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EFFECT OF FRYING ON THE PALM OIL QUALITY ATTRIBUTES – A REVIEW

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ABSTRACT

Frying is one of the most versatile food processing operations employed since antiquity. The establishment of this process is evidenced by a great consumption of fried food around the globe. Despite palm oil is extensively utilised in various frying applications, the preservation of its quality attributes as a result of thermal processing is still a concern to food processors and consumers. This article, therefore, aims to provide an overview of published studies on the behaviour of palm oil, in their pure form and blended with other oils, during frying at various processing conditions. In this review, publications associated to frying stability of palm-based oils were considered to ascertain a series of oil quality indices – i.e. *free fatty acid, smoke point, peroxide and* p*-anisidine values, vitamin E, induction period, fatty acid composition, colour, and polar and polymer compounds – under prolonged thermal processing conditions. Stability of palm-based oil, however, is not solely dependent to the inherent properties of the oils themselves. Hence, the effects of operating conditions (oil temperature, cooking time, frying duration or cycle, oil replenishment, frying system and cookware materials) and food compositions are also discussed in this article.*

Keywords: frying, palm oil, quality indices, operating conditions, food compositions.

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INTRODUCTION

Frying is a ubiquitous and dynamic cooking method used to process a wide spectrum of products. The process is essentially a dehydration of food that involves rapid heat and mass transfer when the food is immersed in hot oil at temperatures greater than the water saturation temperature (Ahmad Tarmizi and Niranjan, 2013). Frying basically shares similar principles as baking where a brownish crust layer is formed on the food surface which contributes to a distinctive fried flavour (Berger, 2005; Ismail and Badri, 2003). However, frying generally cooks food faster than baking, and this can be further explained by the efficiency of heat transfer (Ahmad Tarmizi, 2012). Despite substantial amount of oil being migrated into the food, frying is extensively employed in domestic as well as industrial practice. This is due to its ability to create unique organoleptic characteristics, including texture, flavour and appearance, which make the food more palatable and desirable (Ahmad and Ismail, 2008). In addition, its operational simplicity, convenience, and economic viability have resulted in extensive sales of a large variety of fried products.

Oil stability is always associated with the ability of oil to withstand high temperatures during frying, and thus the degree of saturation becomes a major concern for choosing the right oil. Oil containing higher level of saturated fatty acids is more stable for frying as compared to conventional liquid oils such as soyabean, canola and sunflower oils; the number of double bonds in fatty acids determines the rate of oil oxidation (*Table 1*). Nevertheless, the degree of saturation is not the sole predictor of oil stability

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TABLE 1. RELATIVE OXIDATION RATE OF FATTY ACID

Fatty acid	Relative oxidation rate
Stearic	1
Oleic	10
Linoleic	100
Linolenic	150

Source: Gupta (2005).

(Normand *et al.,* 2006). Factors like the positioning of fatty acid in the triacylglycerols (TAG) and the presence of unsaponifiable constituents such as alcohols, hydrocarbons, fat soluble vitamins (A, D, E and K) and phytosterols could also influence the stability of the oil (Dobarganes *et al.,* 1993).

The liquid fraction of palm oil (PO), known as palm olein (POo), is widely used for frying. This oil is not only often regarded as heavy duty oil, but also found to be an alternative replacement for partially hydrogenated oils which is associated with *trans* fatty acids (Nallusamy, 2006; Nurkhuzaiah *et al.,* 2015; Zaliha *et al.,* 2014). Hence, it is not surprising that POo – either in its pure form or blends with other vegetable oils – is highly preferred frying oil (Ismail, 2002; Matthäus, 2007). Indeed, consistent supply at competitive price, as a result of cheaper production cost, also contributes to wide usage of POo (Ahmad Tarmizi and Ismail, 2014a; Ismail *et al.,* 2005).

As significant amount of frying oil is being absorbed into fried food, serious attention must be paid on the quality aspects and the management of oil with the aim to minimise oil deterioration during frying. Exposing frying oil to excessive heat in the presence of air and moisture leads to a complex pattern of thermolytic, oxidative and polymeric reactions (Dueik and Bouchon, 2011; Karoui *et al.,* 2011). A summary of typical frying oil breakdown as a result of frying is depicted in *Table 2.* The reactions become more complicated when oil degradation components interact with leached food that changes the oil properties. Furthermore, frying oil compositions and food matrices also determine the extent of oil deterioration (Bensmira *et al*., 2007; Ismail *et al*., 2003).

