FACTORS AFFECTING MACADAMIA NUT STABILITY

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INTRODUCTION

The macadamia nut, *Macadamia integrifolia* Maiden & Betche, has become the major tree crop in Hawaii since introduction to the islands from Australia about 100 years ago. Attracted by its unique flavor and texture, consumers have created a growing demand for the roasted macadamia nut. Its increasing commercial value has prompted many growers to produce the nuts. The macadamia nut industry in Hawaii has grown substantially in the last 20 years; 1987-88 in-shell production for the state is estimated at 19.4 thousand metric tons. Farm value of marketed macadamia nuts is estimated at $35.9 million, the crop value ranked third after sugar and pineapple (36). Although macadamia nuts are produced elsewhere, Hawaii continues to be the major producer in the world.

Macadamia belongs to the Proteaceae family and is native to southern Queensland and northern New South Wales in Australia. Botanically, the fruit of *Macadamia* is classified as a follicle. Although the macadamia nut is a seed contained in a follicle, it is commonly referred to as a nut and this term will be used throughout this paper. Edible nuts are produced by two species of the genus, *M. integrifolia*, commonly known as the smooth-shell type, and *M. tetraphyila*, known as the rough-shell type. They differ in tree, flower, and nut characteristics. Presently commercial production in Hawaii is entirely in cultivars of *M. integrifolla.*

The market for macadamia nuts produced in Hawaii has expanded throughout the U.S. Mainland as well as outside the U.S.. Macadamia nuts are harvested, brought to a processing plant, husked, dried, roasted, packaged, and sent out into the marketplace. Macadamia nuts are marketed primarily as roasted, salted kernels. A significant portion of the crop is also sold as chocolate-coated roasted kernel. Chips and diced pieces are used in bakery products and ice cream. A variety of other minor products are also available.

Postharvest quality of macadamia nuts is always a major concern for the macadamia industry. From the time of harvest, macadamia nuts begin to undergo a series of physiological and biochemical changes which can affect quality. Quality characteristics include appearance, aroma, texture, and flavor. Among them, rancid flavor development is the most common form of flavor deterioration. Macadamia nuts are susceptible to rancidity since the kernels have more than 75 percent oil and that oil is mostly unsaturated. The shelf life of macadamia nuts can be defined as the length of time until unacceptable or deterioration is detectable. Some nuts can retain fresh flavor for long periods, while others develop rancidity readily within three months. Such a extremely variable range is not acceptable to processors, marketers, and consumers. Moisture and oxygen were previously identified as factors which affect rancidity development (5, 15). Knowledge of the contribution of harvesting and postharvest handling practices, and other factors which affect rancidity development is still lacking and must be understood for development of suitable handling practices for macadamia nuts.

As a result of successful breeding or selection work in Hawaii, Hawaii macadamia cultivars are recognized for their excellence and are planted around the world. The selection process takes years of testing and evaluating production and processing characteristics. Some characteristics are more easily measured than others. Nut characteristics, such as uniform size, shape, color, and oil content, are included as selection standards for new cultivars. However, one area where knowledge is lacking is shelf life of these cultivars. Few studies have been done on evaluation of oil composition and stability for each cultivar.

Macadamia nuts have an excellent flavor when either oil or dry roasted. Some roasting conditions have been reported to hasten rancidity. Since the majority of macadamia nut products in the market are consumed as either oil or dry roasted, it is

necessary to evaluate roasting methods and conditions and to determine if roasted nuts differ in stability from raw nuts.

Another area where there is insufficient knowledge is in the objective measurement of flavor stability. There is no objective and practical measure of staleness or rancidity that is sufficiently sensitive to be useful. There is also no measure for predicting shelf life of macadamia nuts. Hence, detailed characterization of the factors affecting oil quality and stability and prediction of shelf life of macadamia nuts is essential.

Objectives of this study are:

1. To compare the stability of all commercially-produced cultivars macadamia nuts in Hawaii.
2. To determine the effect of harvesting practices and postharvest handling on the stability of macadamia nuts.
3. To compare the stability of raw and roasted nuts.
4. To determine the effect of roasting conditions on stability of macadamia nuts.

REVIEW OF LITERATURE

Measurement of rancidity

Rancidity is often a problem with edible oils and foods with high oil content. Rancidity is generally defined as the degeneration of fatty acids to produce other volatiles having undesirable flavor and aroma. Rancidity deveiopment is related to changes that result from reaction of oils and fats with atmospheric oxygen (oxidative rancidity), or from hydrolytic reactions (hydrolytic rancidity) catalyzed by lipases from food or by microorganisms. Since rancidity is a sensory state rather than a defined chemical condition, sensory evaluation has been utilized for judging the quality and stability of oils and detecting changes that can affect flavor and aroma acceptance. Sensory evaluation may be the most important and reliable method. However, sensory evaluation is often limited by the panelist's subjective and personal preference. In addition, the procedure is time-consuming, expensive, not always available, and the results can be difficult to reproduce. It is for these reasons that many physical and chemical methods for rancidity measurement have been developed as alternatives to sensory evaluation. Ideally, these methods should correlate with changes in sensory properties of oxidized oils during the entire course of oxidation and they should also be simple, sensitive, inexpensive, and reproducible.

According to Gray (22), the commonly used objective measurements of rancidity in oils can be broadly classified into two methods; static methods which measure the degree of oxidation of oil at a certain moment in time, and dynamic methods in which the oil is subjected to an accelerated aging process and future state of the oil predicted by measuring the response of the oil to oxidative influences in the course of the process.

The analysis of volatiles, peroxide value, thiobarbituric test, and other similar chemical tests for intermediate and end products of oxidation are examples of static methods. The initial and primary products of oxidation are hydroperoxides which are

transitory and break down by further reactions. The oxidized oil can liberate free iodine from potassium iodine (42). The concentration of the peroxides in oil is used as a measure of the extent of oxidation and the results are expressed as peroxide value, the milliequivalents of iodine formed per kilogram of fat. Chemical reaction of the oxidation products of oil with thiobarbituric acid (TBA) results in a red color which can be measured spectrophotometrically. The extent of color change is used as the indication of the degree of oxidation and the level of aldehydes present in the oil.

In dynamic methods, the development of off-flavor through lipid oxidation can be accelerated by increasing temperature and exposure to oxygen. These methods, however, measure the resistance of an oil or fat to rancidity, rather than the rancidity itself. The Schaal oven test involves heating and holding of the sample in an oven with forced draft ventilation at 63°C until rancidity starts (16). The oven test provides an index of keeping quality and keeping-time is measured as the number of days to detect rancidity by sensory evaluation. The weakness of this test is in its subjective measure of rancidity. To obtain consistent results, the test needs to be conducted by qualified taste panelists working under standardized conditions. The Active Oxygen Method (AOM), sometimes referred to as the Swift Test, is a simple and reproducible method for accelerating the time for a fat to become rancid. In the AOM, samples of oil are subjected to aeration in a tube held at a constant temperature (97.8°C) and the extent of oxidation is measured by the peroxide value. The peroxide value is then plotted against time; the induction period is defined as the number of hours required for the sample to reach a peroxide value of 100 meq/kg (2). The AOM is useful for comparing the stability of one fat with another and for determining the relative effectiveness of antioxidants and other treatments designed to improve stability. It is the most widely used procedure for estimating oxidative stabilities of oils. However, this method has a disadvantage of being time consuming and labor intensive. Therefore, attempts have been made to develop alternative tests and improved versions of the AOM.

Rancimat assay

Some of the secondary products of oxidation are volatile and ionic, and the major ionic hydroperoxide decomposition product is formic acid. The volatiles emerging from the oil in the AOM test are carried over into water and the formation of ionic compounds is determined by conductivity measurement. Using this principle, the simplified, automated version of the AOM test was developed by Hadorn and Zurcher (24) to determine oxidative stability of fats and oils. Following additional development work by the same authors, a commercial apparatus, the Rancimat, has been marketed by the Metrohm company.

In the Rancimat, a small amount of oil is heated in a closed vessel at a constant temperature between 100 and 150°C while air is bubbled through the oil. The oxidation of oil is accelerated and volatile products of this reaction are driven off into a second vessel containing distilled water and an electrode to measure conductivity. Increase in conductivity is measured against time, and the time (induction time) required to induce oxidation is graphically evaluated and determined. The curve consists of an induction phase, in which no or little secondary products are formed, followed by an accelerated phase during which a marked increase in volatile reaction products is observed. Induction time is determined by finding the points of sharpest inflection on the oxidation curve by means of a tangent construction. The induction time can be used as a measure of the keeping quality of the oil or the momentary state of oil quality. A longer induction time generally indicates a more stable oil. The reaction conditions for measuring oxidative stability are determined by temperature, air flow, and sample size. Other factors which influence the rate of rancidity are the nature of the oil, the presence of antioxidants, and cleanliness of the glassware.

This method has an advantage over the AOM in the simplicity, automatic evaluation of the secondary oxidation products, and speed. Frank *et al.* (19) compared induction times of vegetable oils (soybean, cottonseed, and corn oil) with various

degrees of rancidity as determined by the standard AOM and by the Rancimat. They reported faster results with the Rancimat (2.5 g sample, 120°C, and air flow rate of 20 liter/hr) than with the standard AOM. The reproducibility of induction times for six identical samples was about ±10 min. Several disadvantages of the Rancimat were pointed out by Rossell (58), namely, secondary oxidation products which might have pro-oxidant activities, are constantly removed. This makes the test less like normal storage.

