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3-Monochloropropandiol and glycidyl esters in heat-processed oil-based food products: Exposure and risk

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ABSTRACT

Fatty acid esters of 3-monochloro-1,2-propanediol (3-MCPDE) and glycidol (GE) are potentially harmful heat-induced contaminants produced during food processing. In this study, 100 heat-treated oil-based food samples covering fried, smoked, grilled, and baked food groups were collected in Koforidua, Ghana and analysed for the two esters using gas chromatography-mass spectrometry. The dietary exposures were estimated by a probabilistic approach using Monte Carlo Simulation. Levels of 3-MCPDE and GE in the foods ranged from <limit of detection (LOD) to 1.28 mg/kg and <LOD to 1.20 mg/kg, respectively, and the highest mean levels were found in smoked foods with concentrations of 0.91 mg/kg (3-MCPDE) and 0.61 mg/kg (GE). The modal dietary exposure to 3-MCPDE and GE in the different food groups ranged from 0.01 to 1.18 µg/kg bw/day and 0.01 to 0.8 µg/kg bw/day, respectively. The 95th percentile estimates for 3-MCPDE exposure (33 %) and GE margin of exposure (MoE) (92 %) contravened the health-based guidance values established by the Joint Food and Agriculture Organization/World Health Organisation Expert Committee on Food Additives (JECFA) and the European Food Safety Authority (EFSA). This suggests health concerns for heavy consumers, especially females and children aged 3 to 9 years. The food groups that contributed to these unsafe exposures were mostly fried and smoked foods. Therefore, reducing the levels of 3-MCPDE and GE in these foods is recommended to lower the health risk.

1. Introduction

The chemical compound, 3-monochloro-1,2-propanediol (3-MCPD), was first identified as a contaminant of acid-hydrolyzed vegetable protein (HVP), a savory ingredient produced from the treatment of defatted vegetable protein with hydrochloric acid (Lee & Khor, 2015). The contaminant was later detected in soy sauces produced using acid-HVP as an ingredient (Chung et al., 2013; Vicente et al., 2015). However, recent studies found various levels of fatty acid esters of 3-MCPD (3-MCPDE) and its associated compound, glycidyl esters (GE), in foods produced without acid-HVP (Becalski et al., 2015; Kamikata et al., 2019). According to reports, 3-MCPDE formation in processed foods arises from the reaction between lipids and chloride-containing compounds (e.g. sodium chloride) at high temperatures. The reaction is promoted by low water activity and pH, as well as high fats and chloride content (Chung et al., 2013; Nguyen & Fromberg, 2019). Similarly, GEs are formed during high-temperature treatment of edible oils and oil-based foods (Cheng et al., 2017). The precursors involved in forming these contaminants in food depend on the food ingredients (origin, conditions of manufacture, and matrix) and food preparation (Chung et al., 2013).

In recent years, the presence of 3-MCPDE and GE in food has become a concern due to the confirmed enzymatic hydrolysis of 3-MCPDE and GE into free 3-MCPD/glycidol moiety in the gastrointestinal tract (Li et al., 2015). This couples with findings that the toxicological effects of oral exposure to 3-MCPDE and GE are the same as exposure to non-esterified 3-MCPD and glycidol in equimolar quantities (Appel et al., 2013). Both 3-MCPD and glycidol are considered toxic, and after absorption by the digestive system, they enter blood circulation and are distributed to tissues and organs (Abraham et al., 2013). One of the main target organs of 3-MCPD toxicity is the testis with chronic exposure resulting in epididymal damage, abnormal cell production, decrease in the weights of the testis, testicular alterations, decreases in sperm count and motility, and spermatogenic arrest, ultimately leading to male