Many publications have reported the behaviour of POo during frying. Nevertheless, almost all of the studies focussed on intermittent frying conditions while published article on continuous frying are still limited. This is probably because of higher cost pertaining to continuous frying experiments and/or trade secret of the food industry to protect their business (Ahmad Tarmizi and Ismail 2014a, b). It is also important to note that these frying techniques have completely different procedures which affect the rate of oil degradation and hence, frying performance. Compilation of recent literatures that discussed on the physico-chemical changes occurring in palm-based oils during heating and frying is listed in *Table 3*. The scope of this review only considers oil quality parameters while the characteristics of products are not included. Palm-based oils, which are largely POo and POo blends, were evaluated under intermittent and continuous frying conditions at frying temperatures of 170°C to 185°C; this also applied for simulated frying studies where the oil was heated in the absence of products.

QUALITY ATTRIBUTES

Free Fatty Acid

Free fatty acid (FFA) – which mainly measures the degree of hydrolysis – is one of the indicators of oil deterioration. Hydrolysis accelerates with the increase in frying temperatures and excessive amount of moisture in food (Ahmad Tarmizi, 2012). The FFA could also be formed due to cleavage and oxidation of double bonds in the oil structure which disintegrate the ester bonds of TAG structures (Faridah *et al*., 2015; Lalas, 2009). Several publications reported that many food processors prefer to use FFA as an indicator to monitor the acidity of used oil (Ahmad Tarmizi and Siew, 2008;

TABLE 2. TYPICAL CHEMICAL REACTIONS DURING FRYING

Reaction	Description	Main constituents
Hydrolysis	Interaction between oil and water causes cleavage of TAG bonds between glycerol and fatty acids	DAG, MAG, FFA
Oxidation	Interaction of oil and oxygen by two reaction stages: (1) Primary oxidation involving formation of hydroperoxides (2) Secondary oxidation involving fission of hydroperoxides	Peroxides, aldehydes, alcohols, hydrocarbons, FFA
Polymerisation	Oxidation of the secondary oxidation constituents at high temperature; and alteration of oil molecules or fatty acids by heat resulted in the formation of large molecules	Oxidised and polymerised TAG, cyclic fatty acid monomers, dimers

Note: TAG – triacylglycerols, DAG – diacylglycerols, MAG – monoacylglycerols, FFA – free fatty acid.
Source: Ahmad Tarmizi (2012).

Maskan and Bağci, 2003). Indeed, the importance of acidity upon heating and frying is evidenced by many studies that have used this indicator as one of the preferred oil quality parameters (*Table 3*). It is noted that the level of FFA in POo is relatively higher; nevertheless, this value is in compliance with the legislative FFA content of maximum 0.1% for refined edible oils (Basiron, 2005). There is also an option for a premium POo, which is graded as 'Special Quality', containing FFA of less than 0.05% (Ahmad Tarmizi and Ismail, 2008). This oil, however, is traded at more premium price than the regular POo.

The discard point for FFA basically relies on the type of food being fried. The FFA of 2% to 2.5% is normally regarded as the end point for breaded and coated food such as nuggets, fillets and chicken parts. The producers of instant noodles and potato chips use 0.5% as the threshold while 1% is applied for pre-fried French fries (Ahmad and Ismail, 2008; Ismail, 2005). It is obvious that the FFA limit is somewhat lower for carbohydrate-based products when compared to protein-based products. This argument is supported by a study conducted by Enríquez-Fernández *et al.* (2011) who concluded that the FFA was greater in POo used for frying chicken nuggets (0.47%) as opposed to French fries (0.27%). Combination of atmospheric frying with vacuum drainage significantly reduced the FFA level in POo by almost two-fold when compared to atmospheric drainage (Ahmad Tarmizi *et al.*, 2013). The authors hypothesised that application of vacuum drainage lowers the water saturation temperature, increases the degree of superheat and thus causes water – which was initially leached out from the product during frying – to partially drawn out from the oil. Ismail (2005; 2001) distinguished the performance of POo during intermittent and continuous frying of potato chips: the former gave the FFA of nearly 0.5% after 40 hr of frying while the latter reached a steady state within a narrow range of 0.19% to 0.24% even after 316 hr of frying. In the case of continuous frying, it is plausible that the oil inside the fryer – which is taken up by the fried product and lost during frying – is continuously compensated with fresh oil having lower FFA content, and hence, gives constant level of FFA in frying oil (Ismail, 2005).

