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Enhancement of palm oil extraction yield by applying underwater shock wave pre-treatment at different voltage

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Abstract

The present work aimed to investigate the effect of underwater shock wave (USW) on palm oil yield. Palm fruits were prepared and treated by applying USW before oil extraction. Strong USWs were generated by discharging high electric voltage into water, and varying the supplied voltage in the range of 2 - 10 kV. Following USW treatment, two methods of palm oil extraction namely screw-press and solvent extraction were used to determine the oil yield. Oil yield extraction and microstructure morphology of palm mesocarp were also investigated. It was found that at 10 kV of the USW treatment, the highest yield of palm oil extraction through screw-press method was 66.35%, while the solvent extraction method yielded 70.38%, which were 3.1 and 6.3% improvement, respectively, as compared to the untreated extraction. Microstructure analysis by scanning electron microscope (SEM) of palm mesocarp showed that the oil cells had significant cracks on the surface following treatment with USW. This confirmed that the application of USW was effective in increasing palm oil yield extraction. With a reliable strength and repetition of the treatment, USW treatment is promising for practical application in the palm oil industry and also other plant oil extraction.

Introduction

Oil palm (*Elaeis guineensis*) is a perennial oil crop which originated from South Africa. In 1968, it began to grow in the southern region of Thailand, and eventually in other regions of Thailand. In 2018, the cultivated area of oil palm in Thailand was about 940,800 ha (811,200 ha in the south, 82,720 ha in the centre, 32,640 ha in the northeast, and 14,240 ha in the north; OAE, 2018). Nowadays, Thailand is the third largest palm oil producer in the world after Indonesia and Malaysia (Chuasuwan, 2018). Palm oil can be categorised into two types: crude palm oil (CPO) produced from the mesocarp, and palm kernel oil (PKO) produced from the kernel (Robbelen, 1990; Gourichon, 2013). Red palm oil is another name for CPO because it is rich in palmitic acid, β-carotene (Mba *et at.,* 2015), vitamin E, coenzyme Q_{10} (ubiquinone), and sterols (Tyagi and Vasishtha, 1996). Approximately, 90% of palm oil is used in the food industry, while the remaining 10% is applied in the production of oleochemicals and soaps (Oil World, 2013). Additionally, CPO is an essential element in many foods and industrial products such as ice creams, cosmetics, toothpastes, and biodiesels (Barriuso *et al.,* 2013). The production of palm oil in Thailand is mainly consumed in the country, and the government has a policy to support the use of CPO to produce renewable biofuel as biodiesel. Therefore, the government strongly encourages the planting of oil palm for commercial purposes. While there are more growing areas, most of the palm oil mills are located in the south of Thailand, and most of them are small and medium enterprises. Moreover, the oil extraction technology is low in terms of machinery size and its efficiency; subsequently affecting the CPO production capacity. Mechanical screw-press system is the most widely used method to extract CPO. Kanjanapongkul (2021) investigated the employment of ohmic and microwave heating on palm oil quality and stability, and found that the CPO yield could be increased up to 47%. According to Md Sarip *et al.* (2016), the use of this system was unable to extract CPO attached to the cell wall. The oil extraction rate is mostly 16 - 17% (the government has a policy to extract to 18%), whereby to increase the production capacity and quality of the extracted oil, the size of the production machinery will have to be increased which will lead to higher production costs. Indonesia and Malaysia have oil extraction

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rates of 22 and 21%, respectively. Therefore, the technology used in CPO extraction is an important part of the production. Moreover, bringing new technology to assist the traditional extraction of CPO will also increase the productivity and decrease the production costs.

There are several technologies used to help extract CPO such as hot compressed water (HCW) (Md Sarip *et al.,* 2016), and the use of propane, ethanol, and compressed solvent solutions (Jesus *et al.,* 2013) using sub-critical R134a to help extract palm oil (Mustapa *et al.,* 2009). While the aforementioned oil extraction methods are rather complex and time-consuming, high voltage electrical discharges (HVED) technique takes a short time to operate, in terms of micro- or nanoseconds. HVED is the breakdown process between positive and negative electrodes submerged under water. This process causes plasma breakdown occurrence, and rapidly releases energy due to the breakdown, which causes underwater shock wave (USW) (Touya *et al.,* 2006; Boussetta *et al.,* 2012; Li *et al.,* 2019). This phenomenon is the same as that of an underwater explosion, and will produce extremely high pressures such as shock waves, which are violent and penetrative, thus damaging the cell walls (Yasuda *et al.,* 2017). Therefore, USW is widely used to increase the extraction yield of many plant compounds such as grape seeds, grape pomace (Boussetta *et al.,* 2009; 2013), sugarcane (Shimojima *et al.,* 2012), *Alpinia zerumbet* leaves (Kuraya *et al.,* 2014), carrot (*Daucus carota* L.; Yasuda *et al.,* 2017), and mango peels (Parniakov *et al.,* 2016).

