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INTEGRATED MICROWAVE-STEAM STERILISATION OF LOOSE OIL PALM FRUITS: ENHANCED HEATING UNIFORMITY, CRUDE PALM OIL QUALITY AND ENERGY SAVINGS

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ABSTRACT

Loose oil palm fruits are often left uncollected in large quantities while harvesting fresh fruit bunches, which incurs considerable losses in crude palm oil yield. Although the free fatty acid content in loose fruits is undesirably high, microwave sterilisation is known to reduce it significantly. The present study enhanced microwave sterilisation using a new integrated microwave-steam method in which steam exiting the fruits during vaporisation is entrapped and used to complement the heat treatment process. The effect of this new method on the heating uniformity, drying rate, oil extraction rate, crude palm oil quality and energy consumption/cost was investigated. Results showed that up to 25.7% and 13.6% reduction in temperature non-uniformity and energy consumption/cost was achieved with MW-steam heating. Moreover, sterilisation duration was reduced by up to 11.6%. The stacked arrangement of fruits improved microwave absorption efficiency, reducing temperature non-uniformity by up to 45.0% and energy consumption by up to 19.2%. MW-steam sterilisation achieved up to a 10.5% increase in oil extraction rate. Crude palm oil with excellent hydrolytic and oxidative stability was acquired, thus, boosting oil value that can facilitate post-processing in palm oil mills.

Keywords: energy, microwave, oil palm, stacking, sterilisation.

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INTRODUCTION

Malaysia's oil palm sector is a significant contributor to its economy (Mumtaz *et al*., 2010) and it is of utmost importance that the palm oil produced is of excellent quality and stability. A major cause of oil quality deterioration is the rise of free fatty acids (FFA) catalysed by lipase enzymes (Morcillo *et al*., 2013). To inactivate lipase enzyme and halt FFA production, fresh fruit bunches (FFB) undergo sterilisation in palm oil mills (Omar *et al*., 2018). However, large quantities of loose oil palm fruits detach from these bunches during harvesting and transportation and end up uncollected and left to rot, resulting in substantial losses to the crude palm oil (CPO) yield. Loose oil palm fruits account for up to 4% to 6% of the total FFB harvested and could contribute to an additional 1% to 2% in the oil extraction rate (OER) (Henson, 2012). Loose fruits are mostly damaged and bruised due to the handling practices in palm oil mills and thus, have a very high amount of FFA content which increases rapidly upon abscission and continues to increase with time (Ali *et al*., 2014). Although the sterilisation

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of loose fruits (high FFA content) together with FFB (low FFA content) offsets the overall FFA content to a certain degree, FFA content should be as low as possible to maximise CPO quality and minimise the refining costs (Chong, 2012). Moreover, the current conventional steam sterilisation method practised in palm oil industries gives rise to highly polluting effluent, which must undergo rigorous and expensive treatment before disposal (Madaki and Seng, 2013).

The conventional steam sterilisation method typically involves the use of horizontal or vertical sterilisers. Other oil palm sterilisation technologies include continuous sterilisers, dry (oven) heating and microwave (MW) heating (Vincent *et al*., 2014). Although these technologies have proven effective in halting FFA production in oil palm fruits, MW sterilisation is known to cease and reduce the FFA content drastically (Tang *et al*., 2017). According to Kanjanapongkul (2021), no significant increase in FFA content was detected even 8 weeks after MW sterilisation. Since no steam and water is utilised, MW heating has been termed a clean and dry technology for CPO production with no effluent discharge (Cheng *et al*., 2011). Moreover, MW heating allows the retention of vital nutrients in CPO, such as carotenoids (Sarah, 2018). However, MW heating has been associated with non-uniform heating in foods which causes incomplete microbial inactivation and overheating (Vadivambal and Jayas, 2010). Heating uniformity can be improved by improving the electric field inside the cavity or the uniformity of MW absorption by the dielectric material (Bae *et al*., 2017). Recently proposed methods to improve electric field uniformity required sophisticated modifications to the MW cavity, such as the use of rotary waveguides (He *et al*., 2020), multiple waveguides (Ahn *et al*., 2020), and MW cavity with adjustable geometry (Wu *et al*., 2020). Other researchers have proposed increasing the MW absorption in a material by minimising the reflections either by optimising the load position (Requena-Perez *et al*., 2004) or by surrounding the load with dielectric layers (Monzó-Cabrera *et al*., 2004).

