shelf-life of at least 1 week for most refrigerated (5°C) products. However, some commodities would require a shelf-life of more than 2 weeks, so that success in their commercialization can be attained. Variations in quality and shelf-life, safety through the control of temperature and hygiene conditions in a “from farm to fork” approach, and quality of raw materials are some of the main points that may raise concerns by consumers (Artés et al., 2007). Maintaining the correct product temperatures through the entire chill chain is often the most important factor in ensuring quality and safety of fresh-cut fruits and vegetables. These products are often packaged under modified atmospheres, having a relatively short shelf-life and exhibiting high vulnerability to temperature abuses. Thus, maintenance of an adequate temperature as close to 0°C as possible is required to keep the product safe for consumption.

A characteristic feature of fresh-cut produce is the need for an integrated approach, where different aspects, such as raw materials, handling, processing, packaging, and distribution, must be properly managed to make shelf-life extension possible. The intelligent selection of different preservation techniques, without obviating the intensity of each treatment and the sequence of application to achieve a specified outcome, is expected to have significant prospects for the future of minimally processed fruit and vegetables. Unit operations such as peeling and shredding need further development to make them gentle. There is no sense in disturbing the quality of produce by rough treatment during processing, and then trying to limit the damage by subsequent use of preservatives.

15.2.1 DISINFECTION TECHNOLOGIES

In order to minimize microbiological spoilage, and at the same time provide safe and high-quality fresh-cut fruit and vegetables, the industry needs to implement improved strategies for commodities disinfection. Although chlorine is still the most commonly used sanitizer due to its efficacy, cost-effectiveness ratio, and simple use, future regulatory restrictions are likely and will require the development of functional alternatives. In some European countries including Germany, the Netherlands, Switzerland, and Belgium, the use of chlorine in fresh-cut products is forbidden (Carlin and Nguyen-the, 1999). As a consequence, several innovative approaches have been explored for the decontamination of minimally processed fruits and vegetables. These alternatives must satisfy consumers and, at the same time, be compatible with the sensory characteristics of the products to be treated. However, different studies have demonstrated that decontamination treatments such as hydrogen peroxide or acidic electrolyzed water can even enhance the microbial growth rate depending on the product and applied conditions (Gómez-López et al., 2008). Consequently, after some days of refrigerated storage, the benefit of the decontamination can be lost. Hence, microbial populations in decontaminated produce could reach higher

levels than those found in their non-decontaminated counterparts. The use of chlorine dioxide and the cyclic exposure to ozone gas outstand among the alternative treatments for decontamination with a higher potential (Cooksey, 2005; Aguayo et al., 2006). However, the practical implementation of gaseous treatments during storage of minimally processed vegetables packaged in retail bags can pose a problem, because gases have to diffuse to any surface and could be degraded by the food before accomplishing their desired effect. Physical treatments for fresh-cut fruit and vegetables are being considered as alternatives to chemical preservation techniques. Low-dose gamma irradiation is very effective in reducing bacterial, parasitic, and protozoan pathogens in raw foods. Its effectiveness has been proven in fresh-cut carrots, lettuce, and cantaloupe. Ultraviolet light (UV) is a relatively inexpensive and easy-to-use technique for food preservation. The application of high UV dose levels requires continuous UV sources that can operate during long time periods, which could compromise quality due to the consequent damage of the treated tissues. Pulsed light (PL) could be an alternative technology for the decontamination of food surfaces and food packages. This technology consists of the release of short intense pulses of broad-spectrum light. It has been suggested that short pulse widths and high peak intensities may have a competitive advantage over continuous UV treatment systems, especially in those situations where rapid disinfection is required, because the energy density can be multiplied manyfold (Dunn et al., 1995; FDA, 2000). PL can be used in the final steps of minimal processing; however, treatments that effectively penetrate packaging materials are still a challenge to this technology. Gómez-López et al. (2007), Elmnasser et al. (2007), and Oms-Oliu et al. (2010) summarized the main limitations of the PL systems for food applications. According to them, one of the most important limitations of PL treatments is the control of heating, which could substantially impair the quality of fresh-like commodities.