In addition, there are studies on the application of USW to increase oil yield in the extraction of plant oils such as sesame oil (Sarkis *et al.,* 2015) and *Jatropha curcas* (Maroušek *et al.,* 2013). The oil yield through USW-assisted extraction was higher as compared to the untreated ones. Boussetta and Vorobiev (2014) reported that HVED was used to help extract palm oil, which achieved 36% oil yield. Previous research has reported the influence of USW on the palm fruit by using the CFD simulation, as well as the prediction and validation of USW pressure generated by explosion and electrical discharge method (Suttiprapa *et al.,* 2017a; 2017b). However, so far, no studies have been carried out on the enhancement of palm oil yield where the USW is applied prior to the oil extraction process. Therefore, the present work aimed to investigate the enhancement of palm oil yield by applying USW prior to the extraction process. The microstructure morphology of palm mesocarp following the USW treatment was also examined. In order to confirm the benefits of the USW application, the conventional untreated sample served as comparison.

Figure 1. Palm fruit preparation: (A) palm fruit bunch, (B) fresh palm fruits, and (C) small pieces of palm.

Materials and methods

Palm fruit preparation

The palm fruits used in the experiment were purchased from a local farmer at Ubon Ratchathani, Thailand. The palm fruits were then cut into small pieces (5 × 5 × 3 mm) with a scalpel, as shown in Figure 1. The small pieces of palm fruits were vacuum-packed in 15 g/bag, and stored at -5°C for subsequent experiments. The samples were divided into two groups; untreated (control) and treated (USW).

Underwater shock wave treatment

The principle of USW generation by using high voltage electric discharge (HVED) is diagrammatically shown in Figure 2. The high voltage power supply was adjustable in the range of 1 to 40 kV D.C. and was charged to high voltage capacitor (5 µF, 50 kV). Voltages of the USW-treated palm fruits were in the range of 2 - 10 kV (2, 4, 6, 8, and 10 kV) (V_{Charge}), and were charged to the high voltage capacitor. In the discharging stage, the discharged current from the positive stainless-steel electrode flowed through the electrode gap to the negative stainless-steel electrode. To find the optimum size of the electrode, electrode diameters sized 3, 6, and 9 mm were tested, while the electrode gap were varied at 1, 2, 3, 4, and 5 mm. The details of the results are shown in next section. The electrode size of 6 mm in diameter was selected to be used in all experiments. Both electrodes were immersed in water in a cylindrical test chamber with a volume of 2 L as shown in Figure 3. The gap between both electrodes was pre-set at 2 mm. The phenomena of the USW could be observed through windows made from a clear acrylic plate with 15 mm thickness on the front and back sides of test chamber. The palm oil fruit, containing of 15 g/bag, was placed at a depth of 50 mm under the centre of the electrode gap. Each HVED generated a single strong USW to impact on the palm oil fruit, and this phenomenon was counted as one pulse or single pulse.