Oil turnover time (OTT) – which is a theoretical time needed by the food to utilise the entire oil inside the fryer during frying – is also crucial to determine how much stress is applied to the oil, which subsequently affect its quality. This principle basically applies for continuous frying operation, where higher rate in oil usage and replenishment can maintain the oil quality in the fryer and hence, replacement of oil may not be necessary (Berger, 2005). For instance, extending the OTT to 14 hr significantly increased the FFA to 0.46% after continuous frying of potato chips for only 56 hr whereby OTT of 8 hr showed a marginal increase within 0.22% to 0.25% in FFA even after extending the frying operation for 81 hr (Ismail and Idris, 2003). Similarly, Ismail (2005) obtained consistency in the FFA formation during 316 hr of continuous frying when OTT was 8 hr. Thus, the OTT between 5 to 10 hr is considered satisfactory for continuous frying operation (Berger, 2005; Saguy and Dana, 2003). Recent studies conducted by Ahmad Tarmizi and Ismail (2008; 2014b) continuously produced potato chips at 50 kg hr^{-1} in order to achieve OTT of 10 hr. The average FFA values ranged between 0.24% to 0.30% for different POo grades while binary blends of POo with liquid oils, *i.e.* sunflower, canola and cottonseed oils, gave broader values (0.15% to 0.28%).

Smoke Point

The formation of FFA is often associated with the smoke point (SP): increase in the FFA inversely affects the SP value (Ahmad Tarmizi and Siew, 2008). The SP is the temperature of which heated oil starts to release a continuous wisp of bluish smoke. The amount of smoke emanating from the oil is correlated with the concentration of low molecular weight components, *e.g.* FFA, monoacylglycerols (MAG), diacylglycerols (DAG) and volatile compounds (Matthäus, 2006). Unlike any other quality parameters, SP is rarely discussed in the literatures and this is clearly shown in *Table 3*. The SP of POo typically ranges between 212°C to 227°C, which is relatively lower than conventional liquid oils with SP greater than 230°C; this is closely related to inherently higher FFA content in POo (Ahmad Tarmizi and Ismail, 2014b; 2008).

The food industry recommends that the SP of the starting oil should be higher than 215°C (Ahmad and Ismail, 2007; Ismail, 2001). Ahmad Tarmizi and Siew (2008) have conducted an extended heating assessment (80 hr) on different types of palm-based oils – *i.e.* PO, single- and double-fractionated POo, red palm olein (RPOo), palm stearin (POs) and palm-based shortening (PBS) – at typical frying temperature (180°C). They observed that the SP values were: 200°C for PO, 203°C for single-fractionated POo, 196°C for double-fractionated POo and RPOo, and 191°C for PBS. It is also expected that the SP values tend to be lower when food is introduced. This can be evidenced when potato chips are fried under intermittent (Ahmad, 2005; Arshad and Sudin, 2000) and continuous (Ahmad Tarmizi and Ismail, 2014b; 2008) frying conditions: the final SP values were within 175°C to 180°C for the former protocol while the latter ranged between 184°C and 189°C. Fortunately, these values were higher than the minimum SP allowance of 170°C (Berger, 2005).

