Hydrogenated Vegetable Oils as Candle Wax

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ABSTRACT: Partially hydrogenated soybean oil, referred to as soywax, is gaining attention as a renewable and biodegradable alternative to paraffin wax for use in candles. However, current soywax candles suffer from several problems, especially poor melting and solidification properties. Fully hydrogenated soybean oil exhibits improved melting properties but owing to its fragile texture, it is not yet acceptable in most candle applications. In the present work, KLX™ (a wax composed of fractionated hydrogenated soy and cottonseed oils) was used as a base material for candles, and the effects of additives such as hydrogenated palm oil (HPO), FFA, and paraffin on the textural and combustion properties were evaluated. Melting and solidification profiles of KLX were better than those of fully hydrogenated soy oil. Adding FFA improved the solidification properties of KLX candles. Adding paraffin improved the compressibility of the wax, while HPO addition decreased hardness and compressibility. Changing the candle diameter and/or wick size along with changing the wax composition resulted in candles with desirable quality attributes.

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KEY WORDS: Beeswax, candles, cottonseed oil, DSC, hydrogenated oil, paraffin wax, soybean oil, soywax, texture analysis, thermal imaging.

Overabundance in the world supply of vegetable oils and the limited supply in petroleum resources provide impetus to the candle industry to use waxes based on vegetable oils. The annual U.S. market for paraffin in candle applications has been estimated at 1 billion pounds (1). This is equivalent to about 5% (w/w) of the current soybean oil production in the United States.

Partially hydrogenated soybean oil, referred to as soywax, has recently been used for manufacturing candles (2,3). Major problems with soywax are the greasy surface texture and the brittle structure of candles made of soywax. Also, poor melting and re-crystallization properties of soywax result in delayed re-solidification and therefore excessive dripping of the wax. Consequently, the use of soywax has been limited to container and large-diameter pillar-type candles. Proper hydrogenation of soybean oil may improve its melting and solidification properties for use as candles.

The melting and re-solidification properties of the wax components considerably influence the candle's acceptability. Although materials with lower m.p. create larger burning pools, materials with unnecessarily low m.p. can cause uncontrolled dripping of the candle wax with taper- and pillar-type candles. Not only does this create a wax spillage problem, but also the life of the candle is reduced and there may be a fire hazard as well. Furthermore, the wick can be drowned and consequently the flame can be extinguished in container-type candles.

Many small-scale candle-manufacturing companies are applying the traditional methods of candle preparation. In response to the growing demand for hand-crafted candles based on hydrogenated vegetable oils, the number of these companies is also growing. In such operations, it is critical to avoid cracking the candles during manufacturing. One approach to reduce cracking is to disrupt the natural crystalline structures of the waxes by adding other components whose presence inhibits crystal formation but does not interfere with the burning properties of the wax. Although large-scale industrial operations (injection molding) may not involve the traditional melting and pouring stages, problems associated with the re-solidification of melted wax such as flowing liquid wax as a result of improper composition of the waxes and/or channeling (a phenomenon caused by a breakdown in the solid structure) need to be overcome.

To change melting, solidification, and/or crystallization behaviors of vegetable waxes and to reduce the structural deficiencies of candles, FFA, paraffin, and other vegetable oils with different melting and solidification properties may be added. We hypothesized that supplementing a properly hydrogenated vegetable oil product with an appropriate additive can improve its melting and crystallization properties and result in better textural and combustion properties. Therefore, the objective of this work was to evaluate the effects of FFA, paraffin, and hydrogenated palm oil on the thermal, textural, and burning properties of vegetable-based waxes.

EXPERIMENTAL PROCEDURES

Materials. Soft paraffin with a broad melting range (25–80°C) and hard paraffin with two melting peaks at 32 (minor) and 49°C (major) were obtained from Dussek Campbell (Skokie, IL), partially hydrogenated soywax (~20°C melting onset and ~39°C melting peak) from Cargill Co. (Minneapolis, MN), and beeswax (35–65°C melting range) from Strahl & Pitsch, Inc. (West Babylon, NY). Stearic acid [Pristerene 4910: ~59°C m.p.; 0.5 iodine value (IV); FA composition of 2% $C_{14:0}$, 28% $C_{16:0}$, and 64% $C_{18:0}$]; KLX™ (a by-product of producing confectionery fat, ~48°C melting peak; FA composition of 20% $C_{16:0}$, 36% $C_{18:0}$, and 44% $C_{18:1}$); fully refined and partially hydrogenated palm oil (HPO; 20–40°C melting range;

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FA composition of 45% $C_{16:0}$, 6% $C_{18:0}$, 45% $C_{18:1}$, and 4% $C_{18:2}$); and fully hydrogenated soywax (melting peaks, 53 and 63°C; FA composition of 11% $C_{16:0}$ and 89% $C_{18:0}$) were provided, respectively, by Uniqema (Chicago, IL); Loders Croklaan (Channahon, IL); Fuji Vegetable Oil, Inc. (Savannah, GA); and C&T Refinery, LLC (Charlotte, NC). Candle molds [2.2 × 19 cm (⅞ × 7½ in.) footed taper and 5.1-cm (2 in.) and 8.9-cm (3.5 in.) diameter pillar], and thin and thick cotton wicks (7.84 and 14.78 mg/cm, respectively) were purchased from Pourette Manufacturing (Seattle, WA).