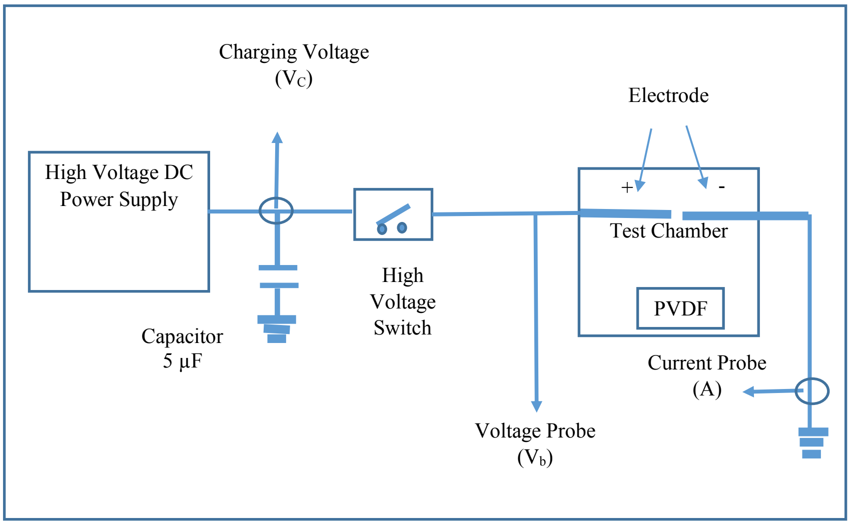

Figure 2. Schematic diagram of the experimental set up for USW generation.

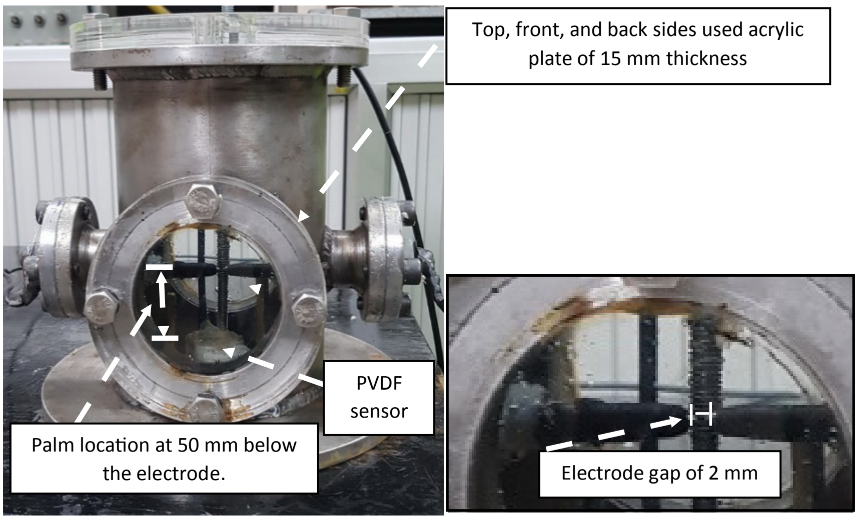

Figure 3. The test chamber and experimental setup.

Pressure measurement

Polyvinylidene fluoride (PVDF) membranes, which are a type of piezoelectric polymer transducer, were used to measure the pulse pressure (or shock pressure) after the USW was generated. The piezoelectric polymer transducers were calibrated by using drop test method (Sahaya Grinspan and Gnanamoorthy, 2010; Hujer and Müller, 2018). The calibration results are shown in Eq. 1, and the R^2 was 0.992.

$$F = 60.627V + 19.665 \quad \text{(Eq. 1)}$$

where, F = impact force of the USW exerted on the PVDF (N), and V = voltage measured from the PVDF (V).

Further details about pressure measurement can be found in the study of Sahaya Grinspan and Gnanamoorthy (2010). The generated pressures were calculated using Eq. 2:

$$P = \frac{F}{A} \quad \text{(Eq. 2)}$$

where, P = generated pressure i.e. shock pressure in the experiment (MPa), F = impact force of the USW exerted on the PVDF, and A = area of the PVDF (10 mm width × 15 mm length).

Oil yield measurement

The palm oil samples were treated by USW at 2 - 10 kV as previously described. Following the USW treatment, the samples were ground by blender into homogeneous fine-sized pieces, smaller than 80 mesh, and then dried in a hot air oven at 50°C for 24 h. The oil in the palm samples were extracted by the two aforementioned methods. Both the treated and the untreated samples were prepared similarly.

Solvent extraction

The dried palm was placed in a Soxhlet extraction apparatus with a semi-continuous process of extraction (AOAC, 2000). Solvent extraction was conducted by using petroleum ether as the solvent for 6 - 8 h, and then followed by solvent removal using the rotary evaporator. The oil samples were dried at 105°C to remove residual solvent, and then the mass of the yielded oil was weighed. The oil yield percentage was calculated using Eq. 3:

$$Oil\ yield(\%) = \frac{W_2}{W_1} x100 \quad \text{(Eq. 3)}$$

where, W_1 = total weight (wet weight) of the palm oil mesocarp sample (g) before extraction, and W_2 = weight of the oil after extraction (g).