TABLE 3. RECENT PUBLICATIONS ON THE QUALITY INDICES OF PALM-BASED OILS AT DIFFERENT FRYING CONDITIONS

Food	Oil type	Protocols	FFA	PV	AnV	FAC	SP	IP	Colour	VE	Polar	Polymer	References
Intermittent frying													
Potatoes	POo	180°C; 5 days; 80 sessions; FR	X	X	X	X	–	–	X	X	X	–	Ahmad Tarmizi *et al*. (2013)
	POo *vs*. others	180°C; 5 days; 400 sessions; FR	X	X	X	–	–	X	X	–	X	–	Cardoso-Ugarte *et al*. (2013)
	POo *vs*. others	170°C; 3 days (12 hr day^{-1}); NR	–	X	X	X	–	–	–	–	X	X	Petersen *et al*. (2013)
	POo *vs*. others	185°C; 5 days (6 hr day^{-1}); 75 sessions; FR	–	–	–	X	–	–	–	–	X	–	Abdulkarim and Ghazali (2012)
	POo *vs*. others	180°C; 6 days (8 hr day^{-1}); 60 sessions; FR	X	X	–	X	–	–	–	–	X	–	Romano *et al*. (2012)
	POo *vs*. POo blends *vs*. others	80°C; 1 day; 5 sessions; FR	X	X	–	–	–	–	–	–	–	–	Ramli *et al*. (2012)
	POo *vs*. others	180°C; 1 day; 5 sessions; NR	X	–	X	–	–	–	–	–	X	–	Tabee *et al*.(2009)
	POo *vs*. others	180°C; 1 day; 15 sessions; NR	X	–	X	X	–	–	X	X	–	–	Khan *et al*. (2008)
	POo *vs*. POo blends *vs*. others	180°C; 3 days (3.5 hr day^{-1}); 50 sessions; NR	X	X	X	–	–	–	X	–	X	X	Serjouie *et al*. (2010)
	POo *vs*. POo blend *vs*. others	180°C; 4 days (5 hr day^{-1}); 16 sessions	–	–	–	X	–	–	–	–	–	–	Farag *et al*. (2010)
	POo *vs*. POo blend	180°C; 5 days (8 hr day^{-1}); 70 sessions; FR	X	–	–	–	–	–	X	–	–	–	Naghshineh *et al*. (2010)
	POo blends *vs*. others	180°C; 5 days (2 hr day^{-1}); NR	X	–	–	–	–	X	X	X	X	–	Farhoosh *et al*. (2009)
	POo blends *vs*. others	180°C; 12 days (1 hr day^{-1})	–	–	–	X	–	–	–	–	X	–	Nzikou *et al*. (2009)
	PO, PO blends *vs*. others	180°C; 45 sessions	X	X	–	X	–	–	–	–	–	–	Choi *et al*. (2014)
Chicken	PO	150°C-250°C; 1 day (8 hr day^{-1}); 48 sessions	X	X	–	X	–	–	–	–	–	–	Chen *et al*. (2014)
Potatoes *vs*. chicken *vs*. fish	POo *vs*. others	185°C; 6 days (8 hr day^{-1}); 60 sessions; FR	X	–	X	X	–	–	X	X	X	X	Aladedunye and Przybylski (2014)
Potatoes *vs*. chicken	POo *vs*. POo blend	180°C; 5 days (13 hr day^{-1}); 200 sessions; FR	–	X	X	X	–	–	X	–	X	–	Enríquez-Fernández *et al*. (2011)
Potatoes *vs*. chicken *vs*. simulation	POo *vs*. POo blend	180°C-185°C; 4 days (6 hr day^{-1}); 40 sessions	–	–	–	X	–	–	X	–	X	X	Bansal *et al*. (2010)
Simulation	POo *vs*. others	175°C-185°C; 12 hr	–	–	–	X	–	–	X	–	–	–	Amrutha Kala *et al*. (2012)
	PO, POo, RPOo, PS *vs*. other	180°C; 10 days (8 hr day^{-1})	X	–	X	X	–	X	X	X	X	–	Ahmad Tarmizi and Siew (2008)
Continuous frying													
Potatoes	Different POo grades	180°C; 56 hr (8 hr day^{-1}); 50 kg hr^{-1}; CR	X	–	–	–	X	X	–	X	X	X	Ahmad Tarmizi and Ismail (2008)
	POo *vs*. POo blends	180°C; 56 hr (8 hr day^{-1}); 50 kg hr^{-1}; CR	X	–	X	–	X	X	X	X	X	X	Ahmad Tarmizi and Ismail (2014b)

Note: PO – palm oil; POo – palm olein; RPOo – red palm olein; PS – palm shortening; FR – frequent replenishment; CR – continuous replenishment; NR – null replenishment; FFA – free fatty acid; PV – peroxide value; VE – vitamin E; AnV – *p*-anisidine value; FAC – fatty acids composition; SP – smoke point; IP – induction period.