Candle preparation. Candle materials (100 and 300 g for 5.1- and 8.9-cm pillar candles, respectively) were melted in a container to a maximum of 100°C. The melted wax was stirred and allowed to cool to 80°C prior to transfer to the mold. To avoid early solidification of the wax during the pouring of beeswax candles and of candles having paraffin as one of the components, the candles were cooled to and poured at 90°C. A minimum of 6 h was allowed before the candles were released from the molds. During the cooling stage, paraffin candles incurred central voids in the vicinity of the wick due to the strong adhesion of paraffin to the mold wall. To fill these voids, additional melted paraffin wax was added after initial cooling. Pure paraffin candles were composed of a 50:50 ratio of soft/hard paraffins.

To evaluate the effects of added FFA in KLX, five different FFA levels were selected (0, 5, 10, 25, 40, and 60%, w/w) for use in 8.9-cm pillar candles with 14.78 mg/cm wicks. Soft paraffin was incorporated at 0, 5, 10, and 20% (w/w) levels to assess the effects of added paraffin. Similarly, 0, 10, 20, and 40% HPO was used to evaluate the effects of added HPO on candle properties.

On the basis of results from preliminary studies, wax containing 60% FFA in KLX was selected to assess the effects of candle diameter on burning characteristics. Two diameters (5.1 and 8.9 cm) were used. Also on the basis of preliminary experiments, 8.9-cm pillar candles with 25% FFA were selected to assess the effects of wick size.

Temperature distribution on candle surface. Thermal imaging (or so-called thermography) was used to measure the temperature distribution profiles of candle surfaces. Thermography is a non-contact, 2-D imaging system based on IR-sensing of certain cameras (4,5). The 2-D images of the objects obtained this way are called thermograms (4,5). Thermal images of the candles were recorded using an Inframetrics™ PM250 ThermaCam™ (Flir Systems, North Billerica, MA). Triplicate sets of candles were burned for 62 min, after which the flame was blown out and the image (top view) was immediately recorded.

Melting and re-solidification properties. A differential scanning calorimeter (DSC 6200, Seiko Instruments, Inc., Chiba, Japan) equipped with a cooling controller using liquid nitrogen and an Exstar 6000 communication device (Seiko Instruments Inc.) was used to measure the melting and re-solidification behaviors of the waxes. Seiko Measurement Software v. 5.8 and Seiko Analysis Software v. 5.5 (both from Seiko Instruments Inc.) were used for data acquisition and processing, respectively. A sample size of 7.00–15.00 mg was used. The AOCS recommended practice Cj 1-94 (6) was modified for temperature programming. An initial 2-min hold at 30°C followed by 30°C/min ramping to 90°C and a secondary 10-min hold, and cooling to −40°C at 10°C/min and a 1-min hold, and a final heating step to 90°C at 10°C/min were used for temperature programming. The first stage was for the homogenization of the wax structure. Therefore, the last two stages, comprising a cooling and a heating step, were used to compile the major crystallization and melting peaks.

Hardness and compression measurements. A TA.XT2i Texture Analyser™ (Stable Micro Systems, Ltd., Surrey, United Kingdom) was used to characterize wax texture by measuring hardness and compression forces. Prior to analysis, the system was calibrated using a 5.0-kg standard weight. By applying 2.0 mm/s pre-speed (the speed at which the probe moved prior to contacting the sample), 0.1 mm/s speed (the speed at which the probe penetrated the sample), and 0.1 mm/s post-speed (the speed at which the probe moved away from the sample), and a 2.0-mm diameter probe, the total force integrated for 2.0 mm of needle (probe) penetration was measured and reported as hardness. A 5-N force was applied to the probe penetrating from the top surface of the candles. Two separate candles of 8.9-cm diameter were prepared for each wax type, and triplicate measurements were made for each candle (i.e., a total of 3 × 2 = 6 measurements for each wax type).