Zurcher and Hadorn (72) studied the induction times of freshly pressed oil (sunflower, groundnut, rapeseed, soybean, and corn) from various producers for a period of five years. They reported that rapeseed oil and groundnut oil had the longest induction times (approximately 5 hr at 120°C), while sunflower oil had the shortest (about 2.5 hr). Soybean oil was about 3.5 hr and corn oil was about 4.5 hr.

Factors affecting rancidity development in nuts

High quality of nuts can be assured by proper cultural and harvesting conditions. Tree nuts such as pecans develop optimum flavor shortly after harvest and gradually lose fresh aroma and flavor during subsequent storage. The sequence of rancidity development in pecan kernels is described by Woodroof (67) as follows: (a) loss of readily volatile substances such that blandness tends to increase; (b) the onset of oxidation, causing color darkening and the development of a stale aroma and flavor; and (c) hydrolysis of fats, resulting in increases in free fatty acids and the development of an acid flavor. As indicators of quality in pecan kernels, peroxide value and free fatty acid content (acid value) of pecan oils are traditionally used. McGlamery and Hood (49) showed that peroxide values increased with development of rancidity. In another study, Forbus and Senter (17) showed that free fatty acids increased as pecan kernels deteriorated during accelerated storage. Rancidity development can be influenced by chemical composition of nuts such as fatty acid and tocopherols, postharvest handling

practices such as shelling, cracking, drying, roasting of nuts, and subsequent storage conditions such as high temperature and relative humidity.

Fatty acid composition. In many tree nuts oil content is very high, exceeding 70% in macadamia nuts and pecans, 60% in hazelnuts and walnuts, and 50% in almonds. Flavor, nutritional value, and the stability of the oil obtained from nuts are dependent upon the oils which they contain (67). The fatty acid composition can vary with cultivar, year, and growing locations. Mehran and Filsoof (50) found significant differences in the fatty acid composition of different cultivars of almonds from one area in Iran. Worthington *et al.* (69) reported considerable differences in the fatty acid composition of 82 peanut genotypes grown in the same area during three seasons. They observed yearly variations in fatty acids within the same genotype as well as variations in the major and minor fatty acids and suggested the variations were probably due to yearly variations in environmental conditions.

The degree of unsaturation as well as the amount of oil largely determines many of the properties of the oil and nuts (37). Oils containing unsaturated fatty acids (such as oleic, linoleic, and linolenic acids) are particularly prone to rancidity because unsaturated fatty acids have double bonds that are readily oxidized. Polyunsaturated fatty acids are more susceptible to oxidation (60). Crawford and Hilditch (13) reported differences in oleic and linoleic acid content of peanut oil from different sources and suggested that the differences should be reflected in oil stability. Fore *et al.* (18) found differences in the fatty acid composition of oils from the Spanish-, Virginia-, and Runner-type peanuts and evaluated their oxidative stability with the AOM test. There was a trend toward increasing stability with decreasing linoleic acid content among the individual oils and they concluded that linoleic acid was a major factor affecting the stabilities of the oil. They suggested that the high stability of the oils from the Runner peanuts which had the lowest linoleic content also may be due in part to the higher

tocopherol content. The high linoleic acid content of some peanut varieties was also shown to decrease the shelf life of roasted peanut products (70).

Tocopherols. Tocopherols are widely distributed natural antioxidants in plant materials such as nuts, seeds, fruits, vegetables, and grasses. Tocopherols are also rich sources of vitamin E in the human diet. There are eight naturally occurring forms of tocopherols; α-, ß-, γ- and δ-tocopherol and α-, ß-, γ-, and δ-tocotrienol. Distribution of tocopherols depends on the plant material. Some nuts are known to be rich in α-tocopherol. Approximate α-tocopherol content in µg/g lipid for some nuts is as follows; almonds, 350; hazelnuts, 340; peanuts, 110; pistachio nuts, 35; walnuts, 12. Pistachio nuts and walnuts have substantial levels of γ-tocopherols, while α-tocopherol is the major tocopherol in almonds and hazelnuts (20).

Tocopherol content in plant materials can vary with species, variety, stage of maturity, season, time and manner of harvesting, processing procedures, and storage time. Guzman and Murphy (23) found statistically significant differences in α-tocopherol and γ-tocopherol content among soybean varieties. The amounts of α-, γ-, and δ-tocopherols in the soybeans ranged from10.9 to 28.4, 150 to 191, and 24.6 to 72.5 µg/g dry matter, respectively. de Lumen and Fiad (14) analyzed 27 varieties of winged bean oil and found γ-tocopherol to be the dominat form of tocopherol with traces of α-, β-, and δ-tocopherols. The concentration of γ-tocopherol in winged bean oil fell within a wide range of values; 8-130 mg/100 g of oil while most of the samples fell in the range of 23-44 mg/100 g oil. Combs and Combs (12) examined the α-tocopherol and γ-tocopherol levels of different varieties of corn with maturation times ranging from 97 to 138 days. They found that there was no correlation between α-tocopherol content and the time required for maturation but γ-tocopherol declined as time to maturity increased and they suggested that vitamin E activity in corn may be independent of the time required to reach maturity because of the low biological activity of γ-tocopherol.

The stability of oils during processing and storage may depend largely on the relative amounts of tocopherols. However, tocopherols are susceptible to oxidation during the handling and processing procedures and α-tocopherol is least resistant to oxidation.

There are several methods for the determination of tocopherols and the procedures for the analysis was reviewed by Bunnel (4) and Parrish (53). The colorimetric methods such as the Emmerie-Engel method and the bathophenanthroline method have been the most popular. Gas-liquid chromatography (GLC) and thin layer chromatography (TLC) also have been widely used. However, colorimetric, TLC and GLC methods are time-consuming and the risk of losing the tocopherols by oxidation during a series of purification procedures is great. In contrast tocopherol analysis by high-performance liquid chromatography (HPLC) can be carried out quickly and accurately with a small amounts of sample (1). HPLC systems consist of a stationary phase, a mobile phase (liquid), a pumping system, and a detector. The liquid mobile phase, carrying the sample, is pumped through the stationary phase contained in a steel column. Interaction in the sample molecules between the mobile and stationary phases effects sample separation. Detectors, commonly ultraviolet spectrometers, fluorescent, or refractive index detectors, are used with HPLC.

Time of harvest. It is generally recommended that tree nuts be harvested as soon as possible after maturation to avoid quality loss and to minimize loss by molds and insects. Optimum harvesting dates are considered to be the time when the highest quality of nuts is reached. Maturation over a prolonged period of time makes the timing of harvest of nuts such as pecans difficult. In Georgia, pecan kernels reach the highest quality in early October when nuts are in their full size and shell color. After this time, significant color changes (darkening and less uniform color) in the seed coat are found (38). Heaton *et al.* (38) determined sensory scores for pecans harvested at six weekly time periods between October and November for three successive crop years and found

that early harvest provided improved color and flavor stability. They suggested that kernels harvested early will be exposed to less severe weathering conditions such as sequences of wet and dry weather. Resurreccion and Heaton (55) studied the pecans harvested early in the season (before November 1) and those harvested traditionally (after November 1). They found that significant differences existed in color, texture, size, and total fat content between early-harvested and traditionally-harvested pecans. The early-harvested pecans were larger in size and slightly higher in oil content than the traditionally-harvested pecans. They also found that the sensory evaluation panel preferred the texture, flavor, color, and appearance of the early-harvested pecans over the traditionally-harvested pecans.

Storage conditions. Godkin *et al.* (21) studied rancidity development in pecans which were stored at room temperature (24-26.5°C), refrigeration temperature (1.5-4.5°C), and elevated temperature (35.5-51°C). They found that fresh pecans resisted rancidity development at room and low temperatures but rancidity was accelerated as the storage temperature was increased. At the high temperature the pecans dried out and loss of flavor, darkening, and brittleness became noticeable followed by rancid flavor after one-month storage. Woodroof and Heaton (68) found that high moisture in pecans is the most important cause of deterioration and a relative humidity of 65-70 percent is required to equalize the moisture content at 3.5 to 4.0 percent for storage of shelled pecans. Storage stability can be influenced by the chemical properties of pecans; the development of rancidity and decreases in total quantities of phenolic compounds in stored pecan kernels are closely related (61).

Roasting. Many nuts, such as peanuts, hazelnuts, and almonds, are roasted either dry or in oil to improve their flavor, texture, color, appearance, and aroma. Raw nuts are generally soft and largely devoid of flavor and often termed as "soggy", while roasted nuts are crisp and sometimes have a sweet flavor. The roasted nuts are eaten

with or without salt. Roasting is usuaily at 121°C to 176°C. Roasting time varies from 5 to 30 min, depending on the kind and size of nuts and the roasting methods.

The effect of roasting on shelf life of nuts is not weli defined. Yuki *et al.* (71) studied the oxidative deterioration of roasted (oil- and dry-roasted) peanuts and found that roasted peanuts were less stable than raw peanuts when the stability was measured by the peroxide value. They also found that peanuts roasted insufficiently or excessively by either method had higher stability against oxidation than properly roasted peanuts. Peanuts roasted excessively had the greatest stability, suggesting the possible formation of a natural antioxidant compound.