Peroxide and *p*-anisidine Values

Oxidation is the main contributor of oil deterioration involving interaction between unsaturated fatty acids and oxygen. This deleterious reaction has raised concerns from the qualitative point of view, by affecting the sensory properties and nutritional attributes of fried food (Dana and Saguy, 2001). Primary oxidation, which measures the formation of hydroperoxides, is expressed as peroxide value (PV). Fission of hydroperoxides further disintegrates into constituents like aldehydes and ketones; the intensity for this secondary oxidation is denoted as *p*-anisidine value (AnV). Regardless to oil compositions, the initial PV for oil used for frying is preferably below 1 mequiv O_2 kg^{-1} (Berger, 2005). This is in agreement with some of the studies reported in *Table 3*. In fact, the PV for 'Special Quality' POo can reach as low as 0.1 mequiv O_2 kg^{-1} (Ahmad Tarmizi and Ismail, 2008). Enríquez-Fernández *et al*. (2011) reported that the final PV was lower when POo was used for frying carbohydrate based product (5.21 mequiv O_2 kg^{-1}) in comparison to protein based product (8.55 mequiv O_2 kg^{-1}).

Nonetheless, PV is considered to be an unstable measurement of oil oxidation during frying since hydroperoxides are destroyed at high temperatures while new peroxides are developed during cooling and storage (Matthäus, 2006; Matthäus *et al*., 2009). For instance, POo used for frying chicken fillets gave the highest PV at 150°C as opposed to much higher temperatures, *i.e.* 200°C and 250°C (Chen *et al.*, 2014). Hence, AnV appears to be more meaningful than PV since aldehydes have more resistant towards heat than peroxides (Pantzaris, 1997). It is expected that AnV increases with frying times; nevertheless most of the studies showed that the AnV starts to reach constant values after certain stage of frying period. For instance, the AnV of POo rose sharply from 4 to 74 units during the first two days of frying in the case of vacuum drainage and remained constant within 92 units, whereas in the case of atmospheric drainage, the AnV demonstrated a rapid increase to 84 units just after one day of frying and remained relatively constant within 103 to 107 units (Ahmad Tarmizi *et al*., 2013). This was probably due to the advanced stage of secondary oxidation where the formerly developed aldehydes were being transformed into higher molecular weight compounds (Tsaknis *et al*., 2002).

Vitamin E and Induction Period

Vitamin E (VE) – which consists of tocopherols and/or tocotrienols – is one of the antioxidants that are inherently present in oils. In general, VE influences the stability of oil during heating and frying by slowing down the oxidative degradation (Matthäus *et al*., 2009). Despite most vegetable oils are good sources of tocopherols, palm-based oils are among the few edible oils enriched with tocotrienols. In fact, the amount of tocotrienols in these oils can exceed 75% from the total VE content (Ahmad Tarmizi *et al*., 2013; Berger, 2005). Nevertheless, some publications quantify VE solely in the form of tocopherols. Such information is definitely not reflecting the actual amount of VE in palm-based oils and this would create negative impressions on their quality and hence, stability.

The rate of VE degradation varies for different types of palm products. Ahmad Tarmizi and Ismail (2008) perceived that the 'Special Quality' POo retained 62% of its initial VE content while 47% remained in POo after 56 hr of continuous frying. Surprisingly, PO, single- and double-fractionated POo gave higher VE retention between 64% to 75% after heating for 80 hr. Nevertheless, this was not the case for RPOo and POs where only residual amounts of VE were detected (Ahmad Tarmizi and Siew, 2008). It is noted that tocotrienols depleted faster than tocopherols when exposed to frying temperatures (Ahmad Tarmizi and Ismail, 2008; Ahmad Tarmizi and Siew, 2008; Aladedunye and Przybylski, 2014). It is plausible that the presence of three double bonds at the hydrophobic side chain of tocotrienols makes it susceptible to thermal and oxidative degradations (Packer and Weber, 2001).

Another method used to monitor the stability state of oil is the induction period (IP) or oxidative stability index. This parameter is an expression of time required for oil to resist oxidation at elevated temperatures (Matthäus, 2006). Unlike PV and AnV – which provide static measures of oil stability – determination of IP is dynamic and thus offers an insight on the fate of oil during storage and heating (Aladedunye *et al*., 2014). Nevertheless, among all quality parameters studied, IP is the least preferred indicator for assessing oil stability during frying. This is evidenced from *Table 3* which clearly shows that only four publications reported IP as one of the oil quality indices (Ahmad Tarmizi and Ismail; 2008; 2014b; Cardoso-Ugarte *et al*., 2013; Farhoosh *et al*., 2009).