Wax textures were also characterized by measuring the force required to compress samples to 80% of their heights [a method modified from those reported by Yang and Taranto (7) and Antoniou *et al.* (8)]. Pillar candles (8.9-cm diameter) were prepared by methods already described and then were cut into pieces of 1.5-cm long × 1.0-cm high × 1.0-cm wide. A 75-mm compression platen was used with the analyzer. To avoid friction between the surfaces, both the probe and the base were lubricated with soybean oil prior to each measurement. Samples were compressed using these parameters: 2.0 mm/s pre-speed, 0.3 mm/s speed, and 0.3 mm/s post-speed; the area integrated for the period was used for comparison. The means of five measurements are reported.

Burn rate, pool diameter, and flame size measurements. To measure the burn rates of the candles, three candles of each wax composition were placed on a bench top and allowed to burn for 6–7 h. Overall burn rate of each candle was obtained by dividing the total weight loss during candle combustion by the total burn time. Pool diameters of the foregoing candles were also measured using a stainless steel ruler when exactly 5 h of burning had elapsed. Comparison of the flame sizes among different candle types was made by visual estimation of the bulk of the flames when approximately 5 h of burning had been completed.

FA composition. To determine the FA compositions of hydrogenated vegetable oils, 40–50 mg samples were esterified by adding 1.0 mL sodium methoxide solution (1 M) and heating at 40°C for ~1 h. After esterification was complete, the reagent was deactivated by adding several drops of water, and the FAME were extracted into 2.0 mL of hexane. The methyl ester analysis was carried out using a Hewlett-Packard series II model 5890 gas chromatograph equipped with an SP-2330 fused-silica column (30 m × 0.25 mm × 0.2 µm; Supelco, Bellefonte, PA). Both the injection port and detector (FID) were set at 230°C, and the oven temperature was set at 190°C. A mixture of external standards was used to identify the chromatographic peaks.

Statistical analysis. The general linear model procedure of the Statistical Analysis System (SAS) release 8.00 (SAS Institute, Cary, NC) was used for data analysis (9). Means, least significant differences (LSD), and error mean squares (EMS) were determined.

RESULTS AND DISCUSSION

Currently, partially hydrogenated soywax (soft soywax) with a FA composition of 11% palmitate, 12% stearate, 54% oleate, and 22% linoleate is used in container- and pillar-type candles. Because of its low melting and re-solidifying points as observed by DSC (~20°C melting onset, 39.0°C melting peak, and 22.0°C re-solidification peak), soft soywax melted extensively, causing the wick to be drowned during the burning of container-type candles. For taper- and narrower pillar-type candles, the liquid wax dripping from the candle did not solidify fast enough to prevent the liquid wax from running onto the bench. These problems stimulated us to evaluate fully hydrogenated soybean oil (referred to as hard soywax, ~0 IV) for candle application. These candles were hard and shiny with no surface greasiness at all. Furthermore, the melting and re-solidification properties were improved. DSC analysis of hard soywax indicated two melting peaks at 52.8 and 63.0°C, and a solidification peak at 46.5°C. Compared to a commercial paraffin candle (with minor and major melting peaks at 40.6 and 59.0°C, respectively, and a re-solidification peak at 49.7°C), the melting and re-solidification properties of hard soywax were highly acceptable. However, the candles had an unacceptably brittle texture and they did not fully melt across the candle surface; therefore, they were not fully consumed during combustion (even with taper candles).

To improve melting and crystallization properties and to avoid brittleness of fully hydrogenated vegetable waxes, a fractionated blend of hydrogenated soybean and cottonseed oils (high *trans* content) was considered for the study. Such product was commercially available as KLX, which was a by-product (hardest fraction) in the production of fractionated hard butter for confectionery applications and high-stability cooking oils (10). Preliminary tests indicated that KLX was suitable for candle applications.

Temperature distribution on candle surfaces. Typical thermograms (top view) from the surfaces of the three different candle types are shown in Figures 1A–C. The plots of temperature abundance (i.e, the area percentage) for 240 data points (0.42°C temperature increments) over a range of 20 to 120°C are shown in Figure 1D. Graphical presentations of this type are referred to as thermal histograms. For KLX candles, the T_{max} (the temperature associated with the largest surface area on the candle) in the melted zone is lower than those of beeswax and paraffin, but in the unmelted zone, the T_{max} is higher than that of beeswax and similar to that of paraffin. The colder liquid wax, in the case of burning KLX candles, may be desirable for safety considerations.

