Scoping Report: Maintaining the quality of unsaturated oils used in food service frying processes

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1. Introduction

Frying involves a chain of "relatively unbridled chemical reactions"[1] including lipid oxidation. Lipid oxidation is a complex degradation process between oxygen and unsaturated fats.[2] More unsaturated bonds result in more oxidation and concomitant changes in taste, aroma, color, safety, and nutritive value of oils.[2–5] Oxidation of unsaturated oils is an important issue as the food industry implements food preparations, such as frying, that comply with legislation[6,7] prohibiting the use of partially hydrogenated oils (PHO). Consumption of fried food is common in Canada[8] and the United States[9] with more than one-third of American adults consuming fast food, mostly fried, on any given day.[9] The possibility of regular consumption of oxidized lipids from fried foods constitutes a potential public health concern.[10–14] This brief review focuses on frying applications and includes a summary of lipid oxidation's potential effects on health and flavor, as well as strategies to curb lipid oxidation during frying.

2. Effects of lipid oxidation

Lipid oxidation is a complex chemical degradation process that involves a free radical chain reaction between unsaturated fats and oxygen.[2] Many interacting factors, such as high temperatures and type of oil, affect oxidation and, therefore, the shelf life of edible oil.[1,2] Energy from the heat of cooking induces what is known as thermal oxidation, a more rapid and less understood degradation process than autoxidation.[1,5] In addition, unsaturated oils are oxidized more quickly than less saturated oils.[1,2,5] The combination of these two factors—high heat and relatively unstable oils used to replace PHOs—could negatively affect the safety, nutritive value, and flavor of commercially fried foods.

2a. Health, safety, and nutritive quality

Chemical end products from the oxidation of unsaturated oils are recognized as potentially harmful to humans.[12,15–18] The ingestion of lipid oxidation products, such as malondialdehyde, triggers oxidative stress.[19,20] The accumulation of oxidative stress is implicated in the development of myriad chronic diseases including atherosclerosis, neurodegenerative diseases (e.g., Alzheimer's and Parkinson's), diabetes mellitus, and cancer.[21–25]

In particular, frying foods with oils rich in polyunsaturated fatty acids (PUFA) has been linked to potential adverse health effects.[10,26,27] For example, thermal oxidation of PUFA during frying generates aldehydes.[14,28,29] Certain aldehydes (e.g., *trans*-2,4-decadienal) are cytotoxic and genotoxic, causing damage to essential biomolecules such as DNA.[18,30] Over two dozen aldehydes, including *trans*-2,4-decadienal, were identified in soybean oil used to deep-fat fry wheat dough and chicken breast meat at 180°C.[31] In addition, fried potato chip samples from seven out of 12 fast food restaurants (including samples from large chain outlets) in the United Kingdom contained potentially health-threatening levels of toxic aldehydes.[14] While there was considerable "between-fast-food-restaurant-source variation," there was a significant, positive correlation between aldehyde concentrations in the chip samples and percent PUFA of the frying oil.[14] Overall, this study demonstrates the possibility of consuming harmful lipid oxidation products through foods fried in PUFA-rich oil. Another study focused on exposure of acrolein, a well-researched genotoxic aldehyde.[32,33] In this study, researchers found that acrolein exposure through consumption of fried chicken and French fries from fast food restaurants negatively affects oral cavity homeostasis (i.e., buccal glutathione levels) which may increase the risk of upper aerodigestive tract cancers.[34]

Another potential problem of thermal oxidation in frying processes is the production of *trans* fatty acids.[5,13,35,36] The relative percentage of t*rans* isomers increased 2.5 fold (from 2.4% to 5.9%) in canola oil used to fry French fries at 215°C.[35] The researchers concluded that increasing frying temperatures above 195°C may annul the *trans* fat free claim for the fried product.[35] The production of *trans* fatty acids from thermal oxidation of unsaturated fats used to replace PHOs is an ironic potential consequence of legislation banning PHOs. More importantly, as demonstrated by the substantial research driving that legislation, *trans* fatty acid consumption is associated with health ramifications,[37] such as coronary artery disease[38] and all-cause mortality.[39,40] In addition to the production of *trans* fatty acids and aldehydes, thermal oxidation reduces oils' overall antioxidant properties,[1,5,11] including concentrations of carotenoid, phenolic compounds, and vitamin E.[13] This depletion of nutrients is yet another reason to curb thermal oxidation of cooking oils used for frying applications.