15.2.2 PACKAGING TECHNOLOGIES

Packaging also has a determinant role in the preservation and quality retention of fresh-cut commodities. In recent years, packaging has developed due to increased demands on product safety, shelf-life extension, cost efficiency, environmental issues, and consumer convenience. Different from other fresh foods such as meat and fish, fruits and vegetables continue to actively metabolize during postharvest periods. By matching appropriate film permeation rates for O_2 and CO_2 with the respiration rate of the packaged fresh-cut commodities equilibrium, modified atmosphere packaging (MAP) can be established inside the package. Products are often packaged after flushing with different mixtures of gases (O_2 , CO_2 , and N_2). The use of low O_2 concentrations (1–5%) and high CO_2 concentrations (5–10%) in combination with storage at refrigeration temperatures (optimally 4°C), is proposed as optimal storage conditions for fresh-cut vegetables to maintain sensory and microbial quality. Polyvinyl chloride (PVC), used primarily for overwrapping, and polypropylene and polyethylene, used for bags, are the films most widely used for packaging minimally processed foods. Multilayered films, often with ethylene vinyl acetate, are manufactured with differing gas transmission rates. However, the most difficult task in manufacturing fresh-cut fruits and vegetable products of good quality with a shelf life of several days is that only a few

packaging materials on the market are permeable enough to match the respiration of fruit and vegetables. Packaging films currently available for fresh-cut produce do not have sufficient O_2 and CO_2 transmission rates, especially when the produce has high respiration, and as a consequence, too low O_2 levels and excessive amounts of CO_2 in package headspace are often detrimental to fresh-cut fruit. In addition, most MAP systems are designed for a specific temperature, and films with adequate O_2 permeability, adequate response to temperature variations, or both are rare (Cameron et al., 1995). Thus, changes in the environmental temperature create a specific problem in MAP systems because the respiration rate is more influenced by temperature changes than is the film permeability used to obtain the modified atmosphere. Packaged fruits and vegetables are usually exposed to varying surrounding temperatures during handling or retail display, resulting in decreased O_2 and increased CO_2 levels inside the package due to a rise in the respiration rate of the product. Due to this fact, it is difficult to maintain an optimum atmosphere inside a package when the surrounding temperature does not remain constant. In designing MAP systems for fresh-cut commodities, it would be prudent to realistically evaluate the time and temperature conditions that the products will likely encounter along the postharvest chain, as well as the likelihood of mixed load conditions. It then will become possible to design systems such as a combination MAP that can maintain optimum atmospheres throughout the postharvest handling chain (Brecht et al., 2003).

To address some of the limitations of using polymeric films for MAP, active packages are being developed. An active package will respond to environmental changes such as temperature or atmosphere composition, or to physiological changes in the product, which may be indicated by the evolution of volatile compounds such as ethanol or ethylene. Some films allow increasing gas transmission when temperature increases due to a reversible melting of the side-chains in the polymers. These films can be tailor made to match changes in permeation properties to the temperature response of respiration rates of a specific commodity. Other permeation patches may consist of other highly permeable films, microperforation, or a combination of the two. Incorporation of patches may facilitate more precise control of permeation properties of packages. Sachets also can be incorporated into packages (Forney, 2007). Other features are being developed that respond to the environment to modulate gas transmission properties of the package (Cameron et al., 1995). Examples include pores that open to increase gas transmission in response to a rise in temperature. Sachets may contain a variety of substances that can absorb or release gases and provide another mechanism for regulating atmosphere composition and product quality (Ozdemir and Floros, 2004).

