LWT - Food Science and Technology 147 (2021) 111552

Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

Sterilization of coconut milk in flexible packages via ohmic-assisted thermal sterilizer

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ARTICLE INFO

Keywords:
Ohmic heating
Coconut milk
Aroma compound
Sterilization
Inoculated pack

ABSTRACT

Extreme heat treatments of canned coconut milk might reduce overall product quality. Therefore, an ohmic-assisted thermal sterilizer (OATS) may be able to preserve packaged coconut milk as an alternative to an overpressure retort. OATS involves converting electrical energy immediately into heat inside medium, which is then transferred to the food packages. This differs from conventional retorts which relied primarily on heat transfer. To ensure food safety, the OATS was microbiologically validated using *Clostridium sporogenes* spores. Physicochemical property and aroma compound profile differences in coconut milk sterilized at F_0 of 5.2 min using OATS were compared with conventional water spray retort. OATS completely inactivated *C. sporogenes* spores with more than 5 log CFU/mL at 121.1 °C for 5 min. The total processing time for OATS was 27 min using 32% less energy compared to the 42 min for the retort, indicating the higher process efficiency of OATS. OATS food products surpassed conventional retort properties in appearance, with minor color changes; off-odor, having a lower cooked odor by reducing methyl-ketone and Maillard reaction products; and desired aromas, by preserving contributors such as ethyl octanoate and δ-lactones. Consequently, OATS could potentially produce sterile coconut milk with minimal changes in appearance while decreasing off-odor formation.

1. Introduction

Coconut milk, with its pleasant, unique flavor, is found in many Asian dishes and has become an important food ingredient throughout Asian and Pacific cultures. Coconut milk refers to the opaque, milky white and protein-stabilized oil-in-water emulsion. It can be obtained from pressing grated coconut flesh with or without additional water (Tansakul & Chaisawang, 2006). Fresh coconut milk has a characteristically mild, sweet aroma. However, coconut milk tends to spoil easily after pressing via chemical and biochemical spoilage due to lipolysis and lipid oxidation. Furthermore, *Klebsiella pneumoniae, Enterobacter cloacae, Trichosporon mucoides, Candida lusitaniae* and *Candida tropicalis* potentially cause spoilage of coconut milk (Phattayakorn & Wanchaitanawong, 2009). Therefore, thermal processing such as cooking, pasteurization and sterilization are used to preserve and extend coconut milk shelf life (Wattanapahu, Suwonsichon, Jirapakkul, & Kasermsumran, 2012). Currently, the most popular commercial coconut milk products worldwide use retort and ultra-high temperature (UHT) sterilization to produce convenient products and extend product shelf stability and shelf life (Jirapakkul, Rodkwan, & Nasution, 2017).

Major volatile compounds in coconut flesh include δ-octalactone, δ-decalactone, and n-octanol (Lin & Wilkens, 1970). 2-methyl-1-butanal acetate and butylated hydroxytoluene are also major compounds found in both the flesh and juice of fresh and thermally processed coconut (Jirapong, Uthairatanakij, Noichinda, Kanlayanarat, & Wongs-Aree, 2012). Maillard reaction compounds including pyrazines, pyrroles, furan, and furfural were found in roasted coconut meat (Saittagaroon et al., 1984). The combination of δ-lactone with Maillard reaction products contribute to its characteristic sweet and nutty aroma. Thermal treatment might, therefore, affect key volatile compounds in coconut milk (Jirapakkul et al., 2017). Conventional heating, commonly used in the food industry, frequently creates undesirable appearances and odors in products due to the large temperature gradient between the surface and interior of foods (Wattanapahu et al., 2012) as well as the changes in volatile compound profiles (Lewis, 2010).

Alternative heat treatments, such as ohmic heating, have grown in popularity within the food industry to overcome these and other disadvantages of conventional heating (McKenna, Lyng, Brunton, & Shirsat, 2006; Müller, Ferreira Marczak, & Sarkis, 2020). Ohmic heating generates heat rapidly with uniform thermal distribution (Sastry &

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https://doi.org/10.1016/j.lwt.2021.111552
Received 31 December 2020; Received in revised form 15 April 2021; Accepted 19 April 2021
Available online 22 April 2021

Kamonpatana, 2014). It can therefore be applied to liquid foods, pumpable foods, beverages, and solids in liquid foods (Goullieux & Pain, 2014). To date, potential applications include thawing, blanching, evaporation, cooking, distillation, peeling, extraction and fermentation (Gavahian & Tiwari, 2020; Wattanayon, Kamonpatana, & Udompijitkul, 2021). Ohmic heating involves applying an alternating electrical current through food and converting electrical energy to heat with a high effective energy transfer (Lee, Ryu, & Kang, 2013). Continuous flow ohmic heating also ensures the food safety and quality required within the commercial food industry (Kamonpatana et al., 2013). However, commercial continuous ohmic heating systems still have limited possibilities due to microbial cross contamination, electrode fouling, and the high costs associated with aseptic packaging (Wattanayon, Kamonpatana, & Udompijitkul, 2021; Kamonpatana, 2018). Moreover, coconut milk contains high fat content as well as protein, carbohydrates and minerals. The potential coagulation and fouling in the high-temperature commercial continuous heating systems (Narataruksa, Pichitvittayakarn, Heggs, & Tia, 2010) can create significant difficulties in the clean-in-place. These limitations with continuous heating systems generate great interest in ohmic heating for sterilizing food using flexible packaging. Ohmic heating involves passing an electric current through the heating medium to rapidly generate heat. This heat is then transferred directly into the packaged food via conduction and convection. This process prevents food material from coming into contact with either the electrode or the surrounding environment.

No literature exists regarding the sterilization of coconut milk in flexible food packaging by ohmic-assisted thermal sterilization to our knowledge. Therefore, this research had two objectives 1) to ensure food safety via ohmic-assisted thermal sterilizer (OATS) for coconut milk in flexible packaging using *C. sporogenes* spore-inoculated pack and 2) to compare the physicochemical properties and aroma volatile profiles of coconut milk prepared in flexible packages between ohmically assisted thermal sterilization and conventional water spray retort.

2. Material and method

2.1. Sample preparation

Fresh coconut flesh, without brown testa was purchased from a local market in Bangkok and washed with potable water before being grated using a commercial grating machine (Sakaya automate Co. Ltd., Bangkok, Thailand). This was the tall-variety (Chumphon Hybrid No. 60) coconut (*Cocos nucifera* L.) and had matured approximately 12 months of age. The grated coconut flesh was pressed by a mechanical hydraulic pressing machine at 340 bar (Sakaya automate Co. Ltd., Bangkok, Thailand) without additional potable water or coconut juice to obtain undiluted coconut milk.

Fat content was determined with a Babcock cream bottle (The Association of Official Agricultural Chemists, 2012). Fresh undiluted coconut milk contained 30.0 ± 0.5% w/w of fat content and 60.0 ± 3.0% w/w of water content. The undiluted coconut milk (10 kg) was then standardized with deionized water (5 kg) to obtain 20.0 ± 0.4% w/w of fat content of standardized coconut milk (15 kg) (Tansakul & Chaisawang, 2006). The obtained fat content was higher than the 10–19% range typically found in commercial coconut milk products (Lakshanasomya, Danudol, & Ningnoi, 2011). The standardized coconut milk was used to represent low-acid food with high fat-content as the worst-case scenario for the both OATS and water-spray retort.