The potential implications of *consuming* thermally-oxidized cooking oils are not the only concern. Extensive research has demonstrated health risks of *inhaling* fumes from oxidized oil, as well.[41–44] Fumes from heated peanut oil, soybean oil, and sunflower oil lead to cytotoxicity and oxidative DNA damage in human lung carcinoma (A-549) cells.[41,42] Epidemiological research has demonstrated a dose-response relationship between cooking fume exposure and lung cancer.[44] Much of the research on oil fumes has been conducted among Chinese women using vegetable oils, such as rapeseed oil, and traditional Chinese cooking techniques, such as stir-frying and pan-frying.[44,45] A recent review found a lack of data on exposures to oxidized oil fumes in North America and a need to investigate at-risk groups such as food service workers frying foods with vegetable oils in place of more stable PHO.[46]

2b. Taste

Deep-fried flavor is an essential factor in the popularity of fried foods.[47] Deep-fat frying that yields the typical desirable fried flavor has been described as "one of the most dynamic processes in all of food processing."[1] Even though deep-fat frying is common, the complexity and high number of variables involved make changes in the oil and fried food difficult to predict.[1,5,48] An optimal concentration of oxygen is necessary to produce the fried flavor: too much oxygen produces off-flavors, and too little oxygen produces weak and poor flavors.[5] During deep-fat frying, the oxidative degradation of linolenic acid increases fishy odor.[49] In addition, aldehydes produced during deep-fat frying exhibit oily, green, paint, metallic, and beany flavors.[47] On the other hand, oxidation of linoleic acid may be more responsible for the typical deep-fried flavor.[1,5] Balancing frying conditions to maximize deep-fried flavor while minimizing toxic lipid oxidation products is a critical challenge potentially affecting consumer acceptance and health.[1,47]

2c. Oxidized frying oils in North America

Research conducted in Canada and the U.S. demonstrates the presence of oxidized oils in the North American food service. In-use and discarded samples of frying oil from six fast food restaurants in Toronto showed high levels of oxidation, including 35% of in-use samples and 50% of discarded samples having peroxide values considered to be rancid.[50] In this study, five of the restaurants used different brands of canola oil and one used hydrogenated vegetable oil. Relatedly, samples of French fries from six fast food restaurants in the Twin Cities, Minnesota contained 4-hydroxy-2-*trans*-nonenal, a toxic lipid oxidation product.[51] Restaurants in this study did not report the type of oils used for frying. Notably, both studies were conducted before the implementation of legislation banning PHOs. Depending on the type of oils used to replace PHOs, the prevalence of oxidized oils and food items containing lipid oxidation products could be even higher because, as previously described, *cis* unsaturated fatty acids are relatively unstable and susceptible to rapid oxidation.[2,11,27,52]

3. Factors affecting the quality of oil during frying

Maintaining the quality of unsaturated oils in frying applications is a complex challenge: A multitude of interacting factors influences a multitude of reactions which influences a multitude of outcomes.[48,53] Furthermore, many factors such as temperature have a narrow range or window of optimization related to oxidation.[1,5,47] In this section, we will outline factors and corresponding strategies for curbing oil oxidation during frying processes. Factors that affect the oxidation—and, therefore, quality and flavor—of oil during frying include the type of oil used; food material being fried; frying time and temperature; replenishment of fresh oil; type of fryer; antioxidants; and oxygen concentration.[1,5,54]

3a. Type of oil

In terms of fatty acid composition, oils rich in polyunsaturated fatty acids are the most vulnerable to oxidation, followed by oils rich in monounsaturated fatty acids. Oxidation is the most rapid in linolenic acids, followed by linoleic, and oleic acids.[4,11,27,55] Olive oil[1,13] and a novel PUFA-deplete monounsaturated algae frying oil[14] are relatively resistant to thermal oxidation from frying processes. Methods to modify fatty acid composition of oils in the manufacturing process include fractionation, hydrogenation, interesterification, conventional seed breeding, genetic engineering, and blending oils; however, these methods may negatively impact nutrition, functionality, and consumer acceptance.[1] Overall, it is critical to carefully select oils used for frying and monitor oil quality through appropriate use application assessments (see section 3h).[1,10,11,56]

3b. Type of food

In general, the presence of food—compared to heating oil without food—slows down thermal oxidation. The type of food, including the composition, shape, and size, is a complicated factor that affects lipid oxidation during frying.[1] Starch, high moisture content, unsaturated fat content, increased cross-sectional area (e.g., thin cut strips versus thick cut strips, rough surfaces versus smooth surfaces), and presence of transition metals (e.g., iron in meat products) accelerate thermo-oxidative degradation in frying oils.[1,5] In one study of six schools, carbohydrate-rich foods (e.g., sweet potato, dumpling, donut) fried in soybean oil produced lower levels of lipid oxidation products than vegetables, meat, and fish.[57] Notably, the levels of lipid oxidation products were significantly different between schools even though the schools used the same oil type that was processed and stored in very similar conditions. This variability demonstrates the complicated challenge of maintaining the quality of oils used for frying.

Related to types of food, various food preparation processes influence oxidation. The application of edible coatings or films to foods before frying may decrease the degradation of oil, but research findings are inconsistent.[1] Likewise, breading materials and batters have various influences on the stability of frying oil.[1] There appears to be an opportunity to develop functional coatings that enhance the thermo-oxidative stability of frying oil while maintaining the sensory attributes of fried foods.