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infertility (Mahmoud et al., 2018). Kidney damage resulting from 3-MCPD-induced adenomas, nephropathy, and tubular hyperplasia, as well as suppression of immune function and liver, heart, brain, and spleen weight gains, occurred in rats (Onami et al., 2014; BfR, 2020). Glycidol has also been associated with axonal injury (Akane et al., 2013), degeneration of renal tubular cells, testicular atrophy, and reduction in sperm count and motility in adult animals (BfR, 2020). In addition, developmental exposure to glycidol was found to have altered the brain's neuronal networks, with dentate gyrus neurogenesis being the most affected (Akane et al., 2014). The International Agency for Research on Cancer (IARC) classified 3-MCPD as a possible human carcinogen (group 2B) based on obvious incidences of renal tubule carcinomas and Leydig cell tumors *in vivo*. The contaminant, however, has not demonstrated any significant genotoxicity potential *in vivo* (IARC, 2012). Meanwhile, IARC (2012) also classified glycidol as a genotoxic compound that is probably carcinogenic to humans (group 2A). The Scientific Opinion of the European Food Safety Authority (EFSA) Panel on Contaminants in the Food Chain (CONTAM Panel) therefore performed a dose-response analysis on 3-MCPD and its esters using the benchmark dose (BMD) approach in risk assessment in 2016. The exercise led to establishing a group tolerable daily intake (TDI) of 0.8 μg/kg bw per day and later revised to 2 μg/kg bw per day in 2017 (EFSA, 2018)). Relying on the same data, the Joint Food and Agriculture Organization/World Health Organization Expert Committee on Food Additives (JECFA) also revised an earlier established group Provisional Maximum Tolerable Daily Intake (PMTDI) of 2 μg/kg bw per day to 4 μg/kg bw per day for 3-MCPD and 3-MCPDE singly or in combination (JECFA, 2016). In the case of GE, available dose-response data were inadequate for the benchmark dose (BMD) approach; instead, the margin of exposure (MoE) approach was adopted with T25 (dose resulting in 25 % incidence of tumors) of 10.2 mg/kg bw per day for peritoneal mesothelioma in rats as the reference point. A MoE $\geq$ 25,000 was considered a low health concern (EFSA, 2016).

Dietary studies conducted in some countries across the world have found unacceptable levels and exposure to 3-MCPDE and GE in several oil-based foods that had undergone heat treatment, such as smoking, grilling, baking, frying and deodorization (Arisseto et al., 2013; Chung et al., 2013; Li et al., 2015; Jang & Koh, 2020; Wong et al., 2020). Consequently, some mitigation measures were employed to curtail the occurrence of these contaminants in food. Prolonged storage of bleached and deodorized palm oil stored at temperatures between 5 and 15 ℃ resulted in GE degradation at 0.2 to 0.4 mg/kg per month (Matthaus et al., 2016). Baking at an elevated temperature of 200 ℃ induced 3-MCPDE and GE degradation (Goh et al., 2019). The addition of antioxidants (tert-butylhydroquinone and oleoresin rosemary) during frying reduced 3-MCPDE and GE levels by inhibiting the formation of radical intermediates (Wong et al., 2019). Furthermore, the addition of potassium acetate during deodorization reduced the levels of 3-MCPDE and GE by 99 % and 49 %, respectively, whereas ethanol as a stripping agent caused a 49 % and 31 % reduction in 3-MCPDE and GE, respectively (Tivanello et al., 2021). However, some of these mitigation measures have negatively impacted food quality, acting as a disincentive to their adoption during domestic and commercial food production (Goh et al., 2019; Tivanello et al., 2021; Yung et al., 2023). Hence, the contaminants continue to be detected in high levels in foods.

In Ghana, most food recipes require oil/fat or oil-containing food materials, usually heated to high temperatures. Consequently, Ghanaian diets are characterized by high intakes of deep-fried foods, bakery foods, processed meat and smoked foods (Azupogo et al., 2023; Rousham et al., 2020). The World Health Organization (WHO) considers the consumption of such foods as one of the main risk factors for non-communicable diseases (NCDs), particularly heart diseases, cancer and respiratory diseases (WHO, 2023), which incidentally account for 43 % of all mortalities in Ghana (WHO, 2022). While available evidence implicates dietary 3-MCPDE and GE in the incidence of these NCDs, there is limited information on the occurrence of these contaminants in Ghanaian foods and their exposure levels among the Ghanaian population. Moreover, the EFSA have called for data on 3-MCPDE and GE in foods across the globe to adequately evaluate the global intake or toxicological significance, which would provide the basis for a more rigorous and extensive approach to addressing 3-MCPDE and GE occurrences in food (Ostermeyer et al., 2021). Therefore, to narrow this information gap, the present study sought to (i) determine the 3-MCPDE and GE content in various heat-treated oil-based local foods in Ghana, (ii) estimate the exposure of consumers of these foods to the two contaminants, and (iii) evaluate the potential health risks associated with the consumption of these foods.

2. Materials and methods

2.1. Materials

2.1.1. Reagents and standards

Petroleum ether (boiling point 40–60 ℃), anhydrous tetrahydrofuran (THF), n-heptane, 2,2,4-Trimethylpentane, and anhydrous sodium bromide (NaBr) were acquired from Surechem Products Ltd (Suffolk, England). Sulphuric acid (H_2SO_4), phenylboronic acid (PBA), toluene, methanol, acetone, anhydrous sodium sulfate, and sodium hydrogen carbonate ($NaHCO_3$) were acquired from Sigma-Aldrich Co. (Missouri, USA). Standards: 1,3-dipalmitoyl-2-chloropropanediol (3-MCPDE); 3-MCPDE-d_5, glycidyl palmitate (GE), and GE-d_5 were obtained from Toronto Research Chemicals Inc. (Toronto, Canada). Calibration standard solutions were prepared in toluene.