Previous studies on MW heating of oil palm fruits have primarily focused on the quality of CPO produced, with little emphasis on improving heating uniformity and energy consumption. According to Shehu *et al.* (2019), researchers have attributed the non-adoption of MW heating for oil palm sterilisation in industries to non-uniform heating and a lack of techno-economic experimental data such as energy analysis. Moreover, the effect of MW heating on trace contaminants in CPO such as iron and phosphorus is also not present in the literature. The novel integrated MW-steam sterilisation method is a clean alternative approach to enhance the sterilisation of loose oil palm fruits in terms of temperature uniformity, CPO quality and energy consumption without requiring additional resources (water or chemicals) or making sophisticated modifications to the MW system. The technique involves enclosing oil palm fruits inside a closed container and subjecting them to MW irradiation. In doing so, the steam exiting the fruits from moisture vaporisation is prevented from escaping into the atmosphere and is trapped inside the container instead. The overall heat treatment process would thereby enhance due to the concurrent influence of MW heating, and convective heating from the entrapped steam. The method differs from hybrid steam-MW sterilisation in which steaming and MW heating are done separately (Hock *et al*., 2020).

The present study investigates the integrated MW-steam sterilisation method at the laboratory scale; the effect on heating uniformity, moisture drying, CPO quality and energy consumption was explored. The investigation seeks to establish the feasibility of implementing integrated MW-steam sterilisation in palm oil industries in the future to add value to high FFA loose oil palm fruits, eliminate effluent discharge and maximise oil recovery. Although industrial MW systems (waveguide perpendicular to sample; belt conveyer system) differ significantly in operation compared to domestic MW systems (waveguide adjacent to sample; turntable system), it is crucial to realise the effectiveness of MW-steam sterilisation at a smaller scale as a proof of concept prior to its application to a larger scale.

MATERIALS AND METHODS

Loose oil palm fruits (*Tenera* variety) were collected 24-36 hr post-harvest from the grounds of a local oil palm plantation in Selangor, Malaysia. The accumulation was a mixture of bruised: bruise-free fruits with a ratio of 4:1. The sterilisation of loose oil palm fruits was carried out in a domestic MW system (Model: ME711K, Samsung, Korea) at a continuous power of 800 W. Experimental parameters included the number of fruit layers (single layer and two stacked layers), heating time (1, 2, 3, 4 and 5 min), and sterilisation method (MW sterilisation and MW-steam sterilisation). The fruits were loaded inside an MW safe polypropylene container in a single layer (~125 g) or stacked layers (~250 g). The United States Food and Drug Administration (FDA) has approved polypropylene for food contact applications; its high heat tolerance (melting point of 160°C) prevents chemical leaching, making it an inexpensive and ideal option for the MW heating of foodstuff (Marsh and Bugusu, 2007). The MW-steam sterilisation involved fastening the container with a lid. A container lid was pierced with two holes

(~2 mm diameter) to allow adequate venting of steam produced from moisture vaporisation and prevent explosion due to excessive pressure build-up. The percentage loss in the moisture of oil palm fruits upon MW heating was calculated on a wet basis using Equation (1):

$$M_l = \frac{(m_i - m_f)}{m_i} \times 100 \quad (1)$$

where M_l is the moisture loss (%), m_i is the initial mass (g) before MW heating, and m_f is the final mass (g) after MW heating. The residual moisture content (M) in fruits upon MW heating was then calculated by deducting moisture loss (M_l) from the initial moisture content in fruits.

The initial moisture content of oil palm fruits was determined using the drying oven method (Ahn *et al*., 2014) in a Venticell LSIS-B2V/VC111 laboratory oven (MMM Group, Germany) in which the fruit samples were subjected to successive heating at 105°C with 24 hr intervals until a steady-state mass was reached.

Temperature Analysis

The internal (mesocarp) and surface (skin) temperatures of up to four oil palm fruits were recorded immediately after each experimental run. Glass fibre insulated type K thermocouples (RS Components Ltd., Malaysia) linked with a TC-08 data logger (Pico Technology, United Kingdom) were used to measure and record the internal temperatures (~3 mm depth) at ± 0.5°C accuracy. The surface temperature readings were taken using an infrared thermometer (DigiTech, Australia).

Quality and Energy Analysis

CPO was extracted using a hydraulic press with a compressive force of 15 MPa, then centrifuged (Model: Centrifuge 5810 R, Eppendorf, Germany) for 5 min at 4000 rpm to separate the oil from sludge and emulsion. The recovered oil was weighed on a mass balance to determine the OER of CPO using Equation (2):

$$\text{OER (\%)} = \frac{\text{Mass of recovered oil (g)}}{\text{Initial sample mass (g)}} \times 100 \quad (2)$$

The CPO was then subjected to quality analysis: the FFA content (as palmitic acid), moisture and volatile matter (MV) content, *p*-anisidine value (AnV), total oxidation in ultraviolet light (UV TOTOX), iron content, phosphorus content, iodine value (IV), carotene content and DOBI of CPO was determined based on the MPOB Methods p2.5:2004, p2.1:2004, p2.4:2004, p2.12:2004, p2.10: 2004, p2.8 Part2: 2004, p3.2:2004, p2.6:2004 and p2.9: 2004 (Kuntom *et al*., 2005). The energy consumption of the MW system was assessed using a Power-Mate Lite power meter (Hypertec, Australia).