The 500 mL of the standardized coconut milk were refrigerated and used as untreated samples. Carboxymethyl cellulose (CMC) and Tween 60 purchased from CT laboratory Co. Ltd. (Bangkok, Thailand) was added into the standardized coconut milk to increase emulsion stability and prevent coconut milk phase separation during the sterilization process. Samples were prepared by heating standardized coconut milk in a stainless steel cooking vessel (32 cm inner diameter and 32 cm depth) with a liquefied petroleum gas (LPG) stove to 80 °C for 1 min to pasteurize and facilitate the dissolution of CMC and Tween 60 at the concentration of 0.6 and 0.6% w/v respectively. The treated coconut milk was subsequently passed through a two-stage homogenizer at 10/3 MPa (Phungamngoen, Chiewchan, & Siriwatanayothin, 2004) and put in 8-oz transparent retort pouches to obtain 100 g prior to sterilization.

The flexible retort pouches were made from a laminate of three layers of polypropylene/polyamide/polyester (PP/PA/PE) with overall film thickness of 83 μm. The PP (inner cast) provides heat seal and thermal resistant properties (Featherstone, 2015). The PA (middle layer) provides toughness, strength, and puncture resistance. Lastly, the PE film (outer layer) has high tensile strength, good oxygen barrier properties and high-temperature resistance (Kropf, Yancey, & Yancey, 2014). Therefore, the three laminated layers of PP/PA/PE potentially provide barrier properties against oxygen and moisture vapor (Kirwan, Plant, & Starwbridge, 2011).

2.2. Ohmic-assisted thermal sterilizer

The OATS was composed of a cover, a pressurized 0.59 m × 0.20 m x 0.38 m heating chamber, and a water-cooling system (Fig. 1(a)). The cover and heating chamber were Teflon (a non-metal and non-conductive material). The heating chamber was equipped with rectangular parallel titanium electrodes (0.59 m × 0.32 m) which were connected to a variable transformer (TSGC2-80K, Silic stable service Co., Ltd., Bangkok, Thailand) having a maximum voltage of 600 V, a current of 80 A, and a constant frequency of 50 Hz. Sample temperatures within the heating chamber were recorded continuously with type-K thermocouples (Primus. Co. Ltd, Bangkok, Thailand) in which wires were covered with electrical insulation tape made from ethylene propylene rubber (23 rubber splicing tape, Scotch®, 3M™, Brazil). The thermocouple was inserted inside the center of the pouch (Devadason, Anjaneyulu, Mendirtta, & Murthy, 2014) and its tip stayed at 30% of bottom of the pouch (Fig. 1(b)). Temperature, voltage, and current were continuously recorded every 4 s during the heating, holding and cooling period for a total time of 27 min with a digital multimeter (Gwinstek, Model GDM-8261A, China) linked to a personal computer.

Twenty 8-oz transparent retort pouches filled with coconut milk (Fig. 1(b)) were placed inside a Teflon rack, prior to being placed inside the ohmic heating chamber. Before the sterilization process, the ohmic heating chamber was filled with 21 L of 0.1% sodium sulfate solution (Na_2SO_4 anhydrous) as the electrical-transmitting and heating medium for sterilizing food products. Subsequently, OATS was tightly closed and pressurized at 1.5 bar before powering on. The coconut milk products were heated to the target temperature, held, and cooled to room temperature. The sterilized coconut milk was immediately sampled for further analysis.

2.3. Thermal distribution

A Teflon rack (0.27 m × 0.21 m x 0.17 m) with 20 sockets was placed inside the ohmic heating chamber (Fig. 2). The ohmic chamber filled with salt solution occupied each location within the Teflon rack to which 10 thermocouples were attached (without contacting the pouch) to record the temperature profiles of each location throughout the sterilization process. Two thermocouples were used to measure medium temperature. The heating medium was heated to 121.1 °C and held for 2 min. The temperature of each location was reported throughout the come up and holding times.

2.4. Sterilization process

The 100 g of standardized coconut milk filled 8-oz transparent retort pouches (13 cm × 16 cm × 2 cm) before sterilization. According to Seow and Gwee (1997), coconut milk must achieve an F_0 of 5 min to produce safe and shelf-life stable products. In general, the F_0 value was calculated based on a reference temperature of 121.1 °C with a Z-value of