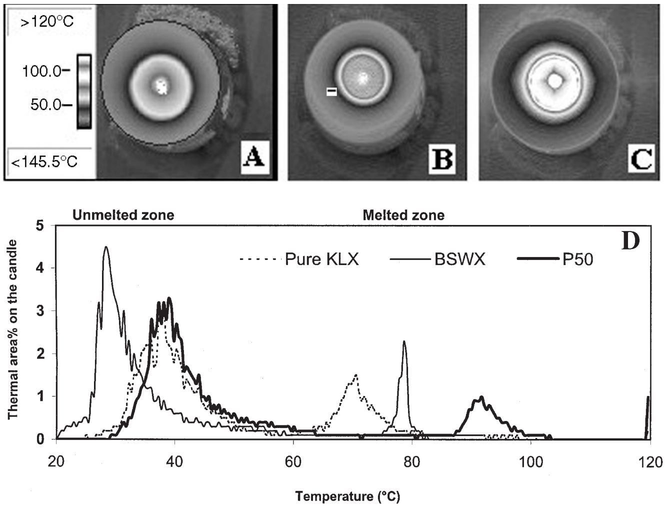

FIG. 1. Histograms of various candle types. (A) KLX™ alone, (B) pure beeswax (BSWX), (C) a 50:50 (w/w) mixture of soft and hard paraffin (P50), and (D) comparison of temperature distributions among the three types of candles.

The effects of FFA, paraffin, and HPO on the thermal profiles of candle surfaces were examined. Figures 2A and 2B, respectively, illustrate the changes in peak temperature and the surface thermal area% of the unmelted and melted zones of the candles with different FFA, paraffin, and HPO contents. With the addition of soft paraffin to KLX candles, the peak temperatures in both melted and unmelted zones increased (more in the melted zone). However, with increased HPO and FFA levels, these changes were minimal. A large portion (~60–85%) of the surface thermal areas of all candles was located on the solid (unmelted) zone (Fig. 2B). With added paraffin, the surface thermal area% of the melted zone decreased; however, with added HPO, this effect was opposite and a desirable increase in the area% of the melted zone was observed. A slight decrease in the area% of liquid zone was observed with added FFA. These changes may be related to the burning and melting properties and to heat conductivity of different waxes as well as chemical and/or physical interactions among the wax components. Surface imaging analysis is a useful means to quantify the changes in the surface temperature profile upon the addition of various wax components.

Melting and re-solidifying properties. Typical DSC profiles for pure KLX and KLX with different FFA levels are shown in Figure 3A. Although the melting properties of KLX alone may be acceptable (peak at ~48°C), the low solidification points (~30 and 23°C) render KLX unusable as a candle wax for taper- or narrow (≤5.1-cm diameter) pillar-type candles due to excessive dripping of the liquid wax. KLX candles

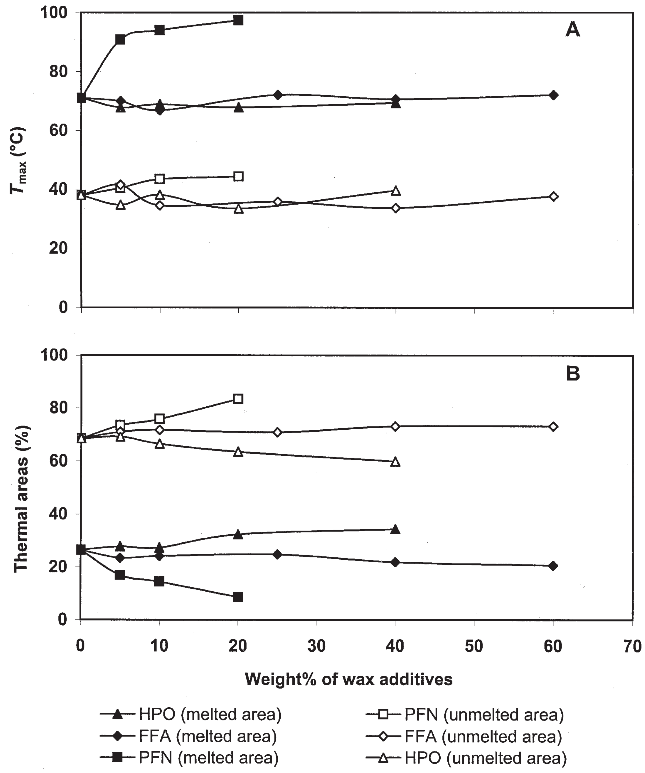

FIG. 2. Changes in peak temperatures (A) and thermal surface areas (B) of melted and unmelted zones of KLX candles with the addition of various components obtained from thermal images. T_{max} is the temperature associated with the largest thermal surface area on the candle. HPO, hydrogenated palm oil; PFN, soft paraffin.