The measurement of IP can be done at various temperatures between 100°C and 130°C. For instance, the IP for POo are 13.7 hr at 130°C, 24.2 hr at 110°C and 44.0 hr at 100°C (Berger, 2005). It appears that the IP value is more or less doubled for every 10°C decrease of heating temperature. As expected, IP decreased with the increment of frying time. By comparing 'Special Quality' POo and regular POo, the IP dropped from 25.5 to 17.5 hr in the case of the former oil and from 22.3 to 14.5 hr in the case of latter oil (Ahmad Tarmizi and Ismail, 2008). The authors found that the trend of IP has some similarity with VE when comparing different grades of POo. Another study showed that IP dropped steeply for the first 79 hr and remained constant within half of its initial value even after 1900 hr of continuous frying (Ismail, 2005).

Fatty Acid Composition

Fatty acid composition (FAC) is commonly used for the establishment of oil authenticity (Ahmad Tarmizi *et al*., 2008). This information enables users to predict the stability state of the oil, and for that reason, it is widely reported in the literatures (*Table* 3). By referring to the FAC of palm-based oils, it is expected that the alteration of FAC during frying is minimal (Abdulkarim and Ghazali, 2012; Aladedunye and Przybylski, 2014; Romano *et al*., 2012). Indeed, changes in FAC, particularly the saturated FA, are contributed by the normalisation of detected fatty acid peaks: the actual FA concentration is quantitatively unaffected because thermal degradation usually occurs in unsaturated fatty acids (Ahmad Tarmizi *et al*., 2013). The main factor contributing for possible alteration of FAC is the type of food being fried. By using chicken nuggets and French fries as illustrative products, Enríquez-Fernández *et al*. (2011) opined that chicken nuggets insignificantly increased the palmitic (C16:0) and oleic (C18:1) acids in POo. Unfortunately, frying of French fries gave significant reduction in C16:0, and at the same time, increased the level of C18:1. Bansal *et al*. (2010) also fried similar products using POo, and regardless of the food types, the level of C16:0 and linoleic (C18:2) acids were somewhat similar after 40 cycles of frying. Furthermore, they even observed that heating the oil without food resulted in higher degree of FAC alteration.

Trans fatty acids, the ratio between linoleic and palmitic acids (C18:2/C16:0) and polyene index (the ratio of polyunsaturated to saturated fatty acids) could also be considered as degradation indicators in oil (Romano *et al*., 2012). Nevertheless, this review only focuses on the formation of *trans* fatty acids because the other two indicators basically measure the extent of polyunsaturation in oil (Che Man and Tan, 1999). Frying potato chips for 20 hr gave the insignificant increase of total *trans*-fatty acids [the sum of *trans*-C18:1 and *trans*-linolenic (C18:3) acids] in POo from 0.11% to 0.14% (Farag *et al*., 2010). The authors also deduced that the total *trans*-fatty acids, particularly *trans*-C18:1, was considerably low despite that POo has higher percentage of C18:1 compared to some conventional liquid oils. A recent study by Chen *et al*. (2014) concluded that, irrespective to frying temperatures, the concentration of *trans*-fatty acids in POo was relatively lower (0.16% to 0.23%) even after 48 cycles of frying chicken fillets. With regard to cookware material, a study by Amrutha Kala *et al*. (2012) showed that *trans*-C18:1 acid in POo significantly increased to 20% after 12 hr of heating in cast iron albeit its initial level was virtually 0%. Stainless steel and aluminium alloy produced 3% while glass did not trigger any formation of *trans*-C18:1 acid.

Colour

Colour measurement is a subjective and rapid method that provides visual indication of oil quality. Generally, oil darkening is often associated with the formation of hydroperoxides, conjugated dienoic acids, ketones and hydroxides (Farhoosh *et al*., 2009). Other possible cause of colour reversion is the diffusion of browning pigments developed from fried food (Lalas *et al*., 2006). Nonetheless, Che Man and Tan (1999) emphasised that oil darkening cannot be solely related to oxidative deterioration. From the appearance of palm-based oils, it is obvious that their colour intensity is relatively higher than that of other vegetable oils. The colour values for PO, single- and double-fractionated POo, and PBS range between 2.1 and 3.1 R whereby RPOo gives the highest value of 63 R (Ahmad Tarmizi and Siew, 2008). Rich orange-red colour in RPOo is due to its high concentration of carotenes (Sundram *et al*., 2003). Except for RPOo, the oils darkened gradually when heated at 180°C: PO was least coloured, followed by PBS (16.2 R), and single- and double-fractionated POo (19 and 21.1 R, respectively). On the other hand, the RPOo had a unique trend of darkening where the colour intensity dropped progressively to 3.1 R before increasing the value to 9.1 R after the extensive heating test (Ahmad Tarmizi and Siew, 2008). Amrutha Kala *et al*. (2012) found that heating POo [initial colour value (CV) = 14.8] for 12 hr using cast iron exhibited the highest degree of colour degradation (CV = 62.3) in comparison to other cookware materials: stainless steel (CV = 15.7); aluminium alloy (CV = 15.5); and glass (CV = 6.2).