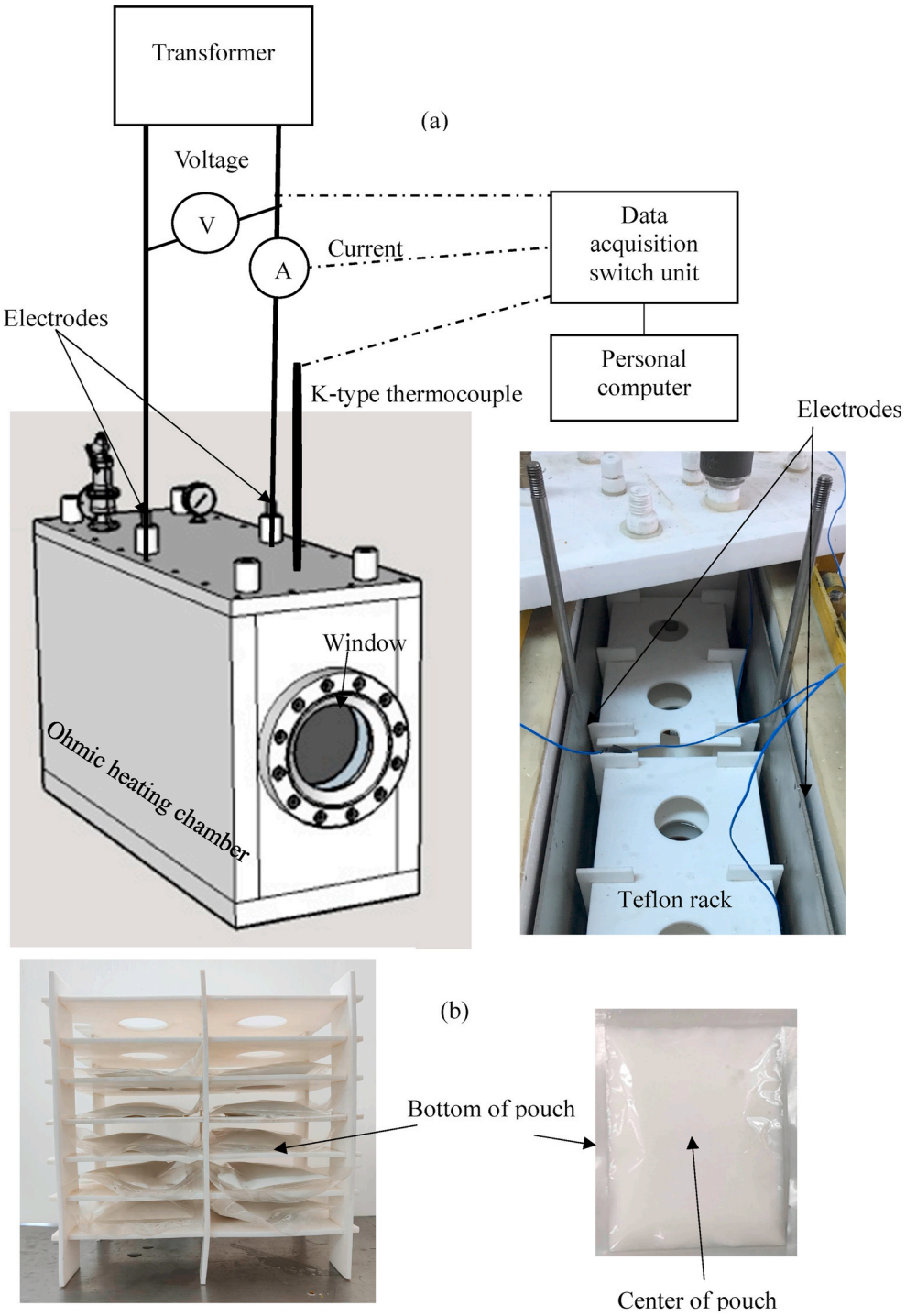

Fig. 1. (a) Schematic of ohmic-assisted thermal sterilizer and (b) Teflon rack with flexible retort pouches filled with coconut milk.

Clostridium sporogenes equal to 10 °C. Accumulated lethality (F_0) at the cold spot during thermal treatment was calculated using Eq. (1) (Kamonpatana et al., 2013).

$$F_0 = \int_0^t 10^{\frac{T_c(t)-T_{ref}}{Z}} dt \cong \sum_0^t \Delta t 10^{\frac{T_c(t)-T_{ref}}{Z}} \quad (1)$$

where T_c and T_{ref} are the cold-spot temperatures and reference temperatures (121.1 °C) respectively, t is time and Z refers to the Z-value. Therefore, microbiological validation experiments were conducted at the base of two process levels on the F_0 value, sterilization (121.1 °C, F_0 = 5 min) and under sterilization (113 °C, F_0 < 1 min). However, Diao, Andre, and Membre (2014) who conducted statistical analysis on numerous scientific projects report a Z-value for *C. sporogenes* of 11.1 °C. Consequently, sterilization conditions for this study was set at F_0 = 5 min with a Z-value of 11.1 °C to simulate a worst-case scenario in low acid foods with high fat contents. In addition, cooking value (CV) was also calculated using Eq. (1) where T_{ref} is 100 °C and Z refers 33 °C (Ranganna, 2002).

To investigate physicochemical property and aroma volatile profile differences, coconut milk was sterilized using two different thermal treatments with identical heating temperatures and holding times to

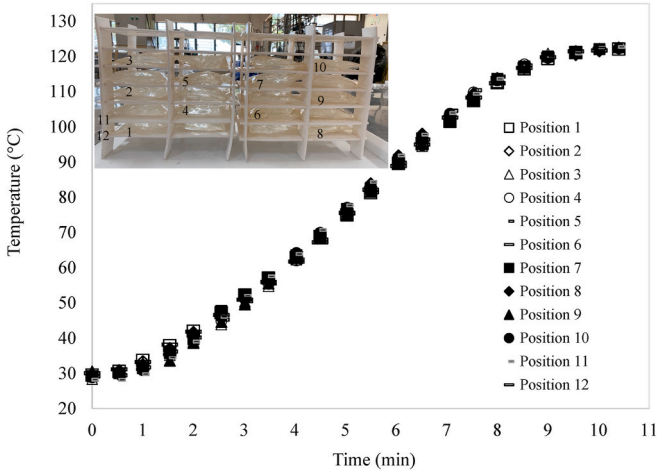

Fig. 2. Thermal distribution inside ohmic-assisted thermal sterilizer.

obtain the similar F_0: a horizontal water spray retort for the conventional heat treatment and OATS for ohmic heating. Twenty coconut milk pouches were loaded in the chamber, heated by a hot medium to the target product temperature of 121.1 °C, held for at least 5 min, and cooled to room temperature with potable water to achieve F_0 greater than 5 min. Conventional heating was conducted using a water spray retort (RCS-60/SPXTGH, Flavor Ace, Hisaka work, Ltd., Osaka, Japan) with five consecutive racks in which each rack contained four packages. Approximately 42 kg of water at ambient temperature (30 °C) was fed into the retort prior to indirect heating using a plate-type heat exchanger (the use of steam as heat source) and circulated until the water temperature reached the target temperature of 121.1 °C. The temperature distribution test of the water spray retort was done and had less than a 1.1 °C distribution at the target temperature (U.S. Food and Drug Administration, 2014) (data not shown). The packaged coconut milk was heated by hot sprayed water, held, and cooled to room temperature.

Energy consumption (E) of OATS was calculated as the integral of the product of voltage (V) and current (I) overtime (t) (Wattanayon et al., 2021):

$$E = \int_0^t VIdt \tag{2}$$

Energy consumption of the water spray retort was calculated as the accumulation of energy required to heat both the water and the packaged coconut milk. This was expressed by the following equation wherein energy required to heat the retort, basket, and divider sheets, as well as heat losses, was assumed to be negligible (Giraldo Gil, Ochoa González, Cardona Sepúlveda, & Alvarado Torres, 2020):

$$E = \left[mc_p\left(T_{final} - T_{initial}\right)\right]_{water} + \left[mc_p\left(T_{final} - T_{initial}\right)\right]_{coconut \quad milk} \tag{3}$$

where m is mass (kg), c_p is specific heat capacity (kJ/kg°C), $T_{initial}$ is initial temperature (°C) and T_{final} is final temperature (°C). c_p of water and coconut milk was 4.18 kJ/kg°C (Cengel and Boles, 2014) and 3.71 kJ/kg°C (Tansakul & Chaisawang, 2006) respectively.

2.5. Bacteria strain and growth condition

C. sporogenes spores were prepared using the same method for sporulating *C. perfringens* cultures (Paredes-Sabja, Gonzalez, Sarker, & Torres, 2007). In brief, 400 μL of growth Fluid Thioglycollate Medium (FTG) culture was inoculated into another FTG medium and incubated for 8–10 h at 37 °C. 400 μL of actively growing culture was transferred to a Duncan Strong (DS) sporulation medium (Duncan & Strong, 1968) and incubated at 37 °C for 5 days. The protocols were repeated until approximately 70–80% of the sporulating cells were observed in the DS medium under phase contrast microscopy (Leica model DM500, Heerbrugg, Switzerland) prior to scaling up in a 800 mL DS medium. *C. sporogenes* spores in the DS medium were collected by centrifuging the medium at 3300 g for 10 min at 4 °C with a refrigerated centrifuge (Tomy model MX 305, Tomy Digital Biology Co., Ltd., Tokyo, Japan). This was then purified by washing with cold, sterilized, distilled water until more than 99% of purified spore was obtained without 1) vegetative cell debris, 2) sporulating cells or 3) germinating cells which was confirmed by observing the spores under phase contrast microscopy. The purified spore was stored at −20 °C until needed.