RESULTS AND DISCUSSION

Effect on Temperature Distribution

Table 1 shows the temperature distribution in a single layer of oil palm fruits during MW heating and MW-steam heating. The geometry and position of the dielectric sample inside the cavity are among the factors that influence temperature distribution (Rattanadecho and Makul, 2016). Temperature non-uniformity was quantified by calculating the coefficient of variance (CV). On average, the CV of internal temperatures was 21.1% lower in MW-steam heating (0.15) than MW heating (0.19) through a heating period of 5 min. In contrast, the CV of surface temperatures was on average 30.0% lower in MW-steam heating (0.14) than in MW heating (0.20). Hence, enhancement in internal and surface temperature uniformity was attained with MW-steam heating. The occurrence is possibly due to convective heat transfer from the entrapped vapours inside the closed container to the fruits, enhancing the overall heat distribution. As opposed to volumetric heating from MW irradiation, convective heating involves heat transfer between the steam and the solid surface, which may justify the greater influence of MW-steam heating in improving the uniformity of surface temperatures than internal temperatures. The combination of MW heating and convective heating from the trapped steam played an essential role in enhancing the sterilisation process of oil palm fruits.

Table 2 shows the temperature distribution in stacked layers of oil palm fruits during MW heating and MW-steam heating. On average, the CV of internal temperatures was 27.2% lower in MW-steam heating (0.08) than MW heating (0.11) through a heating period of 5 min. In comparison, the CV of surface temperatures was 10.0% lower with MW-steam heating (0.09) than MW heating (0.10). Although improved temperature uniformity with MW-steam heating was apparent from our earlier discussion, the constructive effect of MW-steam heating in improving the uniformity of surface temperatures was not as influential in stacked fruits as compared to a single layer of fruits. Nevertheless, stacking of fruits significantly improved temperature uniformity, with the average CV more than 33.0% lower for internal temperatures and 50.0% lower for surface temperatures, as compared to a single layer. The impact of the stacked arrangement of fruits was discovered to be more effective in achieving a more uniform heating pattern and temperature distribution than the effect of MW-steam heating.

Shah *et al*. (2022) investigated the effect of stacking oil palm fruits in layers under intermittent MW heating and reported enhanced heating uniformity.

Effect on Heating Rate and Sterilisation

The mean internal temperature in a single layer of oil palm fruits leapt rapidly during the first minute of MW heating and MW-steam heating at a heating rate of ~1.1°C/s (*Table 1*). However, the heating rate deteriorated by more than 81% after 1 min (~0.2°C/s). An initial heating rate of ~1.2°C/s was reported by Cheng *et al*. (2011) at the same power level (800 W), dropping to as low as ~0.2°C/s as heating continued. Similarly, the mean surface temperature in a single layer initially rose at a rate of ~0.9°C/s but decreased by more than 60% (~0.3°C/s) after 1 min (*Table 1*). MW heating involves rapid agitation of water molecules and charged ions inside a dielectric material for fast heat generation (Tang and Resurreccion, 2009). Due to the low specific heat capacity (2816 J/kg·K) and thermal conductivity

TABLE 1. TEMPERATURE DISTRIBUTION IN A SINGLE LAYER OF LOOSE OIL PALM FRUITS AFTER MW HEATING AND MW-STEAM HEATING

(a) MW heating	Heating time (min)									
	1		2		3		4		5	
Temperature	Internal	Surface	Internal	Surface	Internal	Surface	Internal	Surface	Internal	Surface
T1 (°C)	113.9	87.7	125.9	133.8	145.7	141.6	150.6	173.0	153.9	196.3
T2 (°C)	68.0	62.5	89.8	88.0	101.0	110.3	104.1	116.5	116.3	123.8
T3 (°C)	87.7	93.7	100.1	109.4	117.9	118.6	118.3	147.8	137.9	155.3
Mean (°C)	89.8	81.3	105.3	110.4	121.6	123.6	124.4	145.8	136.0	158.5
SE (°C)	13.3	9.6	10.7	13.2	13.0	9.4	13.7	16.3	10.9	21.0
CV	0.26	0.20	0.18	0.21	0.19	0.13	0.19	0.19	0.14	0.26
(b) MW-steam heating	**Heating time (min)**									
	1		2		3		4		5	
Temperature	Internal	Surface	Internal	Surface	Internal	Surface	Internal	Surface	Internal	Surface
T1 (°C)	97.2	83.0	110.1	100.5	133.1	115.3	141.1	157.4	155.1	189.0
T2 (°C)	78.6	64.3	89.1	76.0	95.1	94.1	98.5	112.8	111.5	147.3
T3 (°C)	91.4	73.0	98.8	92.9	103.6	98.5	110.1	124.9	119.0	160.9
Mean (°C)	89.1	73.4	99.3	89.8	110.6	102.6	116.6	131.7	128.5	165.7
SE (°C)	5.5	5.4	6.1	7.2	11.5	6.5	12.7	13.3	13.5	12.3
CV	0.11	0.13	0.11	0.14	0.18	0.11	0.19	0.18	0.18	0.13

Note: SE - Standard error; CV - Coefficient of variance.