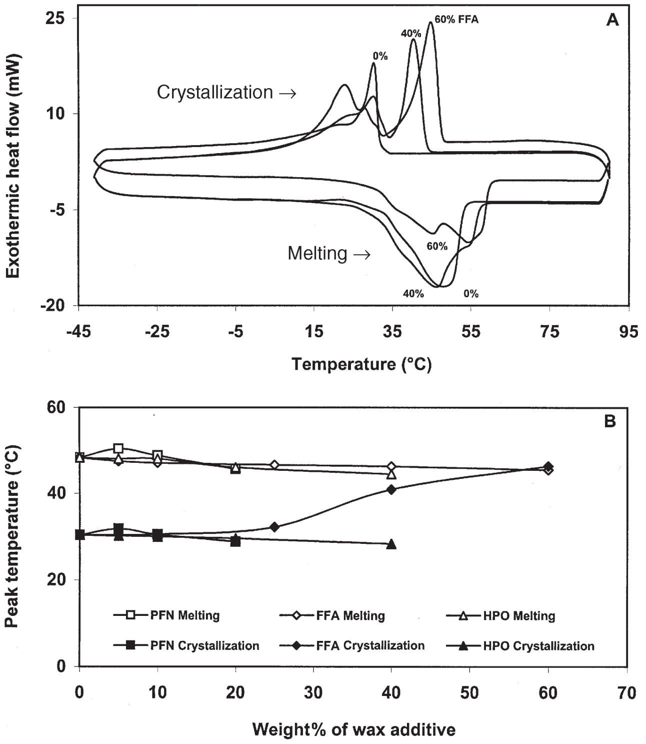

FIG. 3. Effects of candle composition on melting and solidification profiles of waxes. (A) DSC thermograms for KLX candles at 0, 40, and 60% FFA. (B) Changes in the melting and crystallization peaks of KLX waxes with the addition of various components. For abbreviations see Figure 2.

(5.1- or 8.9-cm diameter) in pillar forms cracked during the cool-down period in the molds and channeled during combustion resulting in liquid melt flowing from the candles. Channeling is the formation of a hole or a pathway in the wall through which melted liquid wax flows. This defect was attributed to weak structures resulting from non-uniform solidification of the wax during candle manufacturing.

The solidification peaks of KLX candles shifted to higher temperatures with FFA addition (Fig. 3A), which was partly due to the inherent FFA peak. The melting and solidification peaks of pure FFA were 59 and 49°C, respectively. KLX with 60% FFA solidified at 46°C, which was considerably higher than that of pure KLX (30°C). Such a change in the solidification of the wax is desirable and can reduce problems associated with wax dripping. On the other hand, the slightly earlier melting of the wax due to the decrease in the m.p. from 48°C in pure KLX to 46°C in 60%-FFA KLX did not cause any problems since the wax could still maintain its nongreasy appearance.

The effects of paraffin and HPO additions were also examined. The soft paraffin had a wide melting range of 25–80°C. Adding soft paraffin at 5, 10, and 20% to KLX resulted in a shift in the melting and solidifying points (Fig. 3B). Slight increases in both melting and solidifying points were observed with the addition of 5% paraffin. However, more paraffin addition shifted them back to lower temperatures. Therefore, there were no advantages in the use of paraffin to modify the melting and solidifying properties of KLX. This along with the increased cracking associated with paraffin addition makes such modification undesirable. The addition of paraffin to hard soywax was desirable for taper candles. A decline in the melting and solidifying points was observed as the HPO content was increased (Fig. 3B), which makes the new compositions less desirable for pillar candles. The DSC thermogram of HPO indicated a major melting peak in the 25–40°C range, which was far below that of KLX (~48°C).

Hardness and compression forces. Yang and Taranto (7) and Antoniou *et al.* (8) used cohesiveness as a parameter to characterize the textural properties of cheese, which were measured by applying two consecutive compressions on samples at 80% of their heights and dividing the total area (force × distance) for the second compression by the total area of the first compression. However, in this study, due to the crumbliness of KLX waxes, only the first compression at 80% of the height was used and the total area for such compression was also reported as compression. Furthermore, for paraffin and beeswax, which were used as references, no compression measurements were possible since the samples were so hard and highly cohesive that the Texture Analyser was not able to deform these samples to the dimensions of compressed KLX waxes. Therefore, to compare KLX-based waxes with the references, needle penetration was used to measure hardness.

The effects of FFA (5, 10, 25, 40, and 60%, w/w), paraffin (5, 10, and 20%, w/w), and HPO (5, 10, 20, and 40%, w/w) additions on the texture of candles were evaluated using hardness and compression analyses, which were obtained by integrating the force used on a penetration needle and a compression platen, respectively (Fig. 4). The addition of FFA up to 25% did not significantly affect candle hardness. However, candles with 40 and 60% FFA were significantly ($P < 0.05$) harder compared to those with ≤25% FFA content. Compression, however, did not change significantly ($P > 0.05$) with FFA addition (Fig. 4B). Compared to the variations in hardness, variations in compression were somewhat higher (12.9 vs. 5.6% relative SD), which was related to texture inconsistency within the candles as well as possible variations in the dimensions of the cubes used for compression measurements.