2.6. Microbiological validation

Microbiological validation test was conducted based on the F_0 value for the target process (121.1 °C; sterilization), and below the target process (113 °C; under sterilization). The food material was sterilized by autoclave (121.1 °C for 15 min) prior to inoculating the *C. sporogenes* spore suspension. The initial *C. sporogenes* spore-count in each pouch was approximately 4×10^5 CFU/mL. The number of surviving spores after the thermal treatments were enumerated using 1 mL of homogenized sample with 0.1% peptone water. The homogenized sample was series-diluted in 0.1% peptone water, prior to being spread on reinforced clostridial agars (RCA). The inoculated plates were incubated under anaerobic conditions at 37 °C for 48 h. The presence of any surviving cells indicated that the product was not completely sterilized. On the other hand, commercial sterilization was considered to be achieved if the colony count in each pouch was below 1 CFU/mL, indicating either an absence of cell growth or an absence of cells. The sterilization process was performed in duplicate.

2.7. Solvent extraction for aroma volatile compounds

The solvent extraction method was modified from that of Tinchan, Lorjaroenphon, Cadwallader, and Chaiseri (2015). Twenty (20) μL of 2-methyl-3-heptanone (0.0121 g in 10 mL methanol) was spiked into 100 g of sterilized coconut milk as an internal standard. Sterilized coconut milk was then poured into a 250 mL Teflon extraction bottle with 20 g of NaCl and 50 mL of diethyl ether. Solvent extraction was carried out three times by an incubator shaker at 300 rpm for 30 min before being centrifuged at 850 g for 5 min. The diethyl ether fraction was collected and pooled together.

Subsequently, the extracted fraction underwent non-volatile compound removal by high-vacuum distillation under 10^{-5} torr; the concentrated extract was distilled at room temperature for 2 h and then distilled again at 50 °C for 1 h. The evaporated volatile compound from high-vacuum distillation was condensed and cold-trapped with liquid nitrogen. The distilled extract was concentrated using a Vigreux column in a water bath at 43 °C to achieve a final volume of 10 mL. The resulting aroma extract was dried over Na_2SO_4 anhydrous to remove residual water. The dehydrated aroma extract was concentrated until achieving a final volume of 1 mL. Before chromatography analysis, the aroma extract was concentrated to a final volume of 0.5 mL using a gentle stream of N_2 gas and kept at -80°C until further analysis.

2.8. Gas chromatography-time of flight mass spectrometry (GC-ToFMS) analysis

Volatile compounds were analyzed using a gas chromatograph (7890A; Agilent Technologies, USA) equipped with time-of-flight mass spectrometry (Pegasus 4D, LECO Crop., USA). Aroma extract (1 μL) was injected via the cool on-column technique. The separation was performed using a polar capillary column (Stabilwax®-MS; 30 m length, 0.25 mm diameter and 0.25 μm film thickness, Restex, USA). The GC oven was programmed with an initial temperature of 35 °C which was held for 5 min, then raised at a rate of 4 °C/min to 225 °C where it was

then held for 10 min (Kabir & Lorjaroenphon, 2014). Helium gas was used as the carrier gas at a constant flow rate of 1.0 mL/min. The Mass Selective Detector (MSD) transfer line was held at 250 °C. The MSD was set at 70 V for electron-impact ionization with a scan range of 30–300 m/z and a rate of 20 scans/s.

The retention index (RI) of volatile compounds was calculated based on a retention time of volatile compounds against an *n*-alkane reference standard (C_6–C_{30}), obtained from the GC program. The RI of the volatile compounds were calculated using Eq. (4).

$$RI = 100n + \left[\frac{(t_i - t_n)}{(t_{n+1} - t_n)} \times 100((n+1) - n)\right] \quad (4)$$

where t_i, t_n, and t_{n+1} are the retention times of the compound, the lower alkane, and the upper alkane respectively ($t_n < t_i < t_{n+1}$) where n+1 and n are the carbon numbers of the higher and lower n-alkanes, respectively. Volatile compounds were identified by comparing observed RI values against known RI values of volatile compounds found in literature reviews and also by comparing observed mass spectra with the mass spectra of authentic compounds obtained from Wiley 275 and the National Institute of Standards and Technology (NIST 2.0) mass spectral libraries.

The concentration of volatile compounds was reported as a relative concentration compared to the internal standard. Volatile compound relative concentrations can be calculated as the ratio of the volatile compound to the internal standard area.

2.9. Physicochemical analysis

Samples for physicochemical analysis were obtained via random sampling which included untreated, freshly sterilized samples from both the water spray retort, and OATS. The analysis was performed in triplicate.

2.9.1. pH

While pouring the 100 mL of samples from their transparent retort pouches into a 150 mL beaker, the pH meter probe (Mettler-Toledo, FiveEasy™, Switzerland) was simultaneously submerged into the sample. The pH was determined and the pH data were recorded.

2.10. A_w or water activity

The A_w or water activity of samples were determined using an A_w meter (Aqualab 4 TE, Meter food, Meter group, Inc., USA). The A_w meter was calibrated with deionized water, prior to sample determination. About 10 mL of sample were poured into plastic cups, which were then placed inside the A_w meter for measurement, after which the data were recorded.

2.11. Color analysis

The color of the coconut milk was determined with a spectrophotometer (Ultrascan® pro, HunterLab, Hunter Associates Laboratory Inc., Virginia, USA) with L*, a*, and b* measurements. The spectrophotometer was calibrated with a white ceramic tile and light trap before sample analysis. L*, a*, and b* values indicate darkness/lightness, greenness/redness and blueness/yellowness respectively.

2.12. Viscosity analysis

Viscosity was determined by analyzing 20 mL of coconut milk from each condition with a rotational, concentric cylinder viscometer (DV-III, Brookfield engineering Laboratories, Inc., MA, USA) equipped with a UL adapter. Viscosities were determined at 25 °C by using cylindrical spindle No.00 (2.5 cm diameter and 9 cm length) at 60 rpm. All measurements were triplicated.

2.12.1. Free fatty analysis (%FFA)

The %FFA as oleic acid in the samples was determined by titration method. Samples were subjected to oil extraction with a chloroform/methanol solvent system (1:1, v/v). The mixture was shaken vigorously for 1 min, prior to centrifuging at 700 g for 1 min. The lower chloroform fraction was collected and the residual solvent was evaporated with a gentle stream of N_2 gas (Farhoosh, Johnny, Asnaashari, Molaahmadi-bahraseman, & Sharif, 2016). The %FFA was determined via titration (AOCS, 2004).

2.13. Statistical analysis

Statistical analysis was conducted via one-way ANOVA to indicate the differences in the physicochemical properties and aroma volatile profiles of untreated and sterilized samples. Significant differences were calculated based on a 0.05 level ($\alpha = 0.05$), which post hoc process using Duncan's multiple range test with program SPSS version 16 (IBM Corp., New York, U.S.A.)