TABLE 2. TEMPERATURE DISTRIBUTION IN STACKED LAYERS OF LOOSE OIL PALM FRUITS AFTER MW HEATING AND MW-STEAM HEATING

(a) MW heating	Heating time (min)									
	1		2		3		4		5	
Temperature	Internal	Surface	Internal	Surface	Internal	Surface	Internal	Surface	Internal	Surface
T1 (°C)	89.1	74.2	96.9	96.3	108.9	113.6	111.6	120.7	118.1	126.9
T2 (°C)	68.9	67.4	91.8	88.1	104.3	104.4	105.5	111.7	106.9	113.9
T3 (°C)	65.2	58.7	85.8	83.3	97.5	98.9	100.8	106.0	101.5	108.0
T4 (°C)	58.7	53.6	77.1	77.1	87.3	91.5	92.2	98.2	92.9	102.3
Mean (°C)	70.5	63.5	87.9	86.2	99.5	102.1	102.5	109.2	104.9	112.8
SE (°C)	6.6	4.6	4.3	4.1	4.7	4.7	4.1	4.8	5.3	5.3
CV	0.19	0.14	0.10	0.10	0.10	0.09	0.08	0.09	0.10	0.09
(b) MW-steam heating	**Heating time (min)**									
	1		2		3		4		5	
Temperature	Internal	Surface	Internal	Surface	Internal	Surface	Internal	Surface	Internal	Surface
T1 (°C)	85.1	81.6	98.3	98.8	100.4	105.4	102.4	111.9	108.8	116.1
T2 (°C)	81.1	65.9	93.7	91.2	98.1	101.5	100.2	104.8	103.1	111.4
T3 (°C)	66.7	61.7	88.7	87.1	95.7	98.0	97.4	99.8	98.3	105.3
T4 (°C)	60.3	53.9	82.0	79.2	89.2	91.9	90.2	96.8	92.1	93.3
Mean (°C)	73.3	65.8	90.7	89.1	95.9	99.2	97.6	103.3	100.6	106.5
SE (°C)	5.9	5.8	3.5	4.1	2.4	2.9	2.7	3.3	3.6	5.0
CV	0.16	0.18	0.08	0.09	0.05	0.06	0.06	0.06	0.07	0.09

Note: SE - Standard error; CV - Coefficient of variance.

(0.458 W/m·K) of oil palm mesocarp, less energy per kg is required to incur a temperature change, and a rapid surge in temperature is exhibited (Dogan *et al*., 2014; Law *et al*., 2019). However, the decline in heating rate is likely due to reduced MW absorbance as dielectric properties in oil palm fruits weaken during moisture drying. The same phenomenon applies to stacked layers of oil palm fruits, where the mean internal temperature increased rapidly at a rate of ~0.8°C/s during the first min of MW heating and MW-steam heating and subsequently dropped to as low as ~0.1°C/s (*Table 2*). The mean surface temperature in stacked layers increased at ~0.7°C/s during the first min of heating before dropping to ~0.1°C/s (*Table 2*). Despite a 100% increase in mass, the internal and surface heating rate was only 31% and 23% lower in stacked layers than in a single layer due to the enhanced effect of stacking fruits on MW absorption efficiency (Shah *et al*., 2022). Since MW heating involves volumetric heating, the internal temperatures were initially higher than the surface. The rapid moisture evaporation resulted in a significant pressure-driven flow of vapour transferring heat to fruit surfaces by convection. Ultimately, the surface temperatures exceeded the internal temperatures as the heating was prolonged in both single (*Table 1*) and stacked layers (*Table 2*). The fruit's outer skin being less permeable than its inner flesh may also deter the escape of vapours and confine the heat near the surface.

Figure 1 shows that MW-steam heating (dashed lines) had marginally faster drying rates as compared to MW heating (solid lines). The vapours entrapped inside the container in MW-steam heating escalated the collision frequency between vapour molecules and the container walls, exerting pressure. Consequently, the increase in the average kinetic energy of the molecules allowed faster vaporisation (Connors, 1990). When vapour molecules saturate the air inside a closed container, the vapour condenses to the liquid phase (Wellbeloved, 2020). In the present study, the vapours condensed to liquid onto the container walls and lid. If measures for adequate steam venting are overlooked, the unrestricted build-up of pressure inside the container could result in an explosion resulting in steam burns or injuries from the spilling of hot liquid.