Intermittent frying of chicken nuggets darkened the POo rapidly as opposed to French fries; this could be due to the migration of inherent fat from the nuggets to the frying oil (Enríquez-Fernández *et al*., 2011). Similar trends were also observed by Bansal *et al*. (2010) when frying the same products in POo. In fact, heating the oil without products yielded comparable degree of colour degradation as those obtained from chicken nuggets. Ahmad Tarmizi *et al*. (2013), who conducted 40 hr of repeated frying experiments, observed that the colour of POo was almost 20% lighter when vacuum drainage is applied after each frying session. According to Aladedunye and Przybylski (2014), darkening of palm-based oils could be influenced by the presence of trace pigments and VE – predominantly tocotrienols – which are prone to the formation of red-brown quinine polymers. It is also noteworthy that the quality of fried products is not affected albeit palm-based oils have relatively higher colour intensity and darken faster compared to other vegetable oils (Minal *et al*., 2003; Mohamed Sulieman *et al*., 2006).

Thus, it is deceptive to evaluate the overall quality of palm-based oils by solely monitoring the colour profile.

Polar and Polymer Compounds

Quantification of polar compounds is recognised as one of the most reliable methods to determine the degree of deterioration in frying oil. This is because polar compounds are non-volatile and thus represent the main reaction occurring in heated oil (Aladedunye and Przybylski, 2014; Mohamed Sulieman *et al*., 2006; Warner and Gupta, 2003). Polar compounds represent all the fatty acid breakdowns with higher polarity than TAG, comprising of oxidised and polymerised TAG, DAG and FFA (Dobarganes *et al*., 2003; Santos *et al*., 2013). Many European countries, *i.e.* Germany, France, Italy and Switzerland, only permit a maximum allowance of 25% to 30% polar compounds in used oil (Berger, 2005; Inturrisi, 2013;). Oil containing high level of polar compounds is potentially toxic and can be easily absorbed by human body (Gómez-Alonso *et al*., 2003; Petersen *et al*., 2013; Romero *et al*., 2003; Sánchez-Muniz and Bastida, 2003). In relation to polymerised TAG or commonly known as polymer compounds, the discard point regulated by some countries range between 10% and 16% (Berger, 2005). Belgium has applied a more stringent threshold at 10% discard oil (Ahmad and Ismail, 2008). Countries like The Netherlands and South Africa have set higher limit of polymer compounds (16%) in used oil (Berger, 2005).

Palm-based oils generally contain higher level of polar compounds (typically 6% to 8%) when compared to other vegetable oils (2% to 3%) because these products are inherently rich in DAG (Berger, 2005). As DAG is quantified as a fraction of polar compounds, it can sometimes be misleading to use polar compounds in judging oil quality even when the oil is not heated (Bansal *et al*., 2010). Thus, it is suggested that polar compounds should be expressed in terms of the formation rate rather than its quantitative concentration. As expected, polar compounds increase with frying or heating times, but the rate of formation is dependance on the oil composition. Ahmad Tarmizi and Siew (2008) conducted extensive heating tests at 180°C for different palm-based oils and found that the polar compounds in PO, single- and double-fractionated POo peaked within 13% and 15% whereby the remaining oils exhibited much higher concentration (29%). Conversely, all palm-based oils only showed a minor change in the polymer compounds (less than 2% for PO, single- and double-fractionated POo and 3% for RPOo and PBS), which further suggests that the increase in polar compounds is likely contributed by the elevation of oxidised TAG and hydrolytic breakdown products such as FFA and DAG. Under real frying conditions using POo, the evolutions of polar and polymer compounds were more pronounced during intermittent frying as opposed to continuous frying (Ismail, 2001). Comparison between 'Special Quality' POo with regular POo demonstrated that the development of polar compounds was slightly higher in the former oil, but comparable polymer compounds were obtained in both oils (Ahmad Tarmizi and Ismail, 2008).