Factors affecting stability of macadamia nuts

Cultivars. Macadamia nut selection and breeding work started in 1934 and have largely been done by the University of Hawaii Horticulture Department and the Hawaii Agricultural Experiment Station (HAES). The macadamia industry in Hawaii is based on seiected cuitivars of *M. integrifolia*. The nuts of *M. tetraphylla* are thought to be inferior in quality to those of *M. integrifolia* and no commerciai cultivars of this species have been developed in Hawaii. After extensive yield trials, quality testing, objective evaluation of trees, nuts, and kernei characteristics, thirteen cultivars have been named: 'Keauhou' (HAES 246), 'Nuuanu' (HAES 336), 'Kohala' (HAES 386), 'Pahau' (HAES 425), and 'Kakea' (HAES 508) (63); 'Ikaika' (HAES 333) and 'Wailua' (HAES 475) (35); 'Keaau' (HAES 660) (32); 'Kau' (HAES 344) (31); 'Mauka' (HAES 741) and 'Makai' (HAES 800) (25); 'Purvis' (HAES 294) (28); 'Pahala' (HAES 788) (29). Seven of these cultivars ('Keaau', 'Kau', 'Mauka', 'Makai', 'Pahaia', 'Kakea', and 'Purvis') are presentiy recommended for commercial plantings in Hawaii (26).

Trees are selected for their vigorous branch growth habits and good productivity (27). Minimum acceptable annual production is 80 to 100 pounds of in-sheil nuts from 10-year-old trees. Trees selected are those which have medium size

nuts with 10 to 20 nuts per raceme, 60 to 85 uniformly sized nuts per pound, and 37 to 45 percent kernel. The types of kernels preferred are uniform in size, round, white or cream colored, and without dark circles or off-color tops, and at least 95% with a specific gravity less than 1.000. Selection criteria for macadamia nut quality are based on a specific gravity method developed by Ripperton *et al.* (56) in which kernels are floated in water and salt brines. Specific gravity is highly correlated with oil content. Grade 1 kernels, with an oil content greater than 72% have a specific gravity less than 1.000 and roast golden with mild flavor and crisp texture. Grade 2 kernels, with an oil content between 68 and 72%, have a specific gravity of 1.000 to 1.025 and roast darker in color with a tendency toward off flavors. The study done by Mason and Wills (48) for Australian macadamia nuts supported Ripperton's method and found linear relationships between specific gravity of raw kernels and sensory flavor, texture, general acceptability and acceptance of roasted kernels. They noted that nuts used in their study were tree-harvested, dried immediately to low moisture, and stored under conditions to prevent deterioration. Therefore, they suggested that specific gravity may not always be a reliable quality index of flavor quality and some commercial handling practices of leaving nuts on the ground several weeks before harvest may affect flavor quality.

The cultivars vary in their performance at specific locations and elevations. Hamilton *et al.* (33) observed a variation in average percent of Grade 1 kernels of 'Keauhou' (HAES 246) from 20 different locations in Hawaii. Percent Grade 1 kernels ranged from 60 to 98.8 percent, indicating a large variability in oil content from location to location. Comparing yield and quality of five cultivars grown at one location for 13 years, Ito *et al.* (40) observed that some cultivars cosistently produced higher yield and a higher percentage of Grade 1 kernels. In macadamia breeding and selection programs, emphasis has generally been placed on development of cultivars that are high-yielding and adapted to locations. The chemical composition and nutritional aspects

of kernels have largely been ignored in the programs except for oil content and very few reports are available in which cultivars have been compared.

Fatty acid composition. Fatty acid composition of macadamia nut kernels has been reported (3, 5, 45, 59). Although reported fatty acid composition differs slightly in minor details, authors agree that macadamia kernel oil is highly monounsaturated, basically oleic (approximately 60%), with very little linoleic acid (2%), and no linolenic acid. It is also high in palmitoleic acid (20%). Only minor differences in fatty acid composition were found for the two species of macadamia nuts. Saleeb *et al.* (59) found that the two species had the same oil content but a higher unsaturated to saturated fatty acid ratio in *M. integrifolia* than in *M. tetraphylla*. Rosenthal *et al.* (57) reported slightly higher levels of unsaturated acids in a natural hybrid of *M. integrifolia* and in *M. tetraphylla*, 'Beaumont', than in an Israel cultivar 'Yonik' (*M. integrifolia*). They also found that kernels of *M. integrifolia* were more resistant to rancidity in accelerated oxidation tests than those of 'Beaumont'.

Tocopherols. Wang (64) analyzed tocopherols in macadamia kernels using thin-layer chromatography and studied whether some factors influenced tocopherol content. He found that α-tocotrienol (major) and α-tocopherol (trace) were the two tocopherols present in macadamia nuts. The average tocopherol content ranged from 6.4 to 18.0 µg/g dry matter. There was no significant difference in α-tocotrienol content between kernels from different trees of two cultivars, 'Keauhou' (HAES 246) and 'Ikaika' (HAES 333), at two elevations (150 and 240 m). The α-tocotrienol content decreased with increasing degree of maturity when calculated on the basis of µg/g dry matter or µg/g lipid and it also decreased slightly when the nuts were left on the ground for 3 months. Macadamia kernels picked from the tree had slightly higher α-tocotrienol content than those picked from the ground. The tocopherol content of dry- and oil-roasted kernels was studied and the results showed that there was no difference in α-tocotrienol content of kernels before and after roasting and kernels roasted by the two methods. Because of

very low tocopherol content in macadamia nuts and no significant effect of several factors on α-tocotrienol content, Wang concluded that tocopherols did not account for the stability of macadamia nuts.

Harvesting method and time of harvest. Mature macadamia nuts drop to the ground and are harvested from the ground either by hand or mechanically. In a few situations, shake-harvesting is used. In Hawaii, about 90% of the macadamia nut crop is harvested between mid-September and mid-December with the peak in October, while in Australia harvesting usually extends from March to June. Cavaletto *et al.* (6) noted that mature nuts remain on the tree for some time. As an alternative to ground-harvesting, shake-harvesting to promote nut dropping and tree harvesting can be used to harvest the nuts directly from the tree. Monroe *et al.* (52) showed that macadamia nuts could be harvested from the tree early in the season with the resulting kernel quality and yield comparable to that from a series of ground harvests over a 3-1/2 month period. A study done in Australia also showed that macadamia nuts harvested from the tree at four harvest times were of equal quality to those harvested from the ground (46). However, nuts harvested early in the season were of lower quality in terms of size and roasted flavor, regardless of the harvest method.

Harvest intervals reported for macadamia nuts vary from once a week when the weather is wet to once a month when dry (30, 34). In commercial practice, this interval may extend to two to three months particularly in the off-season. Other factors besides weather conditions to be considered in determining intervals of harvest are labor availability, loss by rats, insect and wild pig damage, mold development, and germination. Shigeura and Ooka (62) reported that an interval approaching four weeks was a good starting point, shortening or lengthening the period to suit conditions of the area. Mason and Wells (47) found that eating quality and storage life of macadamia nuts left on the ground were not affected by up to 4 weeks before harvest; exposure to

sunlight was probably the main cause of quality loss. However, loss of eating quality due to time on the ground (0 to 5 months) was not clearly demonstrated.

Postharvest handling and storage. Macadamia nuts should be husked within 24 hr after harvest or ventilated with forced draft air to reduce the opportunity for heat buildup caused by respiration. At harvest, mature kernels normally contain up to 25% moisture. After husking, nuts are dried to 1.5% kernel moisture or lower to prevent quality deterioration. Alternatively the nuts may be dried to 5 to 8% kernel moisture and cracked, followed by kernel drying to 1.5% or lower. Prichavudhi and Yamamoto (54) studied moisture-drying temperature relationships for macadamia nuts. High-moisture nuts dried at high temperature developed dark brown centers when roasted, the result of high reducing sugar content. They recommended initial drying of freshly harvested nuts at 38°C or lower to reduce kernel moisture to at least 15% before drying temperature is increased. Initial low-temperature drying appears to reduce the total sugar content. After completion of drying, kernel moisture should be 1.5% or less.

Nut stability is largely related to kernel moisture and storage of high-moisture nuts is not desirable because respiratory activity may result in increasing temperature and deterioration of kernel quality. Chu *et al.* (11) reported that quality deterioration of moist macadamia nuts was largely due to action of respiratory, lipolytic, and proteolytic enzymes. They also showed that oxidation and lipolysis caused heating of stored nuts and increase in free fatty acid content in the nuts. Under storage conditions of high temperature and high relative humidity, mold growth and lipolysis occur in high-moisture in-shell nuts (39). Cavaletto *et al.* (5) found that raw kernels with moisture content of 2.3% and 4.3% had poor storage stability. Flavor deterioration of kernels with 2.3% moisture occurred after 4 months storage at ambient temperature. At the higher moisture level (4.3%) and at higher storage temperature (38°C), the flavor changes occurred more rapidly. In addition to the flavor changes, reductions in total sugar and increases in reducing sugar and free fatty acid content were detected in

these kernels. At a lower moisture level (1.4%), only very small changes were found in flavor and chemical composition after 16 mo, regardless of storage conditions. For maximum kernel stability, kernels should be dried to 1% moisture or, if at higher moisture levels, stored at low temperature, preferably -17.8°C (5). Dela Cruz *et al.* (15) reported, in a parallel study on roasted nuts, that kernels with more than 2% moisture did not have the desired crisp texture, browned too rapidly, and had reduced shelf life.

Packaging, which forms as a moisture barrier, protects nuts from quality loss over a long period. Cavaletto and Yamamoto (9) reported that shelf life of 6 to 7 months can be expected when kernels are packed in flexible materials with a water vapor transmission rate of 0.02 g/100 sq in/24 hr at 90% relative humidity and 38°C. Macadamia nuts in cans and jars are normally vacuum sealed to exclude oxygen to reduce possibility of oxidative rancidity.