Oil palm fruits are sterilised to inactivate the lipase enzyme, and soften the fruit mesocarps while preserving the kernel condition (Vincent *et al*., 2014). The initial moisture content of loose oil palm fruits was determined to be 32 wt.% on average. The moisture content should be lowered to at least 15 wt.% to inactivate lipase (Okolo and Adejumo, 2014). Yoosa *et al*. (2018) advised that residual moisture content of 15 wt.% helps preserve fruits from fungi, and halts FFA from increasing while preserving the kernel condition. Shah *et al*. (2022) reported a ~70% reduction in fruit hardness with a residual moisture content of 15 wt.%. From *Figure 1*, the optimum sterilisation duration to reduce the moisture content to 15 wt.% was determined. With MW heating, the requisite heating duration to achieve sterilisation was determined to be 2.8 min for a single layer and 4.4 min for stacked layers. MW-steam heating took 2.5 min of heating for a single layer and 4.2 min of heating for stacked layers for sterilisation. Sample temperatures during optimal sterilisation durations were well below the melting point of polypropylene (160°C) in both single (*Table 1*) and stacked layers (*Table 2*), implying sufficient thermal resistance of the container under MW irradiation. Interestingly, doubling the sample size (number of layers) does not necessarily double the requisite heating time; only a 57% and 68% increase in heating time was required for stacked fruits with MW heating and MW-steam heating, respectively, possibly due to the constructive effect of stacking/dielectric layering on the MW absorption which was earlier discussed. MW heating required ~13% (20 s) and ~7% (16 s) longer heating time than MW-steam heating for single and stacked layers, respectively. It is evident that combining the stacking of fruits with integrated MW-steam heating can reduce sterilisation duration.

Figure 2 shows the appearance of sterilised loose oil palm fruits after MW and MW-steam heating. Raw fruits had vibrant yellowish-orange mesocarps and white kernels. Upon sterilisation, the mesocarps deepened in colour with oil discharges, white kernels, and a caramel-type odour. Excessive moisture removal resulted in brown and dry mesocarp fibres and dark kernels. Similar observations were reported by Cheng *et al.* (2011). No noticeable difference in physical appearance was observed between single and stacked layers. However, the mesocarps of MW-steam sterilised fruits were visibly uniform in appearance throughout (both away and near the surface), likely due to the constructive influence of steam on fruit surfaces.

Effect on Oil Extraction Rate and Crude Palm Oil Quality

Table 3 lists the OER, and quality characteristics of CPO produced from MW and MW-steam sterilisation of loose oil palm fruits. An OER of up to 25.6% was achieved with integrated MW-steam sterilisation. An 8.5% to 10.5% increase in OER was recorded with MW-steam sterilisation in a single layer and stacked layers, respectively, as compared to regular MW sterilisation. The improved heating uniformity with MW-steam sterilisation was likely influential in enhancing the OER. However, the OER is also reliant on the method of oil extraction. Cheng *et al.* (2011) obtained an OER of 21.2% from MW-sterilised oil palm fruits using solvent extraction. Whereas Yoosa *et al*. (2022) reported an OER of 30.3% from MW-sterilised oil palm fruits (15 wt.%

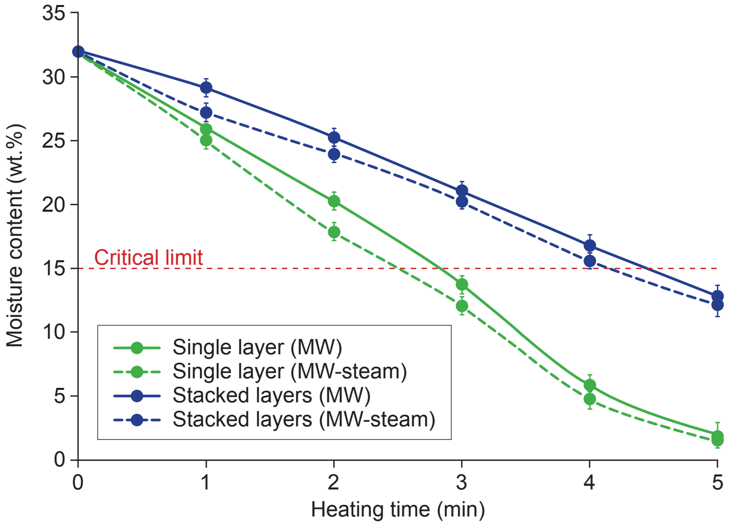

Figure 1. Drying curves of loose oil palm fruits during MW heating and MW-steam heating.