Screw-pressing

In the screw-press method, a palm oil mesocarp sample of 60 g was pressed using a laboratory mechanical screw-press, which was made from stainless steel 304 with a screw diameter of 2 cm and seven teeth for the whole length (10 cm). The capacity of the screw-press was 2 - 4 kg/h. The palm oil samples were fed from hopper to screw-press by gravity. The oil was weighed and kept at 4°C for subsequent analysis. The oil yield percentage was calculated using the same Eq. 3 as previously described.

Free fatty acid content and acid value analysis

The method of titration (AOAC, 1992) was applied to analyse the free fatty acid (FFA) content. The CPO samples were diluted in ethanol, then sodium hydroxide solution (0.1 N) was dropped onto the samples, and phenolphthalein was used to find the end point. The FFA percentage content was determined using Eq. 4:

$$FFA(\%w/w) = \frac{VxNx25.6}{m} \quad \text{(Eq. 4)}$$

where, V and N = volume and concentration of the employed sodium hydroxide solution, respectively, and m = mass of the sample (5 g). The FFA percentage of CPO was computed as palmitic acid, and interpreted as the weight of NAOH (in mg) required to counteract acid from the 5 g sample. Next, the acid value (AV) was determined using Eq. 5:

$$AV = FFA\%x2.19 \quad \text{(Eq. 5)}$$

where, AV = acid value, and 2.19 = conversion factor to convert FFA from palmitic acid to AV.

Scanning electron microscope (SEM) microstructure analysis

The palm mesocarp samples from the USW treated and untreated samples were dried using critical point drier (CPD) (Quorum-K850, United Kingdom), and afterward, the mesocarp samples were coated with gold using sputter coater (JOEL-JEC 3000 FC, Japan). The morphology of mesocarp samples were observed by the scanning electron microscope (SEM) (JEOL JSM-6010LV, USA) at an accelerated voltage of 3 kV.

Statistical analysis

The effect of USW on oil yield was compared using the analysis of variance (ANOVA). The effect of USW treatment on oil yield was considered statistically different if p value < 0.05.

Results and discussion

Optimum parameters

Effect of the electrode diameter on the peak pressure

To determine the optimum size of the electrode, the electrode diameters of 3, 6, and 9 mm were tested at various electrode gaps between 1 - 5 mm. It was found that the generated peak pressure always occurred at the 6 mm electrode diameter. For example, in the case of 7 kV discharge, the peak pressure of 49.6, 54.9, and 40.0 MPa were obtained from the electrode diameter of 3, 6, and 9 mm, respectively. Therefore, the electrode diameter of 6 mm was selected as the optimum size, and was used in subsequent analyses.

Effect of the electrode gap on the peak pressure

After the electrode diameter of 6 mm was determined, the optimum electrode gaps of 1, 2, 3, 4, and 5 mm were tested with the 6 mm electrode. At 7 kV discharge, the peak pressure of 54.9 MPa occurred at 2 mm electrode gap. This was the maximum, while 1, 3, 4, and 5 mm electrode gaps at 7 kV gave the pressure of 29.9, 49.1, 46.6, and 43.1 MPa, respectively. From the experiment, it was found that, at 1 mm electrode gap, the tip of the electrode severely melted and was damaged due to the very strong voltage jump between the electrodes. This is not favourable in practice. For the electrode gap surface of 3 - 5 mm, the electrode tips were in good condition, but they showed high energy loss due to the significant gap *i.e.* giving low shock pressure (Ide *et al.,* 2011). Therefore, the electrode gap of 2 mm was selected as the optimum gap, and was in subsequent analyses.