Roasting methods and stability of roasted nuts. Many roasting methods have been tried to improve the keeping quality of macadamia kernels. Dry roasting can be done with several types of roasting equipment such as a heated rotating drum, a perforated rotating drum with hot air flow, and a continuous mesh belt moving through a heated chamber. Time and temperature for dry roasting vary considerably with roaster design (34, 44). In general, dry roasting requires a longer cooking time to give a good roasted color than oil roasting. Moltzau and Ripperton (51) recommended roasting macadamia kernels in refined coconut oil at 135°C for 12 to 15 min for *M. integrifolia* and at 127°C for 12 min for *M. tetraphylla*. This method is widely used at the present time. Hamilton and Storey (34) reported that macadamia nuts can be cooked in vegetable oil at a temperature between 127°C and 143°C for 8 to 15 min. They suggested that the exact amount of time necessary for cooking is determined by the color of the kernels rather than by a definite time interval. On the other hand, Leverington (43) suggested that the time/temperature relationship is the most important factor in the prevention of

rancidity. Leverington reported that oil-roasted kernels had much shorter shelf life than dry-roasted kernels and the development of rancidity in kernels oil roasted for less than 12 min at temperatures in excess of 135°C was due to the difficulty of controlling the temperature and cooking time, resulting in the inside of the kernel being incompletely cooked even though the outside had desirable brown color. Leverington also suggested that the general perception of the poorer keeping quality of *M. tetraphylla* than that of *M. integrifolia* was the result of the lower cooking temperature normally used for the former type. Leverington reported that the slower cooking employed in dry roasting tended to reduce the development of rancidity. Winterton (65) used the TBA test to compare the shelf life and stability of kernels dry roasted 127°C for 25 min and kernels oil roasted at the same temperature for 15 min. He found that both kernels had a shelf life of 38 days and roasting method did not have any effect on the development of rancidity. However, in a subsequent study, Winterton (66) reported that kernels dry roasted at 127°C for 25 min had higher stability than kernels roasted at 135°C for 20 min. Both authors suggested higher stability of dry-roasted kernels over oil-roasted kernels and better stability obtained by slow roasting at lower temperature, but they did not give any specific reason for their findings.

It is reported that moisture content is of a primary importance for stability of roasted macadamia kernels. Kernels with greater than 1.5% moisture do not have the desirable crisp texture after oil roasting and tend to become rancid (51). Kernels with higher moisture in the raw state were shown to develop roasted color more quickly than dry nuts and to have reduced shelf life. In a study by Dela Cruz *et al.* (15), kernels with 2.3 and 4.3% moisture were roasted 13 and 8 min respectively at 127°C, while kernels of 1.5% moisture were roasted for 15 min to achieve the same color. The decrease in roasting time was probably due to the higher reducing sugar content in the higher-moisture nuts (5). Cavaletto *et al.* (7) reported that oil roasted kernels prepared from in-shell nuts that had been dried to 1.2% kernel moisture and stored for 12 mo had

flavor stability and shelf life comparable to those of roasted kernels prepared from freshly harvested nuts. However, roasted kernels prepared from nuts stored in-shell at 3.8% moisture and stored for 12 mo had poor flavor quality and reduced shelf life. Exposure of roasted kernels to moisture, air or a combination of two may cause rancidity development (15).

Cavaletto and Yamamoto (9) studied the effects of roasting oil quality on the stability of roasted macadamia kernels and found that there was considerable exchange of fats occurring between the macadamia kernels and roasting oil (coconut) during roasting when the same roasting oil was used for a period of up to 13 weeks. However, shelf life and flavor of the oil-roasted kernels were little affected by use of either fresh or used roasting oil. Winterton (65) observed similar results.

MATERIALS AND METHODS

Cultivar study

Several 20-year old macadamia trees (*M. integrifolia*) growing at the Waiakea Experiment Station of the University of Hawaii near Hilo, Hawaii were used as a source of nuts. Macadamia nuts for this study were harvested in October 1986 and November 1987. For each year, macadamia nuts were harvested once at the same location. To obtain fresh-fallen nuts, only green husk or partially green husk nuts were collected from the ground. The harvested cultivars were 'Keauhou' (HAES 246), 'Purvis' (HAES 294), 'Ikaika' (HAES 333), 'Kau' (HAES 344), 'Kakea' (HAES 508), 'Keaau' (HAES 660), 'Pahala' (HAES 788), and 'Makai' (HAES 800). 'Mauka' (HAES 741) was not available in Waiakea and not included in this experiment. The nuts were husked immediately after harvest and in-shell macadamia nuts were shipped immediately by air freight to Honolulu. The nuts were placed in a 55-gallon drum which had ambient air flow provided by a small centrifugal fan and air-dried for one week. After air drying, the nuts were dried for 4 days at 38°C followed by 3 days at 52°C in forced draft ovens. Kernel moisture was determined for the nuts harvested in 1987 by drying at 70°C in a vacuum oven at 76.2 cm Hg for 16 hr. The final moisture was approximately 1.2%. The nuts were machine-cracked, sorted for defects, mold, and insect damage, packaged in vacuum-sealed cans and stored at -18°C until analyzed.

A Metrohm Rancimat 617 was used to test the stability of oil pressed from each cultivar. The instrument consisted of a recorder unit, connecting tubing, electrodes, reaction vessels, measuring vessels, joint clips, and measuring cells (Fig.1). After thawing, the kernels were finely ground in a Cuisinart food processor, then wrapped in a nylon cloth (organdy), placed in a stainless-steel cell, and pressed by a Carver Laboratory Hydraulic Press. The pressed oil was centrifuged for 15 min, or until the

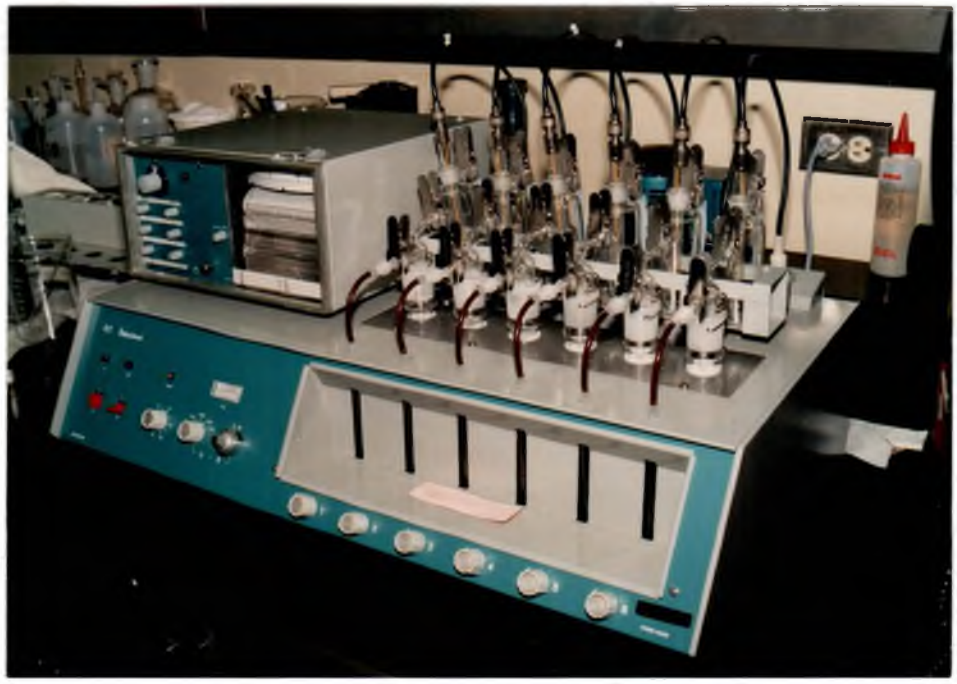

Fig. 1. -- Rancimat apparatus

oil was completely clear, at 47800 RCF (Sorvall, SS 34 rotor 20000 RPM). A two and a half gram sample was weighed directly in the reaction vessels. The vessels were then heated to 130°C and the air flow rate was 20 liter/hr. The samples were run until the induction time was determined.

The type and amount of tocopherols for each cultivar were determined by High-Performance Liquid Chromatography (HPLC). Amino-bonded silica was used as the stationary phase (Rainin, Dynamax column 25 cm X 4.6 mm). The solvent system employed was 0.7% 2-propanol in hexane. The solvent was filtered through a 0.5 micron filter. The flow rate was 2 ml/min. Detection was by fluorescence excitation-emission on a Perkin-Elmer MPF-44A equipped with a flow cell. The excitaion wavelength was 295 nm (slit width 6 nm) and the emission detection 340 nm (slit width 12 nm). The chromatogram was recorded on a Hewlett-Packard 3392A integrator. Two grams of the cold-pressed oil were diluted to 10 ml with 2, 2, 4 trimethyl pentane in a volumetric flask. One ml of this solution was filtered through 0.45 micron HPLC sample filters (Gelman) which had been preconditioned by elution with 2 ml of trimethyl pentane. A twenty microliter injection loop was overfilled for analysis. To quantitate the tocotrienol, a standard of 0.5 µg/ml α-tocopherol was prepared. The twenty microliter sample loop was overfilled with this standard solution as a reference.

Concentration of tocotrienol was calculated by as follows:
Area of sample x standard concentration (µg/ml) / Area of standard x sample concentration (g/ml) x 1000 = concentration of tocotrienol (µg/g), whereas 1000 = conversion factor from µg to mg.