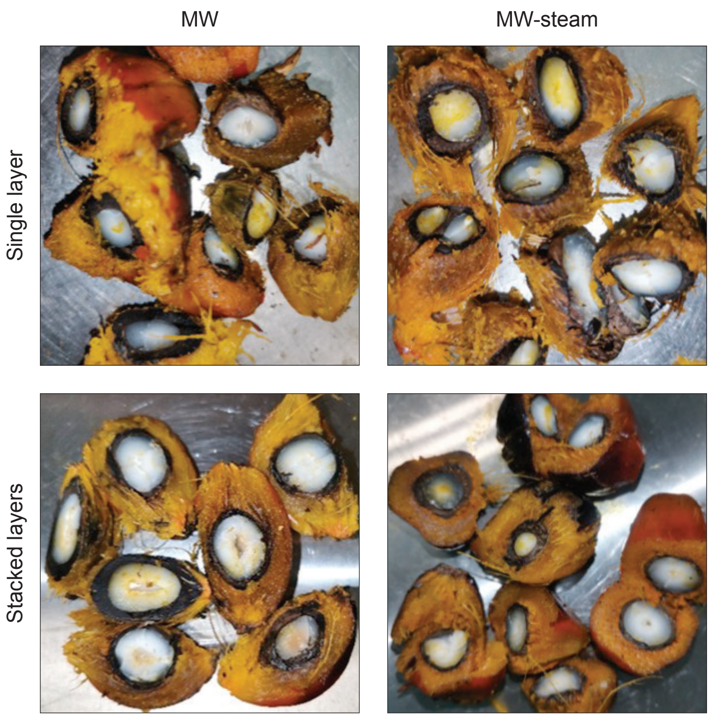

Figure 2. The physical appearance of sterilised oil palm fruits after MW heating and MW-steam heating.

residual moisture content) using an automatic palm oil presser. Although they reported an additional ~3.5% in OER with a lower residual moisture content of 5 wt.%, the requisite sterilisation duration and consequently the energy consumption/cost increased significantly by up to 58.0%. The total OER in Malaysian palm oil mills was 20.0% in the year 2021 (Parveez, 2002).

The quality of CPO extracted from the sterilised oil palm fruits (M = 15 wt.%) was well within the commercial standards (*Table 3*). The FFA content in non-sterilised fruits was determined to be 16.4%, which is undesirably high and unfit for human consumption. *Table 3* shows that MW sterilisation caused a significant drop in the FFA content of oil palm fruits. According to Tang *et al*. (2017), MW heating significantly reduces the FFA content in oil palm fruits. Recently, Shah *et al*. (2022) reduced the FFA content in oil palm fruits by ~94 using intermittent MW heating. In another study, Nokkaew and Punsuvon (2014) reduced the FFA content in oil palm fruits from 38.0% to 3.0% using

TABLE 3. THE OER AND QUALITY OF CPO EXTRACTED FROM STERILISED LOOSE OIL PALM FRUITS

Quality parameter	Single (MW)	Single (MW-steam)	Stacked (MW)	Stacked (MW-steam)	Standard quality CPO*
OER (%)	23.60 ± 1.10	25.60 ± 1.30	22.80 ± 0.90	25.20 ± 1.80	-
FFA (%)	1.2 ± 1.3	1.1 ± 1.0	1.3 ± 1.1	1.0 ± 0.8	5.0 (max)
MV (%)	0.08 ± 0.00	0.08 ± 0.00	0.07 ± 0.01	0.07 ± 0.00	0.25 (max)
AnV	0.54 ± 0.04	0.15 ± 0.90	0.74 ±1.11	0.39 ± 0.20	5.0 (max)
UV TOTOX	0.86 ± 0.08	0.91 ± 0.08	0.91 ± 0.10	0.97 ± 0.02	1.80 (max)
Iron (µg/g)	1.4 ± 4.7	1.8 ± 3.1	2.8 ± 2.1	2.1 ± 1.1	5.0 (max)
Phosphorus (µg/g)	10.5 ± 3.2	15.0 ± 0.8	11.8 ± 2.5	12.3 ± 1.7	20.0 (max)
IV (g/100g)	52.9 ± 0.5	52.6 ± 0.1	51.9 ± 1.2	53.7 ± 0.2	50.4-53.7
Carotene (mg/kg)	535 ± 44	485 ± 62	479 ± 39	503 ± 17	474-689
DOBI	5.2 ± 0.5	4.6 ± 0.9	4.7 ± 0.4	4.4 ± 0.9	2.3 (min)

Source: Farah *et al*. (2019).

MW heating. Recently, Kanjanapongkul (2021) achieved an FFA content of 1.5% using combined ohmic and MW heating. In the present study, the FFA content was well below the critical limit of 5.0% across all CPO samples, even superior to special quality CPO (FFA: 2.5%). MW heating samples experienced the maximum FFA content of 1.2% and 1.3% in single and stacked layers. CPO samples from MW-steam heating had ~10.5% lower FFA content than MW heating, indicating added improvement in oil quality, possibly due to enhanced sterilisation as a result of improved heating uniformity.