The application of superatmospheric O_2 concentrations has also been suggested to overcome limitations of traditional MAP atmospheres. Some researchers have claimed that superatmospheric O_2 concentrations (≥ 70 kPa) can be an alternative to low O_2 modified atmospheres in order to prevent undesired anoxic respiration, inhibit the growth of naturally occurring spoilage microorganisms, and maintain fresh-like sensory quality of fresh-cut produce (Amanatidou et al., 1999; Jaxsens et al., 2001; Van der Steen et al., 2002). Results by Allende et al. (2004) showed that high O_2 atmospheres (80–100 kPa) alleviated tissue injury, reduced microbial growth, and were beneficial in maintaining quality of fresh-cut baby spinach.

Edible coatings can be applied as either a complement or an alternative to MAP in order to improve the shelf-life of fresh-cut fruits. Edible films and coatings may help to reduce the deleterious effects concomitant with minimal processing, not solely retarding food deterioration and enhancing its quality, but also improving its safety due to their natural biocide activity or by incorporating antimicrobial compounds (Petersen et al., 1999). The application of edible coatings to deliver active substances is one of the major advances reached so far in order to increase the shelf life of fresh-cut produce. The functionality of edible coatings can be improved by incorporating antimicrobial agents (chemical preservatives or antimicrobial compounds obtained from a natural source), antioxidants, and functional ingredients such as minerals and vitamins. A technique that can potentially be used to incorporate functional ingredients and antimicrobials into edible coatings for fruits is micro- and nanoencapsulation. Micro- and nanoencapsulation is defined as a technology for packaging solids, liquids, or gaseous substances in miniature (micro- and nanoscale) sealed capsules that can release their contents at controlled rates under specific conditions. Release can be solvent activated or signaled by changes in pH, temperature, irradiation, or osmotic shock (Vargas et al., 2008).

The main problem when applying the coatings to fresh-cut fruits is the low adherence presented by the highly hydrophilic cut surface fruit. Recent studies in the field of edible coatings have focused on the development of new technologies that allow for a more efficient control of coating properties and functionality. To this end, new methodologies have been developed, most based on composite or multilayered systems. Nevertheless, applications to food products are still scarce. One of these new methodologies consists of the development of multilayered coatings by means of the layer-by-layer (LbL) electrodeposition (Bernabé et al., 2005; Marudova et al., 2005; Krzemiski et al., 2006; Weiss et al., 2006). The LbL technique could be used to coat highly hydrophilic food systems such as fresh-cut fruits and vegetables. In the near future, multilayered edible coatings will receive more attention (than single-layer coatings) as they could be specially engineered to incorporate and allow the controlled release of vitamins and other functional or antimicrobial agents (Vargas et al., 2008). A possible multilayered structure could include three layers: a matrix layer (e.g., biopolymer based) that contains the functional substance; an inner control layer to govern the rate of diffusion of the functional substance by allowing its controlled release; and a barrier layer that prevents the migration of the active agent from the coated food as well as controls the permeability to gases. Another approach to improve coating properties is to make nanocomposites by incorporating nanosized clay materials such as layered silicates into biopolymer-based matrices. Rhim et al. (2006) incorporated different types of nanoparticles (montmorillonites, nano-silver, and silver-zeolite) into chitosan matrix, obtaining composites with better mechanical, water vapor barrier, and antimicrobial properties than the traditional chitosan coating. Cellulose nanofibers have also shown good possibilities as reinforcements in composite coatings for food packaging. However, even if these studies seem to be promising, the major concern of the scientific community when incorporating these nanomaterials into edible coatings or food is still unsolved: the lack of studies into their possible toxicity.