Shock pressure generation

After the impact pressure was obtained from the PVDF measurement, the generated pressure was calculated from Eq. 1 and Eq. 2. The trend of the results of impact pressure observed in the present work agrees with the experimental results generated in a previous study (Touya *et al.,* 2006) and the computational fluid dynamics (CFD) simulation (Suttiprapa *et al.,* 2017b). The shock pressure from the 2, 4, 6, 8, and 10 kV discharges were 0.13, 17.70, 28.10, 41.39, and 43.92 MPa, respectively, as shown in Figure 4. At the V_{Charge} of 2 kV, it was found that the pressure was only 0.13 MPa, due to the low V_{Charge} not being able to jump across the electrode gap due to the energy lost in water while it flowed from positive to negative electrode (Ide *et al.,* 2011). Therefore, the lower V_{Charge} did not spark nor did the shock pressure occur, while the V_{Charge} of 4 - 10 kV could jump across the electrode gap from positive to negative electrode, thus generating spark as a result. From these, the maximum shock pressure was generated from the 10 kV discharge at 43.92 MPa. This pressure trend agrees well with previous works (Touya *et al.,* 2006; Bian *et al.,* 2018), showing the increase of shock pressure when voltage increases. This shock pressure was strong enough, and could lead to the cracking of the mesocarp structure as discussed in the next section.

Oil yield percentage

The present work investigated the application of the USW treatment at 2, 4, 6, 8, and 10 kV prior to the oil extraction processes (solvent extraction and screw-press), and compared the treated with the untreated palm samples. The oil yield of USW treated palm oil and untreated samples

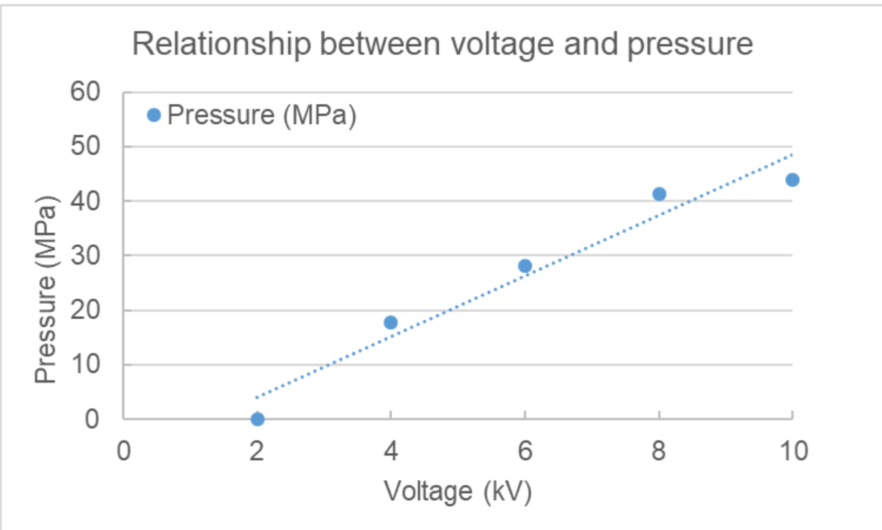

Figure 4. Relationship between voltage and pressure.

are presented in Table 1, which were calculated by Eq. 3. The treated USW samples had higher oil yield percentages when compared with the untreated samples from both solvent and screw-press extraction methods. It was found that the oil yield percentages increased with increasing discharged voltage, *i.e.* the strength of the USW treatments. However, at low voltages (2 - 4 kV) treatment, the yield from both solvent extraction (66.18 - 66.58%) and screw-press (64.33 - 64.66%; $p > 0.05$) methods showed no significant differences when compared with untreated samples. High oil yield percentages of the palm samples were obtained when the discharged voltages were from 6 - 10 kV in the USW treated samples for both solvent extraction and screw-press methods. When the yield of the USW treated samples from the two oil extraction methods were compared with untreated samples, it was found that the oil yield from both methods had significant differences with untreated samples. The oil yield percentages of USW treated samples with solvent extraction was 67.00 - 70.38%, and screw-press method was 65.08 - 66.35%, an increase when compared with untreated samples at the range of 1.2 - 6.3% and 1.1 - 3.1%, respectively. The highest oil yields were obtained from 10 kV USW treatment at 70.38% from the solvent extraction, and 66.35% from the screw-press method. These results suggested that high voltage of the USW treatment during the pre-extraction preparation had stronger effects on oil yield percentage. It was found that higher voltage generation contributed to stronger shock pressure, and could cause severe damage to the oil sac and mesocarp of the oil palm. The values

Table 1. Palm oil yields from different oil extraction methods for treated and untreated USW (control).