The MV content of CPO extracted from non-sterilised loose oil palm fruits (M = 32 wt.%) was determined to be 0.48%. Since lipase is a hydrolase, minimising moisture is of utmost importance to prevent lipid hydrolysis to produce CPO that is fit for storage. In the current study, the MV content was drastically reduced by more than 83.0% in the CPO samples and was way below the standard limit of 0.25%. Up to 5.4%, lower MV was obtained with MW-steam heating than with regular MW heating. Moreover, stacked fruits had 10.8% lower MV than a single layer, hinting at the constructive effect of the stacked arrangement on moisture drying due to increased MW absorption (Shah *et al*., 2022). The combined effect of MW-steam heating and stacking produced CPO with 15.7% lower MV content than from a single layer with regular MW heating.

AnV is the amount of the secondary oxidation products (aldehydes and ketones) broken down from the primary products (lipid peroxides and hydroperoxides) and responsible for the oil's rancid taste and smell (Yang and Boyle, 2016). The AnV was well below the critical limit of 5 for all samples, implying excellent secondary oxidative stability of CPO obtained through MW sterilisation. Moreover, MW-steam heating further augmented oxidative stability as AnV was 72.9% and 47.1% lower in single and stacked layers. CPO with a high AnV has a reduced shelf life and is also unhealthy for consumption. Tan *et al*. (2017) produced CPO with an AnV of 2.2 using MW heating, whereas the AnV recorded in the present study was significantly lower (0.15 to 0.74), especially using MW-steam heating. The specific extinctions at wavelengths 233 nm and 269 nm in ultraviolet light were also used to detect the presence of primary and secondary oxidation products in CPO, respectively. The ultraviolet total-oxidation or UV TOTOX (E233 + E269) was below 1 for all oil samples, indicating better oxidative stability than standard quality CPO.

A pro-oxidant metal such as iron catalyses lipid oxidation in CPO causing oxidative instability and poor bleachability (Bustamam *et al*., 2020). It is essential that the iron content in CPO is minimal and does not exceed 5.0 µg/g. The iron content was below 3.0 µg/g in all cases. Moreover, iron content was 22% (single layer) to 25% (stacked layers) lower in CPO extracted from MW-steam heated samples than MW heated (*Table 3*). Phosphorus is another trace contaminant in CPO that should not exceed 20 µg/g for better bleaching properties. The phosphorus content was well below the critical limit for all CPO samples in the present study and did not exceed 15 µg/g. However, CPO produced from fresh oil palm fruits with low FFA content has a significantly lower amount of phosphorus (2 µg/g) (Hassan *et al*., 2021).

The IV was consistent with the standard quality CPO requirement (50.4 g/100g-53.7 g/100 g) for all cases. Hassan *et al*. (2021) reported a similar IV (52.3 g/100 g) for CPO extracted from fresh oil palm fruits sterilised using the conventional steam method. However, Tripathi and Yadav (2021) reported an IV of 46.1 g/100 g in CPO after 10 min of MW heating, declining further when exposure was prolonged; hence, optimal sterilisation duration is necessary to maintain IV within the desired range. IV is yet another indicator of oxidative stability of CPO as it reveals the degree of fatty acid unsaturation in oil (Noor *et al*., 2020). Since unsaturated compounds in the oil are very reactive toward halogens like iodine, they are more prone to oxidation; hence, IV must be controlled within the recommended range. In a recent study, MW treatment effectively reduced the unsaturated fatty acid to saturated fatty acid ratio and IV in milk thistle seed oil (Fathi-Achachlouei *et al*., 2019).

Carotenoids are vital phytonutrients and potent antioxidants that provide oxidative stability to palm oil. The carotene content (as β-carotene) of all four oil samples was within the standard CPO quality range (474-689 mg/kg), inferring adequate carotene retention. Prolonged heating at temperatures above 60°C can degrade carotenoids; hence, it was advisable to use low temperatures (low MW power level) or low heating periods for sterilisation (Sarah, 2018). The present results were closer to the lower limit, possibly due to heating at a high MW power setting (800 W) with maximum sterilisation temperatures topping 100°C in all cases (*Table 1* and *2*). Carotene content also reduces with an increase in storage time (Ali *et al*., 2014), which was more than 24 hr in the present study. Nevertheless, Sarah *et al*. (2018) produced red palm oil (high carotene content) at an 800 W power level using freshly harvested oil palm fruits.

DOBI is a critical CPO quality characteristic expressed as the ratio of carotene concentration to the secondary oxidation products (Basyuni *et al*., 2017). The DOBI value for all oil samples was above 4.00, which is superior to that of standard CPO quality (DOBI: 2.30). A high DOBI indicates facilitation in the refining process, particularly bleaching. Remarkably, DOBI was as high as 5.16 (single layer) and 4.73 (stacked layers); CPO with a DOBI above 3.00 is recognised to be of premium quality (Nokkaew *et al*., 2019). The results for MW-steam heated samples (4.40-4.60) were comparable to that of CPO obtained using the combined MW and oven drying method (3.89-4.61) in a study by Tapanwong *et al*. (2020).