3. Result and discussion

To ensure that OATS could produce safe foods, temperature distribution and microbiological validation were conducted with the results indicated in Fig. 2 and Table 1 respectively.

3.1. Temperature distribution

The temperature profile of each location inside the ohmic heating chamber was recorded as shown in Fig. 2. Average initial and final medium temperatures were 29.2 and 122.1 °C, respectively. The cold zone was indicated by point 2 while that of conventional retort was expected to be at the bottom of the basket due to water flow being hampered (Smout, Van Loey, & Hendrickx, 2001). The ohmic chamber was designed to allow electric current to pass through every point between two electrodes. Point 2 was also within the passage of the electrical current and is situated near a window with a very thin-walled channel (Fig. 1). This channel may create the cold zone due to slower heating. Nevertheless, the temperature difference between the hot and cold spots at the target temperature of 121.1 °C was no greater than 1.1 °C. Successful uniform thermal distribution by OATS was thereby confirmed in this case.

3.2. Microbiological validation

Target process of 121.1 °C took heating and holding time of 22 min while under target process of 113 °C finished thermal process within 15 min (Fig. 3). The temperature of packaged coconut milk at the cold spot increased from 36 °C to 121.1 °C and was held for 5 min to reach the target process with the F_0 at 5 min; and from 36 °C to 113 °C and held for 5 min for the under-target process with the F_0 at 0.9 min. At the initial step, the electrical voltage was ramped up to a voltage of 350 V, causing a linear increase in the current (Fig. 4). However, the maximum achievable current for the transformer used for the ohmic heating process was only 75 A. Therefore, as the current reached its limit, the voltage was continuously reduced to decrease the current. The voltage

Table 1
Inoculated pack study of coconut milk inoculated with *Clostridium sporogenes* spores (ATCC 7955).

Inoculation level (CFU/mL)	Process level	Target temperature at cold spot (°C)	F_0 at cold spot (min)	Microbiological validation test
4.0×10^5	Target	121.1	5	Negative
4.0×10^5	Under target	113.0	<1	Positive

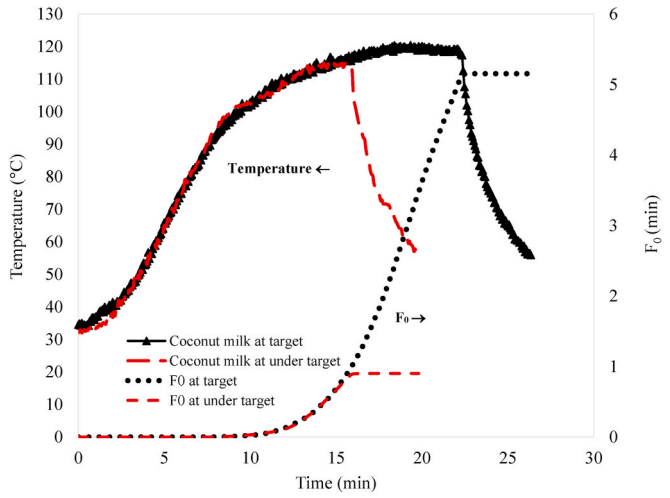

Fig. 3. Temperature profiles and F_0 of packaged coconut milk at cold spot at target and under target processes.

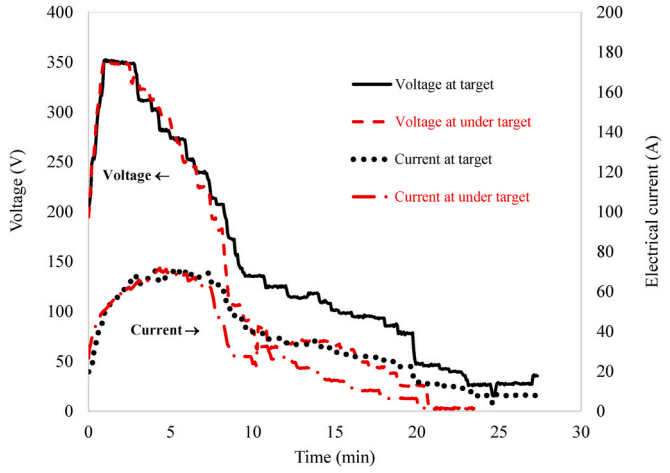

Fig. 4. Voltage and electrical current during ohmic heating at target and under target processes.

and current of both the target and under target process were initially the same at the start of heating; however, at the under target, voltage was sharply reduced at 8 min mark to reduce the temperature to 113 °C, which accounts for the reduction of current. On the other hand, for target process voltage was maintained to be higher to keep the target temperature of coconut milk at 121.1 °C. Voltage and current were identified as critical factors of ohmic heating for food products contained in flexible plastic packages (Wattanayon et al., 2021). Although these packages were electrically insulated (Kamonpatana, 2018), the ample heat and energy from the salt solution rapidly transferred to the internal product (Inmanee, Kamonpatana, & Pirak, 2019).

Ohmic heating at the target temperature at 121.1 °C for 5 min could inactivate more than 5 log of *C. sporogenes* PA 3679 spores which surviving spore counts were lower than detection limit (<1 CFU/mL) (Table 1). This result confirmed that a sterilization process were accomplished. On the other hand, at under target temperature at 113 °C for 5 min ($F_0 < 1$ min), the inoculated pack study showed the presence of surviving spores which indicated insufficient thermal treatment. This also confirmed that *C. sporogenes* PA 3679 spores were thermal resistance. The result showed that OATS has a potential for produce products with food safety even in low acid foods with high fat content.

3.3. Sterilization process

To investigate the effects of OATS on physicochemical properties and aroma volatile compounds, the heating temperature and holding time of both OATS-packaged coconut milk and the conventional retort were kept identical. Coconut milk with an average initial temperature of 36 °C was heated to 121.1 °C. The heating and holding times of the OATS and conventional retort were under 22 min to arrive the F_0 at 5.2 min. For OATS, the salt solution was heated from 36 °C to 121.1 °C in 11.5 min (Fig. 5). Volumetric and rapid heating in salt solution transferred to the packaged food via continuous electrical energy. On the other hand, the conventional water spray retort required steam to heat water. After the water was heated, thermal energy was transferred from the hot water to heat the packaged coconut milk. Conventional retort relies heavily on heat conduction and convection while OATS depends on volumetric heating of the medium and subsequent conduction and convection within the packaged food. OATS can heat food faster than heating by conventional retort by increasing voltage and current. Another difference between OATS and water spray retort was observed in the cooldown period. Since heating for OATS occurs through an electrical current, heating begins and ends comparatively quickly by engaging or disengaging the current. The OATS thermal lag was considerably shorter compared to that of the water spray retort when heating and holding periods were complete; the OATS cooldown rate was under 5 min while the water spray retort took over 20 min to get the temperature of coconut milk down to 60 °C. A long cooling period of water spray retort resulted in the additional F_0 of 2.3 min to obtain total F_0 of 7.5 min. OATS finished the overall process (heat, hold and cool) within 27 min with the CV of 44 min while water spray retort took 42 min resulting in a higher CV of 59 min. The longer processing time and the higher CV of conventional treatment might allow unfavorable chemical reactions to occur during the sterilization process.