3c. Time and Temperature

Frying time increases the thermo-oxidative degradation of oil.[1,5,11] Even though frying is a fast cooking method, the length of time for which an oil is used is usually long, particularly in repeated frying processes in food service operations.[1] Repeatedly heated vegetable cooking oil generates toxic polycyclic aromatic hydrocarbons[45] and has higher peroxide values (i.e., indicative of increased oxidation) than singly-heated vegetable cooking oil.[58] It follows that one recommendation for curbing thermo-oxidative degradation of oil is to limit the number of reheats and avoid intermittent (i.e., discontinuous) heating and cooking of oils.[5,55]

In addition to repeated or long frying times, high frying temperature accelerates lipid oxidation and the production of *trans* isomers.[1] For example, there is a statistically significant increase in the isomerization rate of linolenic acid when the temperature increases from 180^{o}C to 200^{o}C, irrespective of the type of oil.[36] Therefore, one important practice for controlling frying temperature is calibrating and ascertaining the correctness of fryers' temperature controllers.[1]

3d. Replenishment of fresh oil

Multiple reviews report that the replenishment of fresh oil (i.e., maintaining a high ratio of fresh oil to total oil) is a crucial strategy for managing lipid oxidation during frying.[1,5] However, there is a lack of specific recommendations for replenishing *cis* unsaturated oils during frying. One recommended daily turnover is 15-25% of the capacity of the fryer, but this general recommendation is from 1984,[53] well before the legislation prohibiting PHOs.

3e. Type and maintenance of fryer

The characteristics and maintenance of the fryer influence oxidation.[1,5] For example, copper or iron fryers and polymerized fat deposited on fryers accelerate lipid thermal oxidation. In contrast, fryers with a small surface-to-volume ratio minimize the contact of oil to air, thereby slowing down oxidation.[5] Evidence-based selection of a fryer is a viable strategy for maintaining the quality of oil.

3f. Antioxidants

Endogenous and added antioxidants reduce oxidation of oils under storage conditions (i.e., room temperature).[5,59] However, antioxidants are less effective in reducing oxidation under frying conditions, especially at high temperatures.[1,5,60] See Wu et al.[60] for a review of the stabilizing capacity of various phenolic compounds (e.g., rosemary) in different frying conditions. During deep-fat frying, lignan compounds are more stable and effective antioxidants than tocopherols, butylated hydroxyanisole, butylated hydroxytoluene, propyl gallate, and tert-butylhydroquinone.[5] Other promising antioxidant approaches include adding spinach powder or red ginseng extract to flour dough.[5] Overall, the stability-enhancing capacity of antioxidants differs from one to another and can be complicated by both synergistic and antagonistic interactions.[60] Furthermore, above optimal concentrations and conditions, some antioxidants become pro-oxidative.[1] There appears to be an opportunity to design frying antioxidants that are thermally stable; neutral or antioxidative rather than pro-oxidative; cost-effective; feasible to implement in daily food service operations; safe; and appealing to consumers.[1]

3g. Oxygen concentration

Higher amounts of dissolved oxygen in the oil increase oxidation.[1,5] Strategies to maintain the quality of frying oil by controlling accessibility to oxygen include nitrogen or carbon dioxide flushing. A minimum of 15 minutes of nitrogen or five minutes of carbon dioxide flushing prior to heating decreases the oxidation of oil during deep-fat frying.[61] Another strategy to curb lipid oxidation during frying is to decrease the surface-to-volume ratio of oil (see section 3e).[1] Other strategies such as frying in a vacuum system and adding silicon are challenging to implement.[1]

3h. Implementing oil management plans and monitoring oil quality

There is growing attention on the need to curb thermal oxidation of unsaturated oils used to replace PHOs in frying applications.[1,10] However, there is a literature gap on the oil management practices of food service establishments in North America. Food service establishments should design and implement plans to maintain the quality of unsaturated oils used in frying processes.[1] Oil management plans should outline context-specific application conditions (e.g., heat, time, number of reheats) to reduce thermal oxidation. In addition, oil management plans should delineate procedures for monitoring oil quality. There is emergent research on the development of on-the-spot frying oil assessments, such as a portable capacitive sensor[62] and a microfluidic assessment technique.[63] However, there appears to be no research on the implementation (e.g., practicability and adoption) of these frying oil monitoring techniques in real-world food service settings. Developing feasible, appropriate, and cost-effective monitoring techniques for daily use in typical food service settings is critical because common laboratory assessments (e.g., measures of total polar compounds) are complex and time-consuming.[56]

4. Conclusion

This review demonstrates the importance of raising awareness about potential unintended consequences of replacing PHOs with unsaturated oils that are susceptible to thermal oxidation in frying processes. Food service entities need to be aware that oxidized oils may lead to consumer and employee health risks, even more so if PHOs are replaced with PUFAs in frying processes. Complicated factors belie a streamlined, one-size-fits-all prescription for curbing thermal-oxidative degradation of oil. However, awareness of the constellation of factors that influence oil quality could guide the development of oil management plans for frying processes in specific contexts.

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