Harvest-interval storage study

Green husk macadamia nuts, 'ikaika' (HAES 333), were collected in January 1987 from MacFarms of Hawaii at Honomalino on the Island of Hawaii and shipped to

Honolulu immediately after harvest. One fourth of the macadamia nuts were husked and air-dried for one week, dried for 4 days at 38°C then for 3 days at 52°C in forced draft ovens until the kernel moisture was about 1.2%. The nuts were cracked, vacuum-packaged, and stored at -18°C. The remaining unhusked nuts were placed in a cleared area beneath a macadamia tree at the Waimanalo Experiment Station. Black screen was placed about 15 cm over the nuts to provide shade and prevent naturally falling nuts from entering the experimental lot. Nuts were collected randomly after 1, 3, and 6 months on the ground. They were husked and processed as described above. The moisture content was measured before and after drying. The nuts were packaged in vacuum sealed cans, and held at -18°C until analyzed.

At each harvest interval (0, 1, 3, and 6 months), stability of the pressed oil was tested by the Rancimat as previously described.

Changes in kernel color were measured with a Hunteriab Tristimulus Colorimeter Model D25M-9. Thirty whole kernels from each sample were randomly selected and readings were taken on the bottom portion of these kernels. *L* (visual lightness), *+a* (redness), and *+b* (yellowness) values were determined for each sample as a mean of 30 kernels. Reference values for the standard were *L* =78.61, *a* =-2.92, and *b* =22.39 and the specimen port was 13 mm in diameter.

Half of the raw nuts from each harvest were oil roasted in refined coconut oil at 132°C for 13 min in a Hotpoint deep fat fryer. Excess oil from roasted nuts was removed by centrifuging for 2 min in a basket centrifuge. Then 1.6 g coconut oil (mp 43°C) as an adhesive and 1.5 g of Morton's 50/50 flour salt were added per 100 g of nuts. The remaining raw kernels, as well as the roasted kernels, were sealed in cans without vacuum and stored at 38°C for 0 (control), 3, and 6 months to determine the effect of storage on the eating quality of the macadamia nuts left on the ground for a various periods of time. Pressed oil stability of stored nuts was also tested by the Rancimat.

Samples were assessed by an 8-member sensory panel who rated them for the degree of freshness according to a 10-point scale: 10-natural, intense nutty flavor; 9, 8-mild nutty flavor; 7, 6-lacks nutty flavor; 5, 4-stale; 3, 2-rancid; 1-very rancid. The panel, consisting of university faculty and staff of various ages and sexes, was selected on the basis of consistency and ability to distinguish freshness differences in macadamia nuts. Judges were presented whole and half kernels in 2-oz portion cups coded with three-digit random numbers. Samples were presented in random order, each judge receiving 3 or more kernels/sample. Panelists were instructed to sniff and taste each sample. Water was supplied for mouth rinsing. Individual taste booths were utilized in the Department of Horticulture at the University of Hawaii. The booths were painted black and equipped with small sinks. A 25-watt red light bulb illuminated each booth.

At the beginning of the storage study, freshness for raw and roasted nuts was rated for the kernels left on the ground, 1, 3, and 6 months as well as the control. For each of these harvest intervals, freshness was again assessed after 3 months and 6 months at 38°C. At each storage interval, panelists were asked to evaluate the nuts once a day for period of four days.

Analysis of variance was applied to the flavor data from each storage period. Flavor scores were analyzed for differences between treatments, and LSD test was used to determine significance between means.

Color changes in stored (6 months) kernels were measured as described above.

Roasting study

Green husk macadamia nuts, 'Keauhou' (HAES 246), were collected in November 1987 from the Waiakea Experiment Station. The nuts were shipped immediately to Honolulu by air, husked and air-dried at ambient temperature for one week. In-shell nuts were then dried for 4 days at 38°C followed by 3 days at 52°C in a forced draft oven

until the kernel moisture was reduced to about 1.2%. The nuts were machine-cracked, sorted, packaged in vacuum-sealed cans, and stored at -18°C until needed for roasting experiments.

To determine the effect of roasting methods on stability, macadamia kernels were oil and dry roasted at several temperatures and roasting times.

Kernels were oil roasted in refined coconut oil in a J. C. Penney Chef's Pot fryer. Fresh, refined coconut oil was used for roasting and the oil was replaced after a few roastings. About 300 g of kernels were placed in a basket and cooked in oil held at constant temperature. A copper-constantan thermocouple was inserted into the center of one kernel to determine internal kernel temperature during roasting with an Omega digital thermometer. One-third of the kernels were cooked until they were light-roasted. Roasting was continued until the remaining kernels were medium- and dark-roasted. The degree of roasting was determined visually by development of surface color. Color of roasted kernels was also later measured by a Hunter Colorimeter. Excess oil from the roasted kernels was drained and the kernels cooled to room temperature. Kernels with defects such as brown spots or general overbrowning that became apparent after roasting were removed before preparation of the oil samples. Roasted kernels were ground and pressed, and stability of the pressed oil was tested by the Rancimat as previously described.

Dry roasting was done by exposing the kernels to hot air flow in a Precision mechanical oven. A holder, made with galvanized sheet metal, was designed to achieve uniform, fast roasting and installed in the oven (Fig. 2). A single layer of macadamia kernels (300 g) was placed on a perforated panel through which heated air was passed from the bottom. Roasting temperature was held constant and internal kernel temperature was measured by inserting a thermocouple into the center of a kernel. Macadamia nuts were roasted to light-, medium-, and dark color. Roasted kernels were

cooled to room temperature, and the pressed oil was prepared and tested for induction time as described above.

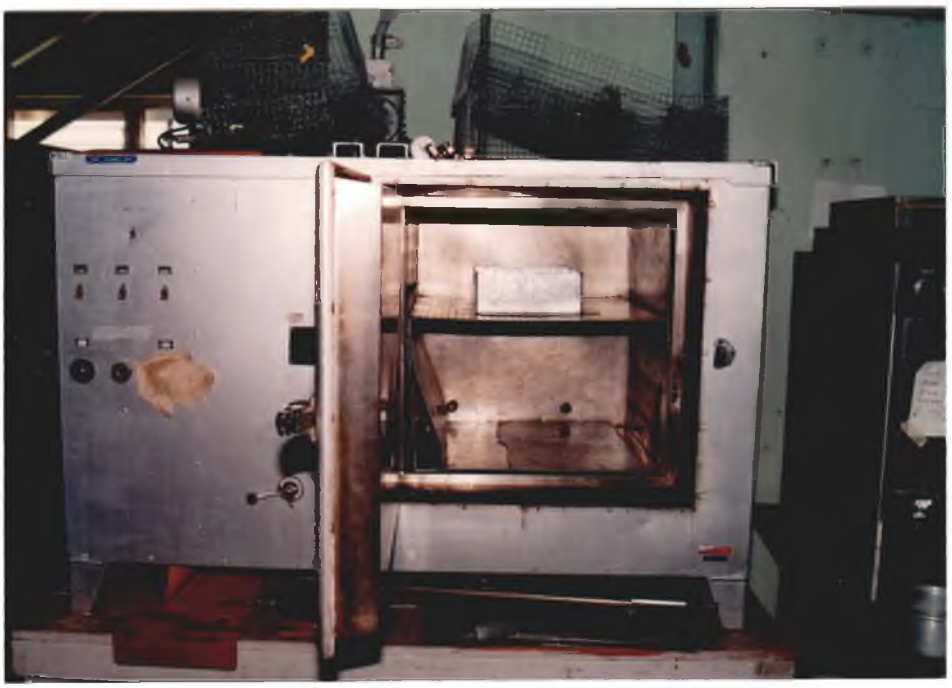

Fig. 2. -- Dry roasting holder.

RESULTS AND DISCUSSION

Cultivar study

Induction time for Hawaii cultivars. Induction times of oils from different cultivars fell into a relatively narrow range between 6 to 8 hours (Table 1). From a preliminary study, pressed oil from freshly harvested macadamia kernels was found to have induction time of 5 to 7 hours, while oil from stale nuts had short induction times of 1 to 4 hours and rancid nuts had no induction time. Therefore, macadamia kernels tested in this study were thought be fresh, and stale or rancid flavor was not detected by informal sensory assessment.

Among cultivars, there were statistically significant differences in induction time. Results were very similar for the 1986 and 1987 trials. According to induction time, Hawaii cultivars can be divided into two groups; cultivars which have relatively long induction times (HAES 246, 294, 344, 660) and cultivars with shorter induction times (HAES 333, 508, 788, 800). 'Purvis' (HAES 294) had the longest induction time of about 8 hours and 'Pahala' (HAES 788) the shortest time of about 6 hours.

Since all cultivars were harvested at the same time from the same orchard and postharvest handling and storage conditions were identical, sources of variation in stability of kernel oils from Hawaii cultivars may be attributed to inherent characteristics of the oil. Variation may be due to the cultivar's adaptability to a particular location, elevation, or weather conditions. Some cultivars are reported to produce better quality kernels at certain locations (33, 40). For example, 'Mauka' (HAES 741) performs well at higher elevations and 'Makai' (HAES 800) adapts well to lower areas. Induction time for cultivars can be utilized to assess quality of kernels at a certain location compared with kernels from other locations, or to compare new cultivars with existing cultivars.

There have been few reports comparing shelf life of macadamia cultivars. Results from the Rancimat assay on kernel oil suggest that cultivars which have a long

Table 1. -- Comparison of the induction time and α-tocotrienol content of Hawaii macadamia nut cultivars.