Energy consumption of OATS was calculated using Eq. (2) and data from Fig. 4 of target process as 3.20 kWh whereas the energy consumption of the water spray retort using Eq. (3) was 4.74 kWh. OATS accounted for an energy savings of 32% compared to the water spray retort. Our study agreed with the study of Inmanee et al. (2019) and Wattanayon et al. (2021). Inmanee et al. (2019) revealed a 52% energy savings of pasteurized vacuum-packaged sausages using ohmic heating compared with conventional heating. Wattanayon et al. (2021) reported 0.11 kWh for ohmic heating and 0.27 kWh for conventional heating of packaged orange juice. Ohmic heating showed higher energy efficiency compared with conventional heating.

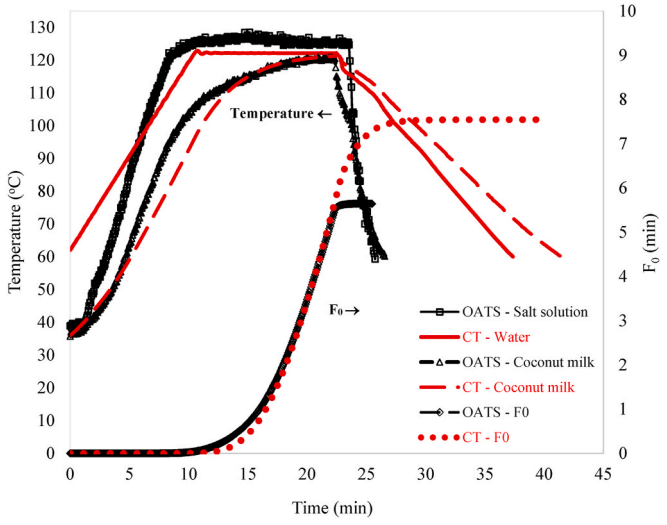

Fig. 5. Temperature of media and temperature and F_0 of coconut milk at cold spot during sterilization process.

3.4. Physicochemical analysis

The physicochemical properties of pH, A_w, viscosity, color and %FFA of untreated and sterilized coconut milk from the different sterilization methods are summarized and listed in Table 2.

The pH of untreated and sterilized coconut milk from different sterilization methods ranged from 6.33 to 6.35, with no significant changes in pH after sterilization ($p > 0.05$). The lack of change in pH for sterilized products is possibly because the charged molecules were not changed in the coconut milk. This phenomenon was also found in packaged sausage which had been ohmically and conventionally pasteurized, where pH values remained the same before and after the pasteurization process (Inmanee et al., 2019).

No significant changes of A_w were found in coconut milk before treatment of 0.9831 and after all treatments ranging 0.9884 and 0.9885 ($p > 0.05$). The high A_w of coconut milk possibly causes lipolysis, oxidation, and other events. This would occur during preparation, sterilization, and even in untreated samples.

Significant differences in L* and b* values between untreated and sterilized coconut milk were observed whereas sterilization had no significant effect on a* value (Table 2). Homogenization required for sterilized coconut milk samples resulted in a higher L* value compared to that of untreated coconut milk. The smaller and more concentrated oil droplets in the sterilized sample possibly increases the reflection index (Chantrapornchai, Clydesdale, & McClements, 1999) resulting in a higher L* value for the sterilized sample compared to that of the untreated sample. Furthermore, the b* value in sterilized samples was significantly higher, especially for those treated conventionally. For coconut milk, non-enzymatic browning can occur when temperatures higher than 100 °C are applied (Hofmann, Frank, & Heuberger, 2001). Owing to the longer processing time of the conventional sterilization process (Fig. 5), browning is more likely to occur. Therefore, OATS-treated samples also had a comparatively low b* value.

Viscosity is a primary factor in determining food quality and consumer acceptance. The viscosity of coconut milk before adding stabilizers and emulsifiers was approximately 2.65 cP, which differed significantly ($p \leq 0.05$) from sterilized coconut milk containing CMC and Tween 60 (70.13–70.27 cP) as listed in Table 2. Tween 60, which was used as an emulsifier, slightly increased the overall food material viscosity (Polychniatou & Tzia, 2013). However, stabilizers or thickening agents, such as CMC, increased the viscosity to a greater extent while preventing droplet aggregation. Consequently, sterilized coconut milk possessed a higher viscosity.

The %FFA content of untreated, ohmically, and conventionally sterilized coconut milk were compared (Table 2). The %FFA (as oleic acid) in the samples ranged from 0.109 to 0.131%, which is still lower than Asian and Pacific Coconut Community (APCC) standards for virgin coconut oil with a maximum of 0.2% (Seneviratne & Jayathilaka, 2016). Moreover, no significant changes in %FFA were found in all treatments ($p > 0.05$). Sterilization apparently had no effect on % FFA content whether using conventional or ohmic heating.

3.5. Aroma volatile compound analysis

Aroma volatile compounds of untreated coconut milk and packaged coconut milk treated by the OATS and water spray retort with the identical heating temperatures and holding times are indicated in Table 3.

3.5.1. Aroma volatile compound profiles in untreated coconut milk

The 31 volatile aroma compounds in coconut milk are classified into six groups: alcohols, aldehydes, ketones, acids, esters, and lactones (Table 3). A large percentage of ester compounds were observed. Among all ester compounds, ethyl octanoate was most abundant in untreated coconut milk, contributing the fruity and fatty aroma considered desirable in coconut milk. (Rychlik, Schieberle, & Grosch, 1998).

The second major category of volatile aroma compounds were alcohols. The most abundant alcohol compound was 2,3-butanediol which provides a fruity and sweet aroma (Kim, Shin, Baek, & Lee, 2001). Additionally, the combination of alcohols coupled with esters and aldehydes provides a fresh, floral and fruity aroma (Jirovetz, Buchbauer, & Ngassoum, 2003).

The third largest group of volatiles in untreated coconut milk were acids. Enzyme activity and the presence of heat and moisture-liberated fatty acid from triglycerides in the sample produced an abundance of acid in untreated coconut milk (Nawar, 1969). Coconut milk extracted from unblanched coconut kernel has been shown to have lipase activity resulting in fatty acid liberation (Waisundara, Perera, & Barlow, 2007). Apart from lipase activity, coconut milk is easily contaminated with microorganisms during the extraction and handling processes. Among microorganisms, genus *Eurotium* and *Penicillium* potentially contaminate coconut milk and increase lipase activity (Kinderlerer & Kellard, 1984). As a result, the high degree of fatty acid compounds might cause the acidic note found in the untreated sample.

Lactones, the volatile compounds common to coconut products, were also identified in coconut milk including δ-hexalactone, δ-octalactone, δ-decalactone and δ-dodecalactone. Lactone is responsible for the coconut-like, creamy, fatty, and sweet characteristics of coconut-related products (Jirovetz et al., 2003; Prades, Dornier, Diop, & Pain, 2012).

In summary, untreated coconut milk was rich in ester, alcohol, and lactone to create the pleasant, creamy, fatty, and unique coconut-like aroma, characteristic of coconut milk. However, acid found in high amounts in untreated coconut milk due to lipase and/or microorganism activity also provided an acidic note in the untreated sample.