2.1.2. Samples collection

Fifty (50) heat-treated oil-based foods that form part of daily meals were procured randomly from markets, retail shops, and restaurants in Koforidua between March and April 2022. Each food was procured in duplicates from different vendors (a sample per vendor), resulting in a total of 100 samples. The samples were divided into four (4) groups: 52 samples of fried foods, 20 samples of smoked foods, 14 samples of grilled foods, and 14 samples of baked foods (Table 1).

2.2. Methods

2.2.1. Study area

The study area was Koforidua, an urban town and regional capital for the Eastern Region, the third most populated region in Ghana, with a settlement population of 2925,653 according to the 2021 population census (Ghana Statistical Service, 2021). The town serves as a commercial center for the Eastern Region, and it is home to many businesses, most of which are into retailing goods and other commodities.

2.2.2. Sample size

The population of study comprised residents of Koforidua. The sample size required for the study was calculated using the Cochran formula (Cochran, 1977):

Table 1
Food samples used in the study.

Food group	Food item
Fried	Spring roll, egg, sausage, doughnut, buff loaf, chips, tilapia, redfish, shrimp, yam, plantain, cocoyam, plantain crips, potato crips, chicken, gizzard, beef, pork, pygmy herring, bonga shad, horse mackerel, “tiko”, local snacks (“poloo”, “koose”, “agawu”, “agbeli kaklo”)
Smoked	Mackerel, tuna, tilapia, bonga shad, catfish, herrings, other fishes (“aeroplane”, “owarefuo”, “tiko”)
Grilled	kebab (gizzard, goat, beef), sausage, chicken, guinea fowl, tilapia
Baked	Cake, sugar bread, butter bread, tea bread, rock buns, ring doughnut, meat-pie

$$n_0 = \frac{z^2pq}{e^2} \tag{1}$$

Where n_o = sample size, z = critical value of 95 % confidence level (1.96), p = 50 % (largest variability), q = (1–p), e = desired level of precision usually set at 0.05. The calculated sample size was 384. However, as the total population of Koforidua is known, Cochran's correction formula (Cochran, 1977) was used to calculate the minimum sample size:

$$n = \frac{n_0}{1 + \frac{(n_0 - 1)}{N}} \tag{2}$$

Where n = sample size, n_o = sample size derived from Equation 1, N = population of Koforidua (218,457), derived from the sum of the population of New Juaben North and South municipals (Ghana Statistical Service, 2021). The corrected minimum sample size was 383, hence a sample size of 420 was used for the study.

2.2.3. Food consumption data

An exposure assessment questionnaire was designed and administered to 50 randomly selected individuals in Srodae, a suburb and business center of Koforidua, to ascertain the suitability of the questionnaire and identify the foods commonly consumed as part of a meal for breakfast, lunch, and supper. The preliminary assessment indicated that, aside from all the selected foods in the four food categories, baked foods were mostly consumed during breakfast and supper but hardly as lunch. Thus, baked foods were excluded from the lunch category in the final questionnaire. During the survey, daily consumption data (breakfast, lunch, supper) of selected heat-treated oil-containing foods were obtained from 420 residents of Koforidua selected through multistage random sampling from August to October 2021. In the first stage, 5 suburbs in the town, namely, Betom, Atekyem, Effiduase, Asokore, and Ada, were randomly chosen as the survey areas. In the second stage, available and willing residents were engaged in 10 households randomly selected in each suburb. In addition to the consumption data, information such as respondent's age and body weight were also obtained. The minimum age of respondents was pegged at 3 years, as children at this age were assumed to be weaned off breast milk. Parents or guardians were asked to provide information for dependents who could not provide it independently. The obtained data were categorized into four age groups: 3–9 years, 10–17 years, 18–64 years, and 65–74 years, as applied in the EFSA Comprehensive European Food Consumption Data (EFSA, 2016).

2.2.4. Sample preparation

The food samples were weighed, and afterwards, edible portions were homogenized using a blender (New German-Crest SC-1589, Germany) or pestle and mortar. Fried chicken was homogenized without bones. The rest of the fried foods, as well as baked food, were entirely homogenized separately because they are usually eaten wholly. For smoked foods, the skins, fins and heads of herrings and bonga shad were removed before homogenization. The rest of the smoked fishes had their bones, fins and heads, removed before homogenization. In the case grilled foods, tilapia was homogenized without the bones, head and fins. The chicken and guinea fowl were also homogenized, minus the bones. The kebabs and sausages were, however, homogenized entirely. The homogenates were put in black plastic bags, sealed, and frozen at −18 ℃.