Cultivar	Induction time (hr)		α-tocotrienol (µg/g oil)	
	1986	1987	1986[z]	1987[y]
246	7.16 b[x]	7.55 a	2.12	1.82 c
294	8.00 a	7.75 a	--[w]	1.77 c
333	6.32 c	6.21 d	1.99	1.33 d
344	7.32 ab	6.82 c	1.84	2.37 b
508	6.56 bc	6.79 c	1.62	2.22 b
660	7.13 b	7.21 b	1.38	2.79 a
788	5.88 c	6.00 d	1.28	1.85 c
800	6.27 c	6.06 d	1.11	1.69 c

[z] Mean of one replicate analyses.

[y] Mean of two replicate analyses.

[x] Mean separation in columns by Duncan's multiple range test, 1% level.

[w] No data available.

induction time (HAES 246, 294, 344, 660) are more resistant to oxidation and might be expected to have longer shelf life than those with shorter induction time (HAES 333, 508, 788, 800). It is necessary to test whether differences in induction time can be translated into shelf life of these cultivars.

Tocopherol content of macadamia nut oil. Using HPLC, small amounts of α-tocotrienol, ranging from 1.33 to 2.79 μg/g oil among cultivars, and a trace amount of α-tocopherol were identified as the tocopherols present in macadamia oil. The result supported the previous finding of α-tocotrienol as a major source of tocopherols in macadamia kernels done by thin-layer chromatography (64), although the α-tocotrienol level was much lower than the reported level of 13.5 μg/g oil. The data show statistically significant differences in α-tocotrienol content between Hawaii cultivars (Table 1).

Correlation of α-tocotrienol contents and induction times among cultivars was poor ($r = 0.64$). An effect of heating on tocopherols during the AOM test for vegetable oils (soybean, corn, safflower, and olive oil) was reported by Kajimoto *et al.* (41). Oils were heated in a glass tube at 180°C for 10 to 25 hrs and they observed decreased oxidative stabilities as a result of the tocopherol degradation. Kajimoto *et al.* suggested that oxidative stability of oils may be dependent upon fatty acid composition of oil as well as amounts of tocopherols. Tocopherol oxidation in a similar condition was reported by Chow and Draper (10). They analyzed the stability of tocopherols in corn and soybean oil heated at 70°C and aerated at 100 ml/min. In corn oil, tocopherol oxidation occurred more rapidly than in soybean oil and 70% of the α-tocopherol and α-tocotrienol disappeared after 9 hr of heating.

The amount of α-tocotrienol alone does not seem to account for differences in induction time in macadamia nut oil from differenet cultivars. Furthermore, because of the very low tocopherol content, it is not likely that the destruction of tocopherols is

directly related to oxidative stabiiity. If natural antioxidants have any effect on stability of macadamia nuts, it may be due to the presence of antioxidants other than tocopherols.

Harvest-interval study

The effect of harvest interval on raw kernels is shown in Table 2. Only small differences were found in induction time for oil pressed from the raw kernels; induction time after 6 months was shorter than after 1 month. The sensory evaluation scores for these kernels showed that kernels left on the ground for 6 months were rated lower than all others. Low sensory score for these kernels may indicate the start of decreasing stability and fresh flavor. However, the differences in induction time and sensory scores between control and 6 mo nuts were so small that oil stability and flavor quality did not seem to be affected greatly by long harvest interval of 6 mo. It should be noted that raw kernels tested in the Rancimat assay and sensory evaluation had been sorted to remove kernels which were immature, moldy, or damaged by insects. Only sound kernels were used for this study. Loss in processed recovery was not recorded in this experiment, but it is estimated that 10 to 20% of the nuts were discarded due to spoilage at each harvest. As the harvest interval increased, a greater number of kernels were lost because of damage. Mason and Wells (47) reported that exposure to direct sunlight as iong as 1 hr/day caused a large quantity of kernels to be rejected when macadamia nuts were left on the ground for 5 mo. However, unhusked nuts were placed in the shade for this study and received no direct sunlight, perhaps contributing to slow changes in stability. Kernel moisture at each harvest and weekly rainfall at the Waimanalo Experiment Station during the experiment are shown in Fig. 3. Changes in kernel moisture generally followed the increase or decrease in weekly rainfall. Kernel moisture at initial harvest was recorded 19%. After one month moisture was reduced to 14%. Kernel moisture of the nuts left on the ground 3 mo increased to 17% because of a

Table 2. -- Effect of time on the ground before harvest on the induction time and flavor of raw macadamia kernels.

Time on the ground (mo)	Induction time (hr)	Sensory score[z]
0	5.42 ab[y]	8.34 a
1	5.84 a	8.44 a
3	5.63 ab	8.47 a
6	5.13 b	7.84 b

[z]Flavor was evaluated on a 10-point scale (10=intense nutty flavor, 1=very rancid).

[y]Mean separation in columns by LSD, 5% level.

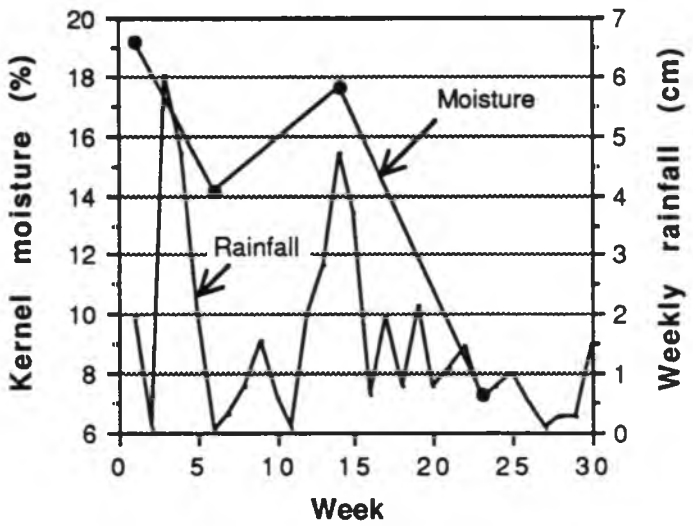

Fig. 3. -- Kernel moisture at harvest and weekly rainfall during the experiment.

Table 3. -- Effect of time on the ground before harvest on the Hunter color values of raw kernels.

Time on the ground (mo)	Hunter color value		
	L	a	b
0	105.27 a[z]	0.34 c	32.72
1	103.30 a	-0.61 d	32.97
3	100.20 b	1.73 b	33.18
6	92.85 c	4.90 a	31.97

[z] Mean separation in columns by LSD, 1% level.

heavy rainfall a few days prior to harvest. After 6 months kernel moisture was reduced to 7% because of dry weather.

The most apparent visual effect of harvest interval was on color of the kernels. The Hunter color values for the whole raw kernels are given in Table 3. As the harvest interval increased, the kernel surface color changed from a light yellow color to darker orangish color (lower *L* and higher *a* values), while yellowness (*b* value) remained relatively unchanged. Macadamia nuts left on the ground for 3 mo had darker kernels with more red in color compared to the control and kernels harvested after 1 mo. Further discoloration of raw kernels was observed after 6 mo at which time darker raw kernels looked similar to the color of lightly roasted kernels. Although the color of the kernel is not the sole means of ascertaining nut quality, it is a limiting factor and it alone can be the basis for rejection. Dark colored macadamia kernels are generally considered unacceptable and white or light yellow color of macadamia kernels is often associated with color at optimum harvest and of freshly harvested nuts. Darkening of the kernel surface occurs with age.

Effect of storage on raw and roasted kernel flavor. Macadamia nuts harvested at different harvest intervals were stored under conditions which would accelerate changes in flavor stability. Raw and roasted kernels were sealed in cans without vacuum and stored at 38°C for 3 and 6 months.

Taste panel results initially and after 3 and 6 months are shown in Table 4 and 5. In the initial taste panel (no storage), raw kernels from nuts left on the ground for 6 mo were rated lower than all others. However, the effect of the long harvest interval that was apparent in raw kernels at the time of harvest disappeared during storage. For roasted kernels, there was variability in the results and neither harvest interval nor storage time had a significant effect on flavor quality. As a whole, roasted kernels were rated higher than raw kernels. This was particulary evident in the first taste panel of the storage period. Since the panel was held soon after roasting, freshly roasted flavor

was probably the most intense. Nonetheless, flavor quality of roasted kernels changed little during the storage. Two possible explanations are; 1) roasted kernels have better flavor stability during storage than raw kernels, or 2) roasted aroma and flavor mask flavor change that occurs in raw kernels.

Effect of storage on induction time of raw and roasted kernels. Induction times of raw and roasted kernels before and after storage are shown in Table 6. Although sensory evaluation did not show that 3- and 6-month storage affected flavor stability, the Rancimat assay showed a statistically significant decrease of oxidative stability in pressed oil from raw kernels after 6 months of storage (Table 6). Rancimat data from the 3-month storage period were insufficient for statistical analysis but indicate that stability loss may have started during the first 3 months of storage and that little decrease in induction time occurred from 3 month to 6 months. For roasted kernels, induction time at the beginning of storage was not tested by the Rancimat. After 6 months of storage, macadamia nuts left on the ground for 3 and 6 months had much shorter induction times than the control and 1-month nuts. This may suggest that freshly harvested nuts have good stability when they are roasted but if harvest is delayed, oxidation in roasted nuts will occur as in raw nuts.