It is known that different food compositions affect the rates of polar and polymer compounds, For instance, frying French fries using POo gave higher polar and polymer compounds than frying chicken nuggets (Bansal *et al*., 2010). Additionally, heating POo without products yielded similar rate of polar compounds with that of frying chicken nuggets, however, the level of polymer compounds was significantly higher (16%). From this observation, the authors concluded that faster thermal degradation occurs rapidly during heating rather than frying itself: moisture release from fried products, in some ways, provides some form of protection in minimising oil contact with air (oxygen). It is worth noting that polymer compounds are responsible for the change in oil viscosity, tendency of foaming during frying, and imparts bitterness and hence, affects the oil content in fried product (Maskan, 2003; Minal *et al*., 2005; Samah and Fyka, 2002).

INTERACTION BETWEEN DIFFERENT QUALITY ATTRIBUTES

As expected, not much publication emphasised on the interactions amongst quality attributes in palm-based oils during heating and frying. From that limited references, most of the parameters were correlated with polar and polymer compounds, and therefore used to indicate the degree of oil deterioration. Bansal *et al*. (2010) perceived strong correlation between C18:2/C16:0 and polymer compounds ($r > 0.95$) when POo was used for frying 40 cycles of French fries and chicken nuggets. On the other hand, strong relationship ($r > 0.95$) was observed when comparing polymer compounds with colour intensity.

Interactions between FFA, PV, AnV, polar and polymer compounds, and colour in POo and its blends were investigated by Serjouie *et al*. (2010). Despite most parameters showed significant correlations in all frying oils, the highest correlation ($r = 1.00$) was only attained in blended oils: (1) interaction of polymer compounds with FFA and AnV for the binary blend of POo and sesame oil; (2) interaction of polar compounds with colour intensity, and polymer compounds with FFA for the binary blend of POo and canola oil; and (3) interaction of polymer compounds with colour intensity for the tertiary blend.

Interactions between polar compounds and fatty acid composition were detailed by Romano *et al*. (2012). The polar compounds exhibited good correlation with C18:2/C16:0 (R = 0.98) and total *trans*-fatty acids, *i.e. trans*-isomers of C18:1 and C18:2 (R = 0.94), when French fries were intermittently fried in POo for 40 hr. In another study, frying French fries for 30 hr in POo has resulted in strong correlation (r = 0.99) when polar compounds were compared with the ratio between C18:1 and the sum of C18:2 and C18:3 (C18:1/C18:2 + C18:3) (Abdulkarim and Ghazali, 2012).

CONCLUSION

This review focusses on the thermal stability of PO (and its products) when food is processed under various frying conditions. For PO or any other oils, exposure to excessive heat triggers deleterious series of complex reactions – hydrolysis, oxidation and polymerisation – which are inter-related with one another. The complexity becomes more pronounced when food interacts with frying oil. As far as heating and frying are concerned, none of the palm-based oils exceeded the legislative limits for used frying oils - *i.e.* 2.5% for FFA, 170°C for SP, 30% for polar compounds and 16% for polymer compounds - regardless of frying conditions, cookware materials and food compositions. Palm-based oils are generally proven to have superior frying performance; nonetheless, their physico-chemical quality is more prominent when food is processed under continuous frying conditions. This is based on the fact that the oil inside the fryer, which is taken up by the fried food and/or loss during frying, is continuously replenished with fresh oil. Continuous frying, in a way, would allow 'infinite' use of oil throughout frying operation provided that the oil turnover time is optimal. As the amount of polar and polymer compounds are considered as the most crucial indicators in quantifying oil degradation, relationships between these two parameters with other oil quality indices were explored. Polar and polymer compounds were observed to have strong correlations with FFA, *p*-anisidine value, colour intensity and FAC, *i.e.* the ratio between linoleic and palmitic acids and *trans*-fatty acids. This review provides useful information on how PO behaves when exposed to excessive temperatures. Stability of PO not only provides opportunity for food processors to reduce their operational cost but also retains its quality attributes since significant amount of oil is an integral part of the fried food. For future studies, identification of quality attributes in palm-based oils can be done for other cooking methods such as microwave heating and roasting. Additionally, establishment of database which correlates frying quality indices and frying protocols with oil absorption and sensory attributes of fried products is interesting to look into.

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