Although adding FFA reduced the greasy texture of KLX candles, the appearances of candles with 40 and 60% FFA were not as desirable as those of the candles with ≤25% FFA

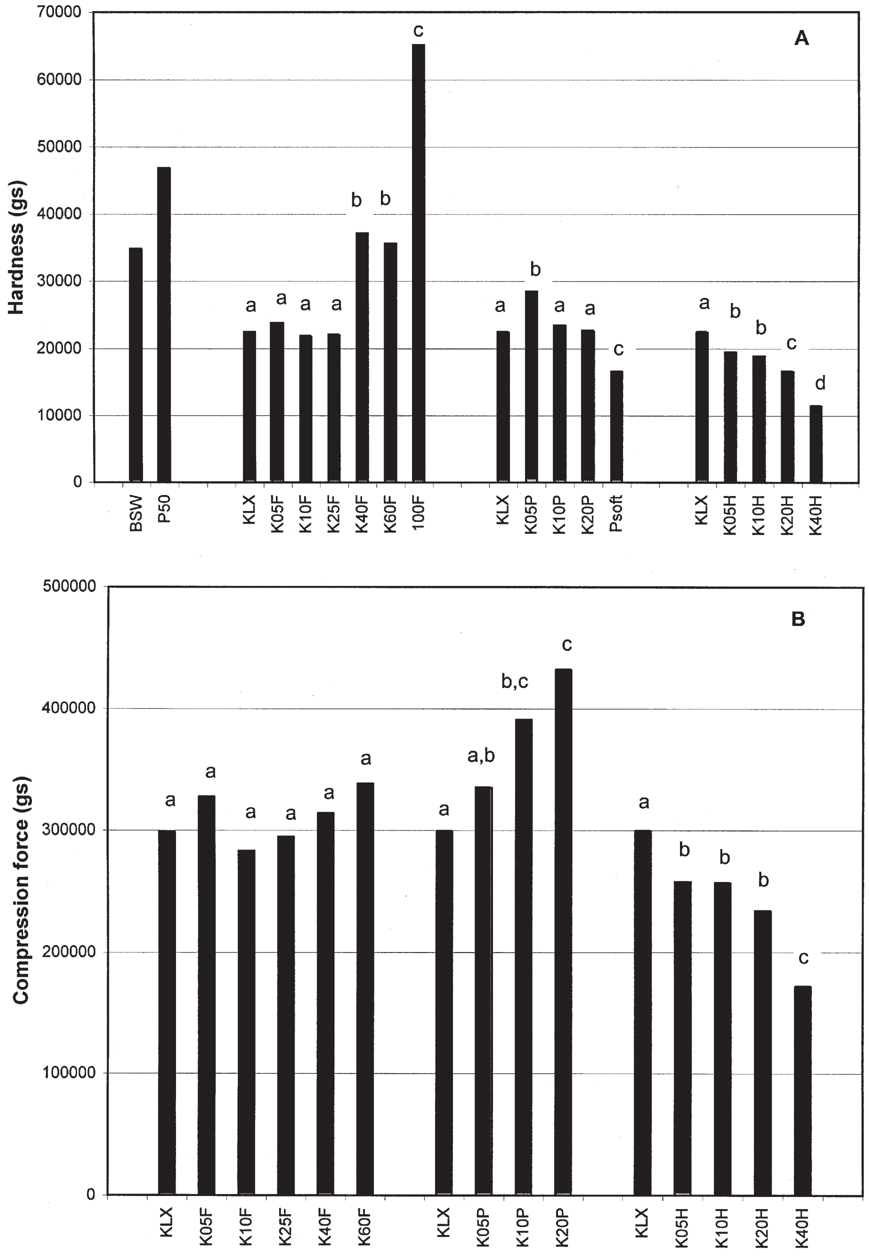

FIG. 4. Effects of various additives on hardness (A) and compression (B) of KLX waxes. Within each treatment, means with the same letter are not significantly different ($P < 0.05$). BSW: beeswax; P50: a 50:50 (w/w) mixture of soft and hard paraffin; K05F, K10F, K25F, K40F, and K60F: KLX with 5, 10, 25, 40, and 60% (w/w) FFA, respectively; K05P, K10P, K20P: KLX with 5, 10, and 20% (w/w) soft paraffin, respectively; Psoft: soft paraffin; K05H, K10H, K20H, and K40H: KLX with 5, 10, 20, and 40% (w/w) partially hydrogenated palm oil (HPO), respectively.

because the wax became more powdery. On the other hand, candles with ≤25% FFA did not release well from the molds. Both 40%- and 60%-FFA candles separated from their molds during cooling. In fact, candles with 60% FFA had greater shrinkage (i.e., better separation) than those made with 40% FFA. In practice, a compromise between these two properties needs to be made to achieve certain textural and burning properties.