Effect of storage on raw kernel color. The Hunter color values of raw kernels before and after storage are shown in Table 7. The effect of storage was most apparent in darkening of kernel (decreasing *L* value) and a statistically significant difference was found between *L* values before and after storage. Storage of macadamia nuts at high temperature (38°C) resulted in undesirable color changes.

Table 4. -- Effect of time on the ground before harvest on flavor of raw macadamia kernels after accelerated storage.

Time on the ground (mo)	Sensory score [z] Storage (mo) 0	3	6
0	8.34 a [y]	8.13	7.94 b
1	8.44 a	8.75	8.63 a
3	8.47 a	8.34	8.25 ab
6	7.84 b	8.25	7.72 b

[z] Flavor was evaluated on a 10-point scale (10=intense nutty flavor, 1=very rancid).

[y] Mean separation in columns by LSD, 5% level.

Table 5. -- Effect of time on the ground before harvest on flavor of roasted macadamia kernels after accelerated storage.

Time on the ground (mo)	Sensory score [z] Storage (mo) 0	3	6
0	8.81	8.13	8.44
1	8.78	8.44	8.25
3	8.81	8.69	8.28
6	8.59	7.78	7.88

[z] Flavor was evaluated on a 10-point scale (10=intense nutty flavor, 1=very rancid).

Table 6. -- Effect of accelerated storage on the induction time of raw and roasted kernels.

Storage (mo)	Induction time (hr)							
	Time on the ground (mo)							
	0		1		3		6	
	Raw	Roasted	Raw	Roasted	Raw	Roasted	Raw	Roasted
0	5.42	--[z]	5.84	--	5.63	--	5.13	- -
6	3.17	5.50	4.03	5.31	3.69	4.17	3.72	4.25
Significance	* *		* *		* *		* *	

[z]No data available

* *Significant at 1% level in *t* test.

Table 7. -- Effect of accelerated storage on the Hunter color values of raw macadamia kernels.

Storage (mo)	Hunter color value											
	Time on the ground (mo)											
	0			1			3			6		
	L	a	b	L	a	b	L	a	b	L	a	b
0	105.27	0.34	32.72	103.30	-0.61	32.97	100.20	1.73	33.18	92.85	4.90	31.97
6	97.83	0.44	31.66	95.61	1.33	31.73	92.85	2.49	32.43	86.84	4.75	31.91
Significance	**	NS	*	**	**	*	**	NS	NS	**	NS	NS

NS,*,** Nonsignificant or significant at the 5% or 1% level in *t* test, respectively.

Roasting study

Color of roasted kernels. Hunter color values for raw kernels and those oil roasted and dry roasted at 138°C are shown in Table 8. These are in close agreement with visual ratings of degree of roasting (light, medium, and dark). As kernels were roasted, they became darker (lower *L* value) and more red-orange (higher *a* value). Lightly roasted kernels were slightly brown on the surface, but the center of the kernels often remained white, indicating that the nuts were insufficiently roasted. Medium roasted kernels had a good roasted appearance outside as well as inside, and they also had characteristic roasted aroma. Dark roasted kernels appeared overcooked. When kernels were roasted excessively, damaged or immature nuts that were not noticeable in the raw state became more apparent and they were removed prior to the preparation of sample oil for the Rancimat assay.

Effect of roasting method and degree of roasting on induction time. Center kernel temperature during dry roasting and oil roasting at 138°C and induction time for kernels from each treatment are shown in Figs. 4 and 5. For dry roasting, center kernel temperature increased slowly during roasting. It took 8 min to reach 127°C, and 20 min to reach 138°C. On the other hand, kernel temperature increased rapidly in oil, 127°C in 3 min, 138°C in 11 min. Differences in increase of center kernel temperature between two roasting methods indicate that the oil roasting process was much faster. Color development of oil-roasted kernels was also much faster than that of dry roasted. At the same roasting temperature, dry roasting required a longer time than oil roasting to reach a comparable roasted appearance on the kernel surface. Large differences in induction time between roasting methods (oil and dry) and the degree of roasting (light, medium, and dark) were found. Induction time was also different between raw and roasted kernels. Raw kernels (0 min roasting time) from the same lot had an induction time of 6 hr while roasted kernels generally had longer induction time

Table 8. -- Hunter color values of raw, and light-, medium-, and dark-roasted macadamia kernels.[z]

Hunter scale	Raw	Dry roast (Roasting time in min.) Light (12)	Medium (15)	Dark (30)	Oil roast Light (4)	Medium (11)	Dark (17)
L	104.06	91.29	88.70	77.02	93.77	86.15	76.38
a	-0.58	-0.13	2.56	8.61	-1.03	4.28	10.30
b	33.37	33.13	34.57	32.88	33.22	34.58	34.02

[z]Macadamia kernels were dry and oil roasted at 138°C.

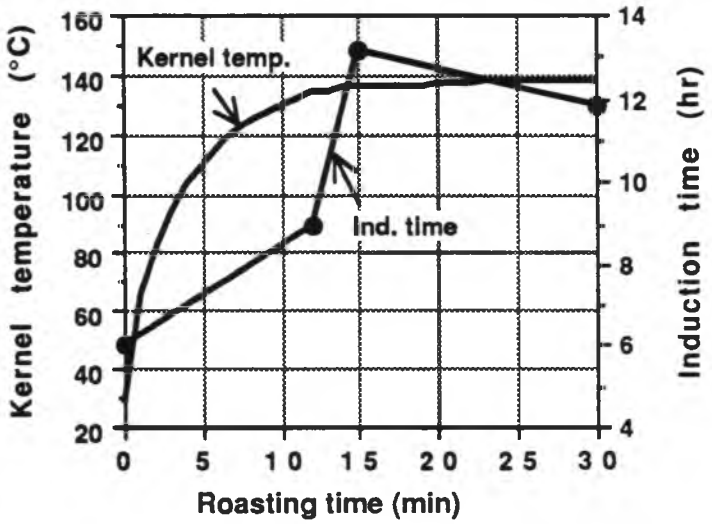

Fig. 4. -- Center temperature of macadamia kernel during dry roasting at 138°C and induction time of dry-roasted kernels.

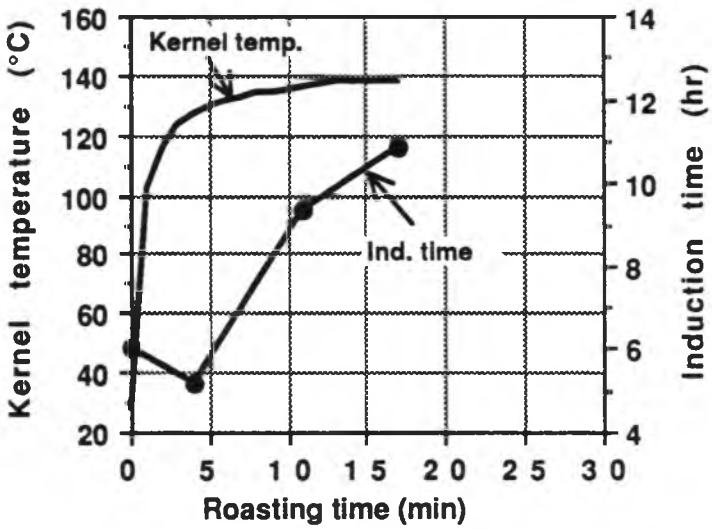

Fig. 5. -- Center temperature of macadamia kernel during oil roasting at 138°C and induction time of oil-roasted kernels.

than raw kernels, suggesting that roasted kernels have higher oxidative stability. Furthermore, dry-roasted kernels showed higher resistance to oxidation than oil-roasted kernels, regardless of the degree of roasting. This result agrees with the previous findings reported by Leverington (43) and Winterton (66). The higher resistance to oxidation in roasted kernels generally coincided with degree of roasting. For light, dry-roasted kernels, induction time was extended to 9 hr and induction time was further increased to 13 hr for medium, dry-roasted kernels. Induction time of dark, dry-roasted kernels was still much longer than raw kernels but slightly shorter that that of medium, dry-roasted kernels. On the other hand, induction time of light, oil-roasted kernels was 5 hr and was shorter than that of raw kernels. Leverington (43) reported that incompletely oil-roasted kernels had short shelf life and became rancid readily. Short induction time of light oil-roasted kernels indicates the decreased stability of these kernels and the result appears to support Leverington's finding. As kernels were roasted, induction time was increased to 9 and 11 hr for medium, and dark, oil-roasted kernels, respectively.

It appears that heat applied to kernels caused increased induction time for roasted kernels. It may be possible that heating promotes formation of antioxidant or prooxidant depending on roasting conditions.

Effect of roasting temperature and degree of roasting in dry-roasted kernels. Induction times of kernels dry-roasted at various temperatures are shown in Fig. 6. There was a general trend that induction time was increased as the degree of roasting increased. Longer induction time was obtained for kernels roasted to medium or to dark color. However, at high roasting temperatures (138 and 149°C) induction time of dark-roasted kernels decreased from that of medium-roasted kernels. Excessively roasted kernels did not have good appearance because they were often too dark and not acceptable for eating. It appears that properly dry-roasted kernels have the greatest stability. This differs with the finding for peanuts reported by Yuki *et al.* (67) that

light- and dark-roasted peanuts were more stable to oxidation than medium-roasted peanuts. The decrease in induction time for macadamia kernels dark roasted at 127°C was not observed. Therefore, a decrease in induction time may be related to the rate of heating at high temperature. Roasting at 116°C and 127°C was very slow and required a long time to obtain good roasted color. At 116°C, kernels were roasted for 30 and 60 min, but the kernels did not develop medium-roasted color at the end of roasting. Induction time of kernels roasted for 60 min was 1 hr longer than those roasted for 30 min.