Voltage (kV)	Oil yield (%)	
	Solvent extraction	Screw-press
0 (control)	66.21 ± 0.40^{a}	64.37 ± 0.24^{a}
2	66.18 ± 0.38^{a}	64.33 ± 0.32^{a}
4	66.58 ± 0.40^{ab}	64.66 ± 0.34^{ab}
6	67.00 ± 0.30^{bc}	65.08 ± 0.22^{bc}
8	67.44 ± 0.38^{c}	65.23 ± 0.23^{c}
10	70.38 ± 0.30^{d}	66.35 ± 0.20^{d}

Values are mean ± SD from triplicate determination ($n = 3$). Different lowercase superscripts in a column indicate significant difference at $p < 0.05$.

of oil yield extracted from the USW treated samples in the present work agree well with Owolarafe *et al.* (2002) who found that the crude oil yield from the digester-screw press (DSP) and hydraulic press system were 79.3 and 67.0%, respectively. Mustapa *et al.* (2009) reported oil yield extraction by using sub-critical R134a range of 43.5 - 66.06% at 40 - 80°C and 45 - 100 bar, and the maximum oil yield was 66.06% at 80°C and 100 bar. Mustapa *et al.* (2011) reported oil yield extraction by using sub-critical R134a range of 48.57 - 66.06% at 40 - 80°C and 60 - 100 bar, and the maximum oil yield was 66.06 at 80°C and 100 bar. Jesus *et al.* (2013) reported oil yield extraction by using compressed ethanol (100%), propane (100%), solvent mixtures, and Soxhlet extraction with *n*-hexane; it was found that the oil yield were 53.3 - 70.6%, 69.5 - 73.9%, 66.1 - 75.3%, and 61.3%, respectively. Moreover, this method gave more oil yield than the one pre-treated by the ohmic combined with microwave heating whose oil yield was 47.11% (Kanjanapong-kul, 2021). The aforementioned values of oil yields are comparable with those observed in the present work. Moreover, the results of palm oil yield in the present work were higher than those reported by Boussetta and Vorobiev (2014) (36% oil yield) who used similar HVED treatment. Further, the results and discussion can be clearly explained by the shock pressure of the generated shockwave which had an influence on the surface and the cell structure of palm mesocarp as discussed in the next section. Additionally, USW treatment has also been applied to increase extraction efficiency in sugarcane (Shimojima *et al.,* 2012), *Jatropha curcas* (Maroušek *et al.,* 2013), *Alpinia zerumbet* leaves (Kuraya *et al.,* 2014), grape seeds (Boussetta *et al.,* 2013), grape pomace (Boussetta *et al.,* 2009), sesame seeds (Sarkis *et al.,* 2015), and *Camellia oleifera* seed cake (Li *et al.,* 2020). A similar result was reported by Maroušek *et al.* (2013) that the shock pressure of 50 - 60 MPa could enhance oil extraction from *Jatropha curcas* to over 94%. Furthermore, HVED has been known to improve the antioxidant properties of phenolic compounds from an Iranian brown seaweed which showed that the stability of emulsion increased to 94.7% at 2% (w/v) concentration due to the cell wall cracking from high pressure (Abka *et al.,* 2021). This confirmed USW suitability to be used in assisting and improving extraction.

Microstructure analysis

The SEM micrographs of palm mesocarp with and without USW treatments are shown in Figure. 5. It was clearly observed that the morphology of palm mesocarp significantly differed from the USW-treated samples (Figures 5C - 5F) when compared with untreated palm samples (Figures 5A and 6A) and 2 kV USW-treated samples (Figure 5B). The SEM micrograph of the control sample and 2 kV USW-treated sample showed intact cells (shown by black circle) and uniform pore cells (Figures 5A - 5B). On the other hand, the 4 - 10 kV USW-treated samples exhibited completely cracked cells (shown by white dash circle). Therefore, the broken cell structure could release oil to the cells that appeared on the surface (shown by white circle) as oily, shining, and glossy at the cells structure (Figure 6B). Similar results were found by Mustapa *et al.* (2009), Md Sarip *et al.* (2016), and Mohd Omar *et al.* (2017). Suttiprapa *et al.* (2017a) reported that the front of palm fruit surface had more ruptures than the other sides when impacted by USW generated by explosion and electrical discharge method. Although a single shock pulse was used in the present work, it still showed very promising results to increase the oil yield for palm oil extraction. Further research on optimising the appropriate shock strength and perhaps a number of pulses is still required.