Figures 4A and 4B also show the changes in the hardness and compressibility of KLX waxes with the addition of paraffin. Although with an increase in paraffin content the hardness was reduced, the products were more cohesive. Furthermore, wax shrinkage during solidification was improved and the candles were released easily from the mold. However, the candles developed two or three cracks radiating from the candle center to the circumference in the order 10% > 20% > 5% (beginning with the most severe). Although these cracks did not interfere with candle structure, their presence was an apparent defect.

The changes in the hardness and compressibility of KLX waxes with added HPO are also shown in Figure 4. As HPO content increased, both hardness (Fig. 4A) and compressibility (Fig. 4B) decreased, which were consistent with the more greasy appearance and softer structure of the higher-HPO candles. When making candles, none of the KLX candles with added HPO released easily from the molds and candle release had to be aided by heating the molds under hot water. HPO candles were very soft and greasy. Error mean square (EMS) and least significant difference (LSD) values for mean comparisons are shown in Table 1.

Burning characteristics. Changes in burn rate and liquid pool size were observed with the addition of FFA, paraffin, and HPO (Figs. 5A,B). As FFA content increased, both burn rate and pool size decreased. Changes in the burn rates are shown over a 6–7 h burning period. Although the candles made of pure KLX burned at 4.6 ± 0.4 g/h, the candles with 60% FFA burned at 2.8 ± 0.1 g/h, which was significantly different. Similarly, flame size decreased with added FFA. The mean flame size of pure KLX candles was almost five times that of candles containing 60% FFA. The mean burn rate of paraffin candles (i.e., 50:50 mixture of soft and hard waxes) was 5.0 ± 0.5 g/h, which was similar to that of KLX candles; however, the mean burn rate of beeswax candles was 2.7 ± 0.8 g/h. Ooi and Ong (11) reported 8% greater candle life (i.e., a decrease in the burn rate) along with a smaller flame size when 70% palm FA were added to paraffin candles. Changes in the mean pool diameters for KLX candles with different FFA levels are shown in Figure 5B. Candles made of pure KLX developed a 6.7 ± 0.3 cm (diameter) liquid pool after 5 h of burning, whereas those made from KLX containing 60% FFA created 3.9 ± 0.2 cm (diameter) liquid pools, which is not desirable for pillar candles. This formulation, however, may be better for narrower candles.

TABLE 1
Statistical Data for the Textural and Burning Properties of Various Candles Studied[a]

	Hardness (gs)		Compression (gs)		Burn rate (g/h)	
Treatment	EMS	LSD	EMS	LSD	EMS	LSD
FFA	4.2·E6	2.3·E3	1.7·E9	5.5·E4	0.08	0.51
Paraffin	1.1·E6	1.2·E3	2.3·E9	6.7·E4	0.56	1.36
HPO	2.7·E6	1.8·E3	8.0·E8	3.1·E4	0.20	0.81
Diameter effect	N/A	N/A	N/A	N/A	0.02	0.44
Wick effect	N/A	N/A	N/A	N/A	0.05	0.52

[a] EMS, error mean square; LSD, least significant difference; HPO, hydrogenated palm oil; NA, not applicable.