Effect of roasting temperature and degree of roasting in oil-roasted kernels.

Fig. 7 shows induction time of kernels oil roasted at the same temperature range as in dry roasting. Except for kernels roasted at 116°C, induction times of medium-roasted kernels fell between 8 and 9 hr and induction time of dark-roasted kernels were 10 to 11 hr. The increase in induction time was much smaller than in dry-roasted kernels at the same degree of roasting. The most distinctive difference from induction times of kernels dry roasted at various temperatures was the decrease of induction time for light, oil roasted kernels. This phenomenon occurred in oil roastings at any temperature used in the study. It appears that the decrease of induction time or "dip" started as soon as the kernels were immersed in oil. This is particularly evident in roasting at 116°C. To confirm the presence of this "dip", short roasting periods (2, 6, and 10 min) were used. Two minutes of roasting was long enough to cause a decrease of induction time. Induction time became gradually shorter until kernels were roasted for 10 min. Then, induction time started to increase, but even after 30 min it was still shorter than raw kernel induction time. The results confirm that kernels which are oil roasted insufficiently or at relatively low temperature, tend to have lower stability to oxidation. This findings have a significant implication for the macadamia industry. In practice, macadamia nuts are often lightly oil roasted mainly because lower rejected kernels become noticeable and lower sorting is required. However, this practice may be at the cost of shelf life.

Effect of roasting temperature on induction time. There was a close relationship between center kernel temperature and decrease in induction time for oil-roasted kernels. As shown in Fig. 5, induction time was short for the kernels when center temperature was below 127°C. Induction time increased when center kernel temperature exceeded 127°C. This was also observed for kernels roasted at 149°C. For kernels roasted at 127°C, center kernel temperature reached 127°C in 13 min and remained at that temperature during the rest of roasting. At 10 min of roasting when center temperature was below 127°C, induction time was shorter than for raw kernels. However, induction time increased as kernels reached 127°C. Induction time of kernels roasted at 116°C did not increase, irrespective of roasting time. This suggests that any roasting temperature at or above 127°C will increase induction times; also that the time to reach 127°C and the roasting time/temperature relationship affects induction time of oil-roasted kernels.

However, this relationship was not clearly demonstrated in dry roasting. Lightly, dry-roasted kernels in which center temperature was carefully monitored during roasting were tested for induction time, but induction time was normally either very similar to that of raw kernels or slightly longer and there was no distinctive decrease in induction time as found in oil-roasted kernels.

Exposure to high heat in oil, particularly in the first few minutes of roasting, was thought to cause this reduction. Thus, to obtain a similar oil roasting effect (quick increase in center kernel temperature) kernels were dry roasted at higher temperature than 169°C and induction time were tested for lightly roasted kernels. However, there was no decrease of induction time. In another experiment, kernels were slowly oil roasted at 127 and 138°C by controlling the temperature setting and increasing oil temperature slowly so that similar rate of heating to dry roasting could be obtained. The Rancimat assay resulted in short induction times for light-roasted kernels at both temperatures.

Effect of roasting oil on induction time. Monitoring center temperature of the kernel is a good indicator of the roasting taking place inside the kernel. However, changes that may take place on the surface of the kernel during roasting will not be measured. Cavaletto and Yamamoto (9) reported that considerable exchange occurred between roasting oil and macadamia kernels during roasting. In this study, fresh coconut oil was used for roasting to assure roasting in virtually 100% coconut oil. Induction time of fresh coconut oil was about 14 hr. This is probably due to coconut oil being highly saturated. Induction time of coconut oil after a few roastings did not show any change from fresh oil. To test an effect of roasting oil absorbed by the kernels on induction time, a small amount of coconut oil (up to 30% by volume) was added to oil pressed from roasted kernels. Induction time for oil-roasted kernels (138°C for 13 min) and dry-roasted kernels (149°C for 28 min) was 10 hr and 14 hr, respectively. Induction times of pressed oil with coconut oil did not result in a significant change as an amount of coconut oil added increased, suggesting that the small amount of roasting oil absorbed by the kernel dose not affect its stability.

Effect of oxygen during roasting. Since kernels were completely submerged in oil during roasting, oil roasting was done in the absence of oxygen. On the other hand, dry-roasting was done by circulating constant hot air in the oven. A difference in induction time between roasting methods may have been caused by the absence/presence of oxygen during roasting.

To test the effect of oxygen, macadamia kernels were dry-roasted in a vacuum oven under vacuum or constant flow of argon gas. Because there was no circulation of air in the oven, roasting conditions were not identical to those of previous experiments. It was also difficult to maintain complete anaerobic condition during roasting, particularly in the beginning of roasting. There was no difference in induction time of kernels roasted with or without oxygen.

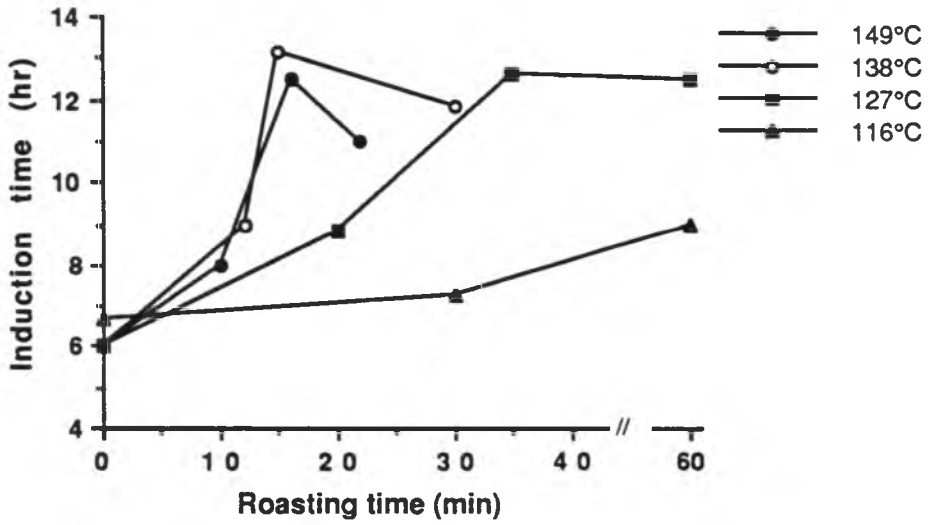

Fig. 6. -- Induction times of macadamia kernels dry roasted at various temperatures.

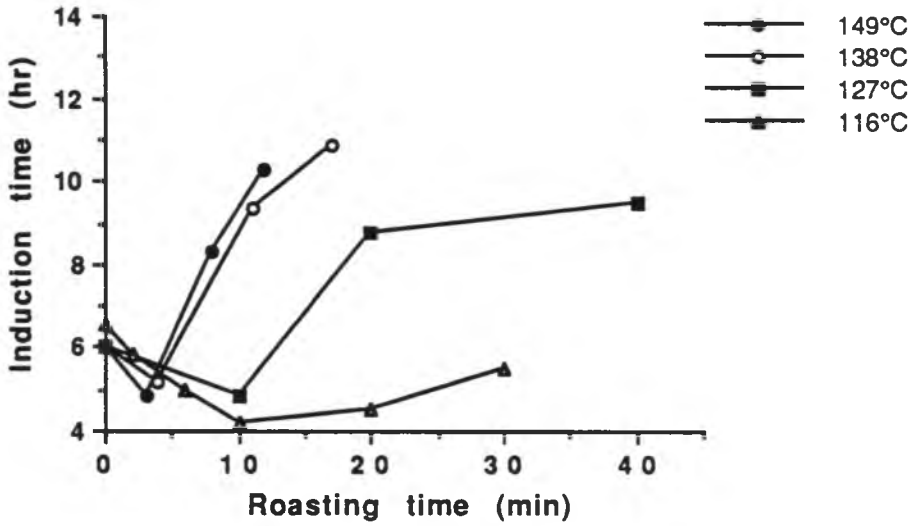

Fig. 7. -- Induction times of macadamia kernels oil roasted at various temperatures.

SUMMARY AND CONCLUSIONS

Factors (cultivar, harvest interval, and roasting) affecting stability of macadamia nuts were studied. Stability of oil pressed from raw and roasted kernels was tested for induction time with the Rancimat apparatus.

A study of the stability of oil from Hawaii macadamia nut cultivars showed that there is a small difference in induction time among cultivars and that a small amount of α-tocotrienol is present in the oil but does not account for stability difference in oil.

A study of the effects of harvest interval on postharvest quality of macadamia nuts showed that a harvest interval of up to 6 month does not markedly affect the stability of their oil. The sensory evaluation of raw and roasted kernels showed little flavor changes due to harvest interval. However, a large number of kernels were rejected due to damage and darkening of the raw kernels resulted in significant quality loss as the harvest interval increased. Accelerated storage of the kernels for 6 months caused a significant decrease of stability of oils pressed from raw kernels regardless of harvest interval but flavor of the kernels were relatively unchanged.

A study of the effects of roasting on the stability of oil pressed from roasted kernels showed that stability of pressed oil was greatly affected by the roasting method and the degree of roasting. The induction time of oil pressed from oil-roasted or dry-kernels increased as the degree of roasting increased. However, the oii pressed from lightly oil-roasted kernels had short induction time. Increase/decrease in induction time may be dependent upon the roasting time and temperature and the roasting method.

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