Effect on Energy Consumption/Cost

The electricity consumption in palm oil mills for FFB processing is 0.02 kWh/kg, excluding costs of fuel, water, chemicals and refining (Norfaradila *et al*., 2014). With MW-steam sterilisation, CPO of commercial standards was produced, simplifying the palm oil milling process to only two major steps: Sterilisation and oil extraction. The reduced sterilisation duration due to MW-steam heating and stacking allowed significant energy savings. *Figure 3* presents the energy consumption data calculated in this study using the E1 tariff (0.337 MYR/kWh) of Tenaga Nasional Berhad, Malaysia (TNB) utility company. In a single layer, electricity consumption was 0.44 kWh/kg with MW heating (*Figure 3a*), and 0.38 kWh/kg with MW-steam heating (*Figure 3b*). In stacked layers, consumption was 0.35 kWh/kg with MW heating (*Figure 3c*), and 0.32 kWh/kg with MW-steam heating (*Figure 3d*). Using MW-steam heating, energy consumption was 13.6% lower in a single layer and 8.6% lower in stacked layers as compared to regular MW heating. Moreover, 19.2% and 17.9% lower energy consumption/costs were attained by stacking under MW and MW-steam heating, respectively, as compared to a single layer. To the best of the author's knowledge, MW-steam heating combined with stacking (0.32 kWh/kg) is the lowest energy consumption process for MW sterilisation of oil palm fruits. Kanjanapongkul (2021) reported energy consumption of 0.38 kWh/kg using combined ohmic and MW heating of oil palm fruits, but at the expense of CPO quality with poor carotene retention (438 mg/kg). Recently, Yoosa *et al.* (2022) attained a similar energy consumption of 0.38 kWh/kg using regular MW sterilisation.

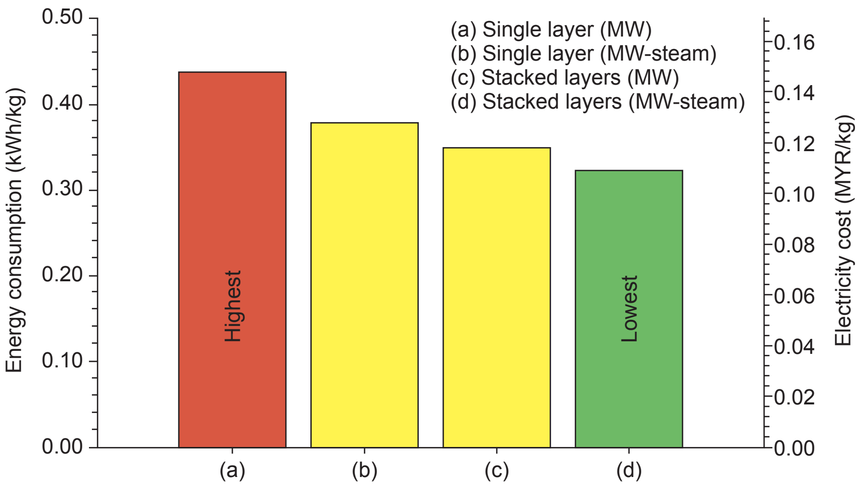

Figure 3. Energy consumption and energy cost to sterilise per kg of loose oil palm fruits using MW heating and MW-steam heating.

CONCLUSION

A significant improvement in temperature uniformity in both internal and surface temperature distributions was discovered with MW-steam heating. The stacked arrangement of fruits was also influential in enhancing heating uniformity. MW-steam heating had no significant effect on MW absorbance; however, stacking fruits enhanced the absorption efficiency significantly. CPO extracted from MW and MW-steam sterilised fruits met commercial standards: While the IV and carotene content were comparable to standard CPO quality, the FFA content, MV, PV, AV, UV TOTOX, iron and phosphorus were superior to standard CPO. Moreover, MW-steam heating boosted the oil extraction rate and augmented the CPO quality, particularly the FFA, MV and AV. The reduction in energy consumption and cost for sterilisation was noteworthy: Stacking reduced energy consumption by up to 19.2%, while MW-steam heating reduced it by up to 13.6%. It can be concluded with certainty that MW sterilisation of oil palm fruits was enhanced using the integrated MW-steam sterilisation method allowing improved temperature uniformity, a faster drying rate, increased oil extraction rate, superior CPO quality and lower energy consumption. In doing so, the value was added to high FFA loose fruits to minimise oil yield losses by increasing the OER. The findings of the present research work intend to serve as a prologue to incorporating integrated MW-steam heating in industrial MW systems to enhance the sterilisation process. Although food industries could readily adopt the technique due to its minimalism, experimental work in an industrial MW system is crucial to truly realise the effectiveness of MW-steam sterilisation on a larger scale.

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