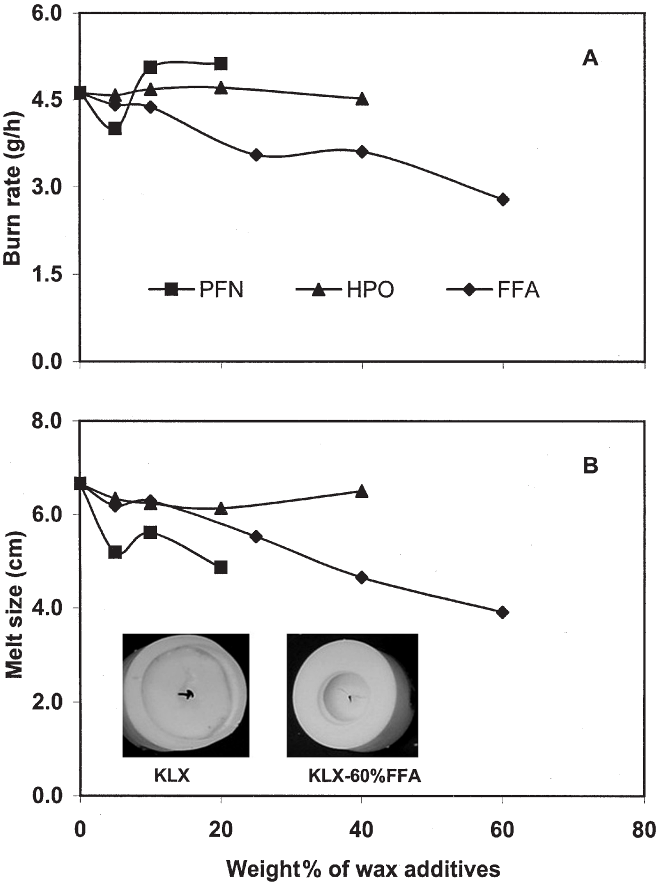

FIG. 5. Changes in the burning rate (A) and melt size (B) of KLX candles with different added components. Insert is a comparison of images (top view) of candles made of KLX alone (left) and KLX with 60% (w/w) FFA (right) burned for 7 h. For abbreviations see Figure 2.

The effects of adding paraffin (5, 10, and 20%) on the burning rate and the pool size of KLX candles are also shown in Figures 5A and 5B. Burning rate was not significantly affected by adding paraffin ($P > 0.05$). Adding soft paraffin to KLX (up to 20%) increased the flame size by approximately 20–30%, which was consistent with the changes in the burn rate. As was the case with adding FFA to KLX, soft paraffin additions to KLX decreased the melt size (Fig. 5B). KLX had a somewhat narrow melting peak, about 48°C (Fig. 3A). However, soft paraffin had a wide melting range (beginning at ~25°C and increasing to as high as 80°C), and as paraffin content was increased, less wax was melted and a smaller liquid melt was obtained.

To understand how adding a low-melting component affects the textural and burning properties of KLX candles, 0, 5, 10, 20, and 40% HPO addition was examined. No significant changes ($P > 0.05$) in the burn rate were observed when increasing the HPO content (Fig. 5A). However, a slight increase in the melt size was observed as HPO content increased from 10 to 20%, which was consistent with the melting properties of HPO (a wide peak at 20–40°C). EMS and LSD values are shown in Table 1.

Effects of candle diameter and wick size. The effects of candle diameter on surface temperature profiles and burn rates were investigated by using 5.1- and 8.9-cm diameter candles with 60% FFA in KLX. Surface temperatures of the liquid zones in the 5.1-cm candles ranged from 67 to 90°C and comprised 49% of the candle surface while those of the 8.9-cm candles ranged from 66 to 84°C and comprised only 21% of the total candle top surface. $T_{\max}$ values for the solid and liquid zones of the 5.1-cm candles were 53 and 74°C, and those of the 8.9-cm candles were 38 and 72°C, respectively. Because of the lack of wax beyond the candle area of 5.1-cm candles, the heat remained around the candle center, which indicated that the overall candle surface considerably influenced the heat dissipation profiles. A hotter liquid wax, such as those of the 5.1-cm candles, can be consumed easier during the burning process, which was consistent with the burn rates. The mean burning rates of the 5.1- and 8.9-cm diameter candles made with 60%-FFA were 3.17 ± 0.23 and 2.79 ± 0.07, respectively.

To evaluate wick size effects, 25%-FFA KLX candles with two different wick sizes were used. When Ooi and Ong (11) studied the wick size effect, they used multiple wick strings to increase the wick size. However, in this study, two wicks of cotton strips having different thicknesses were used and their masses for the unit length were used for specification (7.84 mg/cm for thin wick and 14.78 mg/cm for thick wick). There were major differences in the surface areas and $T_{\max}$ values for the melted and unmelted zones of the two types of candles. The surface areas of the unmelted zone for the candles with the thinner wick were larger (77%), for which a lower $T_{\max}$ value (31°C) was obtained. For the candles made with the thicker wick, these values were 71% and 36°C, respectively. Compared to candles made with the thicker wick, smaller surface areas were obtained for the melted zone in candles made with the thinner wick (17 vs. 25%). The $T_{\max}$ values for this zone were not different (72°C). At 25% FFA, the burn rate of candles made with the thicker wick was significantly ($P < 0.05$) higher than that of the candles made with the thinner wick (3.55 ± 0.30 vs. 2.29 ± 0.11 g/h). Since the consumption of wax was not limited by the supply of liquid wax (i.e., more liquid wax was available than the amount consumed), a larger amount of wax was withdrawn from the liquid pool when a thicker wick was selected. The melted pool size of the candles with thinner wicks after 5 h of burning was smaller than those of candles with the thicker wicks (4.0 ± 0.2 vs. 5.5 ± 0.4 cm).

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