3.5.2. Effect of sterilization on aroma volatile compounds of coconut milk

After sterilization, most volatile compounds showed a decreasing trend, potentially caused by thermal degradation (Table 3). A similar phenomenon was also observed in coconut sugar and syrup production (Purnomo, 2007) as well as thermally-treated coconut water (Nasution, Jirapakkul, & Lorjaroenphon, 2018). Tinchan et al. (2015) suggested that during thermal treatments, chemical reactions including auto-oxidation, lipolysis and Maillard reaction might cause the formation of new volatile compounds.

Among the ester compounds, ethyl octanoate was the most abundant in both untreated and sterilized coconut milk, which agreed with other

Table 2
Physicochemical properties including pH, Aw, color, viscosity and free fatty acid (FFA) in untreated and sterilized coconut milk.

Treatment	pH^{ns}	A_w^{ns}	Color			Viscosity (cP)	% FFA as oleic $acid^{ns}$
			L*	$a^{*,\ ns}$	b*	at 60 rpm	
Untreated	6.33 ± 0.02	0.9831 ± 0.0047	86.85^{b} ± 1.07	−0.44 ± 0.03	4.14^{c} ± 0.31	2.65^{b} ± 0.62	0.131 ± 0.013
Water spray retort	6.35 ± 0.02	0.9885 ± 0.0008	89.55^{a}± 0.60	−0.44 ± 0.01	7.47^{a} ± 0.01	70.27^{a} ± 0.35	0.113 ± 0.010
OATS	6.34 ± 0.01	0.9884 ± 0.0002	89.49^{a}± 0.79	−0.43 ± 0.03	6.60^{b} ± 0.47	70.13^{a} ± 0.21	0.109 ± 0.010

OATS means an ohmic-assisted thermal sterilizer.
[a-c] means within the same column with different annotations are significantly different ($p \leq 0.05$).
[ns] means not significantly different ($p > 0.05$).

Table 3
Concentrations of aroma volatile compounds with odor description in coconut milk for unheated and sterilized sample from water spray retort and ohmic-assisted thermal sterilizer (OATS).

Aroma volatile compound	RI[a]	Odor description[b]	Relative concentration of aroma volatile compounds (ng/g)		
			Untreated	Sterilization	
				Water spray retort	OATS
Alcohols					
2-Methyl-1-propanol	1081	Sweet, whiskey-like (a)	$657.0^{a} \pm 90.6$	$144.4^{b} \pm 22.3$	$118.4^{b} \pm 11.2$
1-Butanol	1110	Fruity (b)	$164.4^{a} \pm 5.7$	$32.4^{b} \pm 7.7$	$25.6^{b} \pm 2.5$
2-Ethyl-1-hexanol	1453	Rose, green (b)	$1.3^{c} \pm 0.1$	$8.7^{a} \pm 0.7$	$6.6^{b} \pm 0.3$
2,3-Butanediol	1530	Fruity, sweet (c)	$4351.3^{a} \pm 39.5$	$1190.7^{b} \pm 755.6$	$660.1^{b} \pm 65.6$
2-Furanmethanol	1612	Caramel, brut sugar, musty, sweet (d)	$9.5^{b} \pm 0.4$	$125.0^{a} \pm 20.0$	$130.7^{a} \pm 2.3$
Benzyl alcohol	1769	Sweet, floral (d)	$9.8^{c} \pm 3.5$	$91.2^{a} \pm 30.8$	$38.8^{b} \pm 0.8$
Aldehydes					
Hexanal	1040	Grass, tallow, fatty, leaf (b)	$0.0^{b} \pm 0.0$	$14.8^{a} \pm 1.1$	$12.0^{a} \pm 0.7$
Nonanal	1353	–	$0.0^{b} \pm 0.0$	$13.1^{a} \pm 1.1$	$12.2^{a} \pm 0.3$
Benzaldehyde	1469	Almond, bitter (a)	$7.8^{c} \pm 3.2$	$23.6^{b} \pm 3.5$	$38.6^{a} \pm 4.0$
Ketones					
2-Heptanone	1144	Fruity, cheesy, cinnamon (a)	$0.0^{b} \pm 0.0$	$18.1^{a} \pm 1.8$	$17.0^{a} \pm 0.7$
Acetoin	1250	Buttery (b)	$401.3^{b} \pm 54.2$	$1680.4^{a} \pm 254.1$	$871.4^{b} \pm 57.5$
2-Nonanone	1349	Fruity, fatty-cheese (a)	$0.0^{b} \pm 0.0$	$69.8^{a} \pm 17.0$	$81.7^{a} \pm 3.5$
2-Undecanone	1561	–	$8.4^{c} \pm 7.6$	$125.6^{a} \pm 9.9$	$100.3^{b} \pm 3.9$
2-Tridecanone	1730	–	$0.0^{b} \pm 0.0$	$39.8^{a} \pm 8.5$	$49.9^{a} \pm 5.5$
Acids					
Acetic acid	1393	Pungent, vinegar (b)	$699.4^{a} \pm 263.2$	$0.0^{b} \pm 0.0$	$0.0^{b} \pm 0.0$
Butanoic acid	1591	Sweaty, cheesy, rancid (b)	$201.4^{a} \pm 4.8$	$45.0^{b} \pm 15.2$	$48.7^{b} \pm 1.6$
Hexanoic acid	1755	Goat-like, sweaty (b)	$1092.6^{a} \pm 265.5$	$102.6^{b} \pm 34.6$	$100.3^{b} \pm 3.2$
Octanoic acid[ns]	1919	Sweaty (b)	3141.4 ± 1512.5	734.9 ± 168.2	872.6 ± 3.8
Decanoic acid	2122	Fatty, creamy, milky, peach, nutty (a)	$170.6^{a} \pm 56.2$	$50.5^{ab} \pm 30.5$	$100.8^{b} \pm 0.3$
Dodecanoic acid	2328	Soapy (b)	$320.3^{a} \pm 11.8$	$107.1^{b} \pm 15.8$	$121.2^{b} \pm 16.2$
Esters					
Ethyl octanoate	1404	Fruity, fatty (b)	$13949.6^{a} \pm 1006.5$	$8266.5^{b} \pm 640.4$	$12276.5^{ab} \pm 2169.7$
Ethyl decanoate	1604	Grape (b)	$421.4^{a} \pm 16.1$	$170.3^{b} \pm 26.1$	$416.0^{a} \pm 9.7$
Ethyl dodecanoate[ns]	1759	Leaf (b)	252.1 ± 142.0	174.8 ± 23.0	160.8 ± 9.7
Lactones					
δ-Hexalactone[ns]	1726	Sweet, whiskey-like (a)	701.8 ± 245.0	370.4 ± 137.4	289.2 ± 5.5
δ-Octalactone[ns]	1826	Coconut-like (b)	1566.8 ± 510.9	2856.8 ± 1072.1	2552.1 ± 168.5
δ-Decalactone[ns]	2050	Sweet, peach, coconut (b)	1930.7 ± 777.3	576.5 ± 125.1	833.3 ± 0.5
δ-Dodecalactone	2270	Sweet (b)	$5.0^{c} \pm 0.6$	$20.7^{b} \pm 6.6$	$42.4^{a} \pm 3.7$
Other					
Methyl pyrazine	1220	Raw, roasted (e)	$0.0^{c} \pm 0.0$	$35.5^{a} \pm 3.6$	$26.1^{b} \pm 1.7$
4-Methyl-5H-furan-2-one	1769	Roast, nutty, sweet caramel (d)	$2.7^{a} \pm 1.3$	$1.3^{a} \pm 0.5$	$1.8^{a} \pm 0.0$
Phenol	1943	Phenolic (b)	$0.7^{b} \pm 0.2$	$4.5^{ab} \pm 1.9$	$5.9^{a} \pm 1.4$
5-Methyl furfural	2351	Cooked aroma (e)	$0.0^{b} \pm 0.0$	$13.2^{a} \pm 5.1$	$2.0^{b} \pm 0.3$