Quality analysis of the crude palm oil

In this section, the quality of the crude palm oil that was USW treated at the electrical discharge of 2 - 10 kV, as well as the untreated are discussed. The free fatty acid (FFA) was calculated by Eq. 4, and analysed following the standard method. It was found that the FFA were 3.28, 3.41, 3.46, 3.60, and

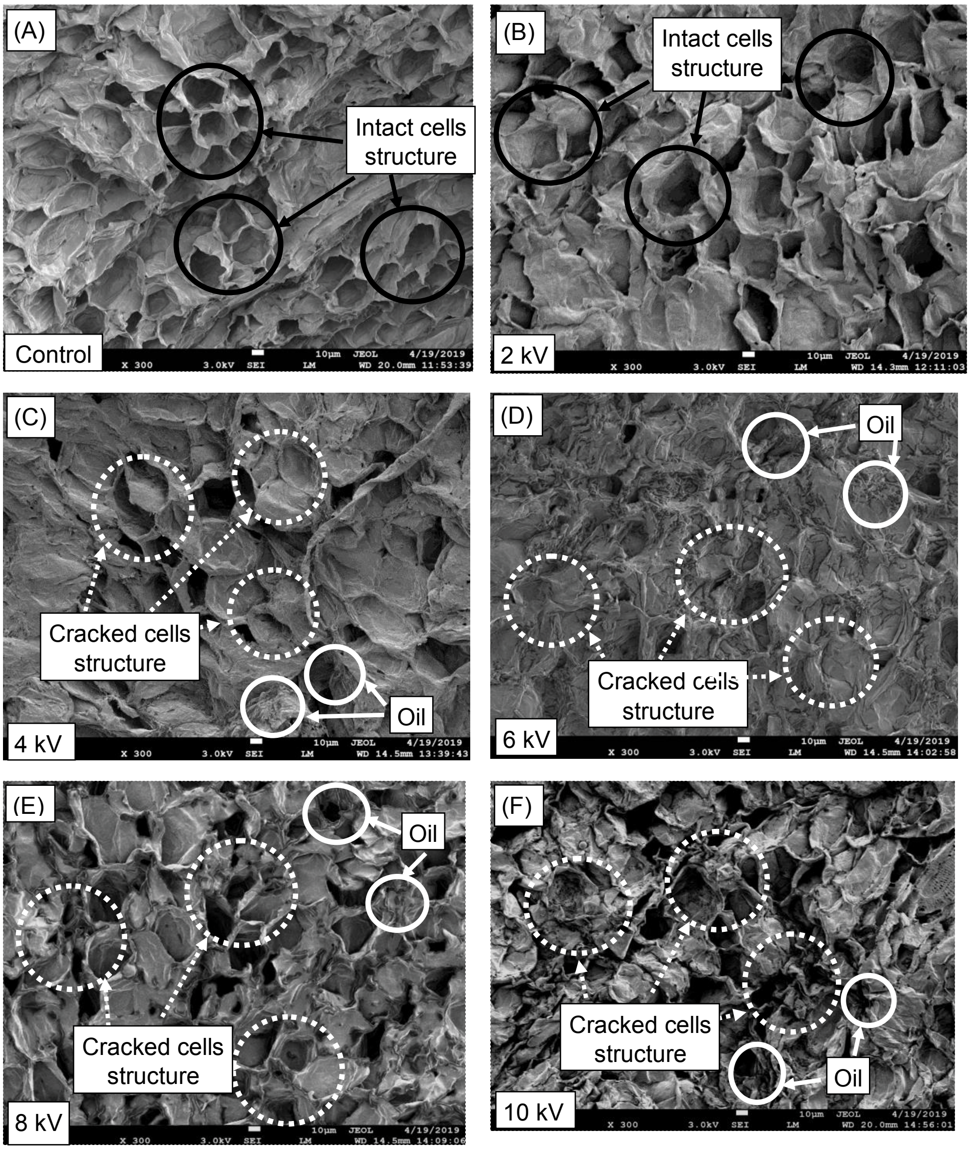

Figure 5. Electron micrographs obtained by scanning electron microscope (SEM) of palm mesocarp: (A) control (without USW treatment), (B) 2 kV treatment, (C) 4 kV treatment, (D) 6 kV treatment, (E) 8 kV treatment, and (F) 10 kV treatment. Dash white circles, white circles, and black circles indicate cracked cells structure, release oil on surface, and intact cells, respectively.