15.2.3 BIOTECHNOLOGICAL APPROACHES

Biotechnological approaches have been developing in order to extend the shelf life of fresh-cut fruits and vegetables. Molecular methods for detecting human pathogens or plant genetic transformation may create fruits or vegetables best suitable for minimally processed foods (Rodov, 2007). Fresh-cut fruit and vegetables are typically eaten raw, without thermal sterilization procedures like cooking or pasteurization, and therefore represent a significant food safety challenge (Bhagwat, 2006). Modern biotechnology provides fast and sensitive methods for detecting foodborne pathogens on fresh-cut produce. Real-time polymerase chain reaction (RT-PCR) is probably one of the most popular tools for detecting foodborne pathogens. Various commercially available RT-PCR systems have been tested for recognition and quantification of *Listeria monocytogenes* (Liming et al., 2004) and *Salmonella* spp. (Cheung et al., 2004) on fresh-cut products such as fresh-cut cantaloupe, mixed salads, and cilantro leaves. In addition to PCR techniques, other biotechnological methods were employed for detecting various foodborne pathogens in fresh-cut fruit or vegetable products. Among those methods, enzyme-linked fluorescence immunoassay and immunostrip test (Huang et al., 2005), pulsed-field gel electrophoresis (Francis and O'Beirne, 2006), random amplified polymorphic DNA (RAPD), and restriction endonuclease analyses (REA) (Aguayo et al., 2004). In spite of the impressive progress made in the sphere of molecular diagnostics of human pathogens, the problem of efficient detection and elimination of microbial hazards in fresh-cut foods is still far from its practical solution. Neither sensitivity nor reaction times of the available methods allow online monitoring of raw materials or final products for the presence of pathogens. Its application for fresh-cut produce needs additional revolutionary technological changes. These changes are expected to come from the progress of nanotechnology. Development of inexpensive disposable nanobiosensors will improve food safety control in food chain management, in particular, the rapid detection of foodborne pathogens (Rodov, 2007).

On the other hand, genetic transformation may create fruits or vegetables best suitable for fresh-cut processing. Desirable traits for such genotypes would include inhibited enzymatic browning, firm texture, slow tissue degradation, inhibited senescence, and protection against microbial proliferation. However, prospects of practical implementation of these genotypes depend on their acceptance by consumers. So far, just a few gene-engineering projects have been directly and intentionally oriented to the needs of the fresh-cut industry. Antisense inhibition of polyphenol oxidase (PPO) gene expression suppressed browning potential in apple tissues (Murata et al., 2000, 2001). In lettuce, isolation and characterization of a wound inducible phenylalanine ammonia-lyase (PAL) gene from Romaine lettuce (Campos et al., 2004) may bring more efficient biotechnological control of enzymatic browning in this crop. Inhibition of cell wall degrading enzymes, which are involved in tissue softening, may also positively affect the texture of fresh-cut produce. Antisense suppression of the tomato β -galactosidase codifying genes (TBG4) resulted in fruits that at red-ripe stage were 40% firmer than the wild-type control (Smith et al., 2002). Such tomatoes might be expected to preserve good texture as fresh-cut products and be good candidates for minimal processing. Some benefits can be reached by using transgenic fruits or vegetables with inhibited ethylene production or sensitivity.

Slices of Vedrantais melon with antisense gene for the key ethylene biosynthesis enzyme ACC-oxidase demonstrated better storage performance than those of the wild-type fruit. The advantages of the transgenic fresh-cut melon were expressed as higher firmness, soluble solids content, and acidity; preferable flavor; sweetness; texture; and visual quality (Fonseca et al., 2001). Biotechnology can also render the fresh-cut produce an additional protection against microbial colonization. Modern genomic methods may provide a tool for determining the specific pathogen mechanisms involved in the interaction between plant tissue and pathogenic microorganisms. A study carried out by Palumbo et al. (2005) in fresh-cut cabbage has been one of the first steps on the way to biotechnological modulation of the fresh-cut produce–pathogen interaction.

15.3 SUMMARY

The fresh-cut produce market has experienced a dramatic transformation during the past decade, and the expectations for forthcoming years are encouraging. Vegetables have made up the majority of fresh-cut produce sales, and it is expected that this will continue to be the case. However, the fresh-cut fruit sector started to gain ground during the last decade because technical limitations that precluded the industrialization of fruits are being overcome. However, growth will not happen at the same rate if increased innovation through new products development is not conducted appropriately. The adaptation of the distribution chains to these changing requirements is of vital importance to allow for growth of the fresh-cut industry. Development of tailor-made crops through biotechnology as well as research on novel preservation treatments and packaging strategies are required to continue to boost the progress of the fresh-cut sector in the next years.

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