[a-c] means within the same row with different annotations are significantly different ($p \leq 0.05$).
[ns] means not significantly different ($p > 0.05$).
[a] RI means retention index of volatile compound of Stabliwax®-MS column (30 m × 0.25 mm × 0.25 μm).
[b] Odor description of each compound was obtains from (a) Leffingwell (2004), (b) Rychlik et al. (1998), (c) Kim et al. (2001), (d) Kabir & Lorjaroenphon (2014) and (e) Jayalekshmy et al. (1991).

literature (Jirovetz et al., 2003; Lin & Wilkens, 1970; Tinchan et al., 2015). The concentration of ethyl octanoate in sterilized coconut milk with OATS was not significantly different from that of untreated coconut milk while sterilized coconut milk water-spray retort was lower than that of the untreated. This confirmed that OATS degraded ethyl octanoate (fruity and fat note) in coconut milk to a lesser degree than conventional retort.

Lactones are the second largest group of volatile compounds in sterilized coconut milk which contribute to the characteristic aroma (coconut-like, creamy, and sweet odors) of coconut-related products (Tinchan et al., 2015). The concentration of δ-hexalactone, δ-octalactone, and δ-decalactone in untreated, OATS, and conventionally sterilized coconut milk was not significantly different ($p > 0.05$). However, δ-dodecalactone in coconut milk processed by OATS showed the highest value (42.4 ng/g) followed by that of the water spray retort (20.7 ng/g) and untreated coconut milk (5.0 ng/g). Our results were inconsistent with the study of Wang et al. (2020) who reported unchanged concentrations of δ-octalactone and δ-decalactone and a decrease in δ-dodecalactone in coconut milk after sterilization at 121 °C for 30 min. The 30 min heating time of conventional retort at 121 °C compared to 22 min heating time needed for OATS might affect lactone concentrations.

In contrast to untreated samples, the sterilized coconut milk was rich in ketones. Among all the ketone compounds, acetoin was the most prevalent in sterilized samples, especially in conventionally-treated samples. The concentration of acetoin in sterilized samples using the retort (1680.4 ng/g) was approximately 4 times greater than untreated samples (401.3 ng/g) and twice that of OATS (871.4 ng/g). The increase of acetoin could provide a buttery aroma in food material (Lasekan & Abbas, 2010) and could be an indication of Maillard reaction products in the sample (Chen & Ho, 1998). The significant increase in acetoin in conventional sterilized samples is possibly caused from the increased processing time due to a slower cooldown rate which may allow the Maillard reaction to occur (Fig. 5). Apart from acetoin, methyl-ketone compounds such as 2-heptanone, 2-nonanone and 2-undecanone significantly increased in sterilized coconut milk. Unfortunately, the presence of methyl-ketone compounds might provide an undesirable aroma in sterilized coconut milk since 2-heptanone, 2-nonanone, and 2-undecanone were reported as an off-flavor contributor in UHT milk (Badings & Neeter, 1980).

Other Maillard reaction products, such as methyl pyrazine and 5-methyl furfural were also detected in sterilized samples. These

compounds were identified as Maillard reaction products in roasted coconut flesh (Jayalekshmy, Narayanan, & Mathew, 1991; Saittagaroon, Kawakishi, & Namiki, 1984), which contributed the cooked and nutty odor in the conventional sterilized samples. Therefore, the longer process time of conventional sterilization might cause lipid degradation, oxidation, and Maillard reactions. The conventional treatment tended to have a significant volatile aroma profile change, due especially to the Maillard reaction products which contributed off-odor in sterilized coconut milk.

Aroma volatile compound profiles were directly affected by the sterilization process. After sterilization, concentrations of ester, alcohol, and acid decreased due to thermal degradation, while ketone and Maillard reaction products increased. The longer processing time with respect to the higher CV of conventional retort might generate chemical reactions higher than that of OATS. This resulted in significant increases in Maillard reaction products which contributed to an off-aroma (roasted and cooked odor). On the other hand, OATS could preserve the characteristic aroma of coconut milk (coconut like, creamy and nutty) and potentially reduce off-odor formation in sterilized samples.

This study revealed the advantages of OATS over the water spray retort in terms of shorter processing time, lower energy consumption, less water consumption, and higher food product quality. Moreover, by replacing steam boilers with electrical power supplies (Assiry, Gaily, Alsamee, & Sarifudin, 2010), required space, maintenance, and carbon footprints are all reduced (Sakr & Liu, 2014). Although the per unit cost using electricity is currently more expensive than gas and oil, energy cost stability and renewable energy options may lead to greater economic viability in the future (Atuonwu, Leadley, Bosman, & Tassou, 2019).

4. Conclusion

Ohmic-assisted thermal sterilizer (OATS), is an alternative to overpressure retort which applies an electrical current through a salt solution to generate thermal energy which is subsequently transferred into food material within the packaged product. Voltage and amperage can be adjusted to increase or decrease the heating rate; however, power and current limitations should be considered. Temperature distribution throughout the OATS showed uniformity, with a temperature difference of less than 1.1 °C at the target temperature. An inoculated pack study at a target process of 121.1 °C confirmed OATS reached the required 5 log reduction of *C. sporogenes* PA 3679 spores for sterilization. Compared to the conventional retort, OATS possessed a shorter total processing time with the added advantage of rapid cooling, higher energy efficiency, less water consumption, and clean energy (no need of using boilers). In addition, OATS produced sterile packaged coconut milk with minimal physicochemical changes and off-odor formation while maintaining a better appearance. The ohmic-assisted thermal sterilization system was proven to safely sterilize packaged coconut milk, a low-acid food with high fat content, with high quality and is therefore recommended as an alternative to overpressure retort in food industries. Future studies on a larger industrial scale is considered worthwhile.

CRediT authorship contribution statement

Chavis Tiravibulsin: Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **Yaowapa Lorjaroenphon:** Resources, Supervision. **Pathima Udompijitkul:** Resources, Supervision. **Pitiya Kamonpatana:** Conceptualization, Data curation, Visualization, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank and acknowledge the Kasetsart University Research and Development Institute, Kasetsart University, Bangkok, Thailand for their financial support.

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