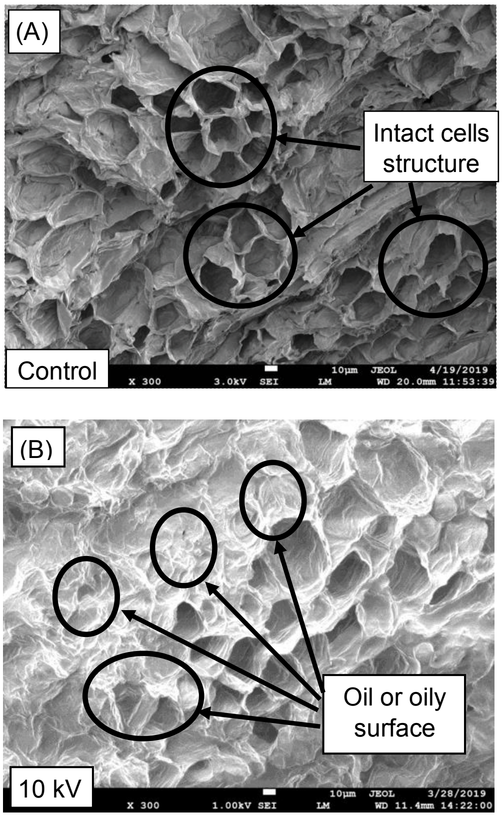

Figure 6. Electron micrographs obtained by scanning electron microscope (SEM) of palm mesocarp: (A) control (without USW treatment), and (B) 10 kV treatment. Black circles indicate released oil on the surface or oily surface.

Table 2. Palm oil quality between treated and untreated USW (control).

Voltage (kV)	Oil quality	
	FFA (%)	Acid value (%)
0 (control)	3.71 ± 0.01[a]	8.11 ± 0.01[a]
2	3.28 ± 0.00[b]	7.18 ± 0.01[b]
4	3.41 ± 0.00[c]	7.46 ± 0.01[c]
6	3.46 ± 0.00[d]	7.57 ± 0.01[d]
8	3.61 ± 0.01[e]	7.88 ± 0.01[e]
10	2.79 ± 0.01[f]	6.11 ± 0.01[f]

Values are mean ± SD from triplicate determination ($n = 3$). Different lowercase superscripts in a column indicate significant difference at $p < 0.05$.

2.79% at 2, 4, 6, 8, and 10 kV, respectively, while it was 3.70% for the untreated as shown in Table 2. The FFA of USW-treated sample at 10 kV had a slightly lower FFA than the untreated sample. Importantly, the FFA of all have values were lower than the FFA standard (< 5%). The acid value (AV) was calculated by Eq. 5, and had the values of 7.18, 7.46, 7.58, 7.88, and 6.10%, respectively, while that of the untreated sample was 8.11%. The AV of all USW-treated samples had slightly lower FFA than that of the untreated sample. The AV is significantly related to the FFA, and generally used in the industry. The FFA decreasing trend observed in the present work agrees with Kanjanapongkul (2021) who used ohmic and microwave treatments. The AV observed in the present work was lower than HFFA-CPO and LFFA-CPO by 19.1 and 8.3%, respectively (Japir *et al.,* 2017). The UWS pre-treatment shows promising benefits for CPO extraction and quality.

Conclusion

In the present work, USW pre-treatment was applied before oil extraction of palm mesocarp by solvent extraction and screw-press methods. Results showed that maximum pressure of 43.92 MPa was obtained from high voltage discharge at 10 kV. The maximum oil yields extracted by solvent extraction and screw-press methods were 70.38 and 66.35%, respectively, at 10 kV. The oil yield increased by 6.3 and 3.1% when compared with untreated samples. The microstructure of palm mesocarp as observed by the SEM showed that the mesocarp cell wall was significantly cracked due to the impact of USW. Therefore, the oil contained in the cell wall was readily released. These confirmed that the application of USW has high potential in assisting palm oil extraction. It is henceforth suggested that this technique can also be applied in other extraction processes such as juice extraction, bioactive compound extraction, and oil extraction of other plants.

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