2.2.5. Fat extraction

Fats from the homogenates were extracted with minor modifications according to the standard method of AOAC 960.39 (AOAC, 2012) and (Zelinkova et al., 2017). Briefly, fat from 20 g of each sample was extracted for 8 h by soxhlet extraction at 90 ℃ with petroleum ether as the extracting solvent. The residual solvent was removed from the extracted oil with a rotary evaporator vacuum concentrator (BÜCHI 011, Switzerland) at 40 ℃. The fat content was determined gravimetrically for each sample. The extracted fats were placed in plastic bottles and stored at −18 ℃ for analysis.

2.2.6. Determination of 3-MCPDE and GE

One hundred (100) mg of each of the extracted fats was dissolved in 2 mL of anhydrous tetrahydrofuran (THF) and treated according to the AOCS Official Method Cd 29a-13 described by Zelinkova et al. (2017). GC-MS determinations were performed on a GC2010 plus gas chromatograph coupled to a QP 2020 mass spectrometer (Shimadzu, Kyoto, Japan). The treated sample extracts (1 μL) were injected at 260 ℃ in splitless mode. Separations were achieved with capillary column VF-5MS 30 m x 0.25 mm (0.25 μm) (Agilent Technologies) and carrier gas (helium) at 1.2 mL/min flow rate. The oven's temperature program was set as 60 ℃ for 1 min, 6 ℃/min to 150 ℃ for 2 min, and 30 ℃/min to 300 ℃ for 10 min. Detection was performed with selected ion monitoring (SIM) following positive electron impact ionization (70 eV). The ions monitored for quantitative analysis were: m/z 147, 196, and 198 for derivatized 3-MCPD; m/z 150, 201, and 203 for derivatized 3-MCPD-d5; m/z 147 and 240 for derivatized 3-monobromopropanediol (3-MBPD); m/z 150 and 245 for derivatized 3-MBPD-d5. Strong linearity was obtained for 3-MCPDE ($r^2 = 0.9998$) and GE ($r^2 = 0.9995$) within the 0.05–4.0 mg/kg range and 0.03–6.0 mg/kg, respectively. The limits of detection (LOD) and quantification (LOQ) were calculated respectively as 0.02 and 0.05 mg/kg for 3-MCPDE and 0.02 and 0.03 mg/kg for GE. The average recovery (3-MCPDE: 113.9 %; GE: 91.7 %) and repeatability (3-MCPDE: 6.1 %; GE: 8.4 %) of the analytes were determined after spiking blank extra virgin olive oil with 3-MCPDE (0.1, 0.5, 2.0 mg/kg) and GE (0.2, 1.0 and 5.0 mg/kg).

2.2.7. Exposure assessment

The probabilistic analysis approach was adopted by using Palisade @Risk 8.0 software in combination with Microsoft Office Excel 2010 to fit distributions for 3-MCPDE or GE concentrations in the food sample (C; mg/kg), mass of food consumed per day (FC; g/day) and body weight of the respondents (bw; kg). Hazard concentrations below the LOD were assigned half of the LOD values (WHO, 1995). The exposure distribution was deduced by integrating the variables into Equation 3, where the estimated exposure (μg/kg bw/day) was run in the risk software for 100,000 iterations. The different exposure estimates, i.e. mode, median, and 95th percentile, were obtained and studied.

$$\text{Exposure} = \frac{\text{C} \times \text{FC}}{\text{bw}} \tag{3}$$

2.2.8. Risk assessment

The potential health risk posed by 3-MCPDE was assessed by comparing the exposure distributions of 3-MCPDE with the PMTDI 4 μg/kg bw per day prescribed by JECFA (2016) and TDI of 2 μg/kg bw per day estimated by EFSA (2018). There is a risk if the exposure estimate exceeds the reference values. For GE, the MoE was calculated using the T25 estimate of 10.2 mg/kg bw per day as the reference point (EFSA, 2016). The MoE was run in the risk software, iterating at 100,000 times. A MoE of 25,000 or more was considered of low health concern. The formula is as follows:

$$\text{MoE} = \frac{\text{T25}}{\text{Exposure}} \tag{4}$$

3. Results and discussion

3.1. Levels of 3-MCPDE and GE contamination in food samples

The present study analyzed 3-MCPDE and GE in heat-treated oil-based food samples. The average fat contents of fried, smoked, grilled, and baked food samples were 22.3 %, 7.0 %, 11.7 %, and 12.5 % respectively (Table 2). To estimate exposure to contaminants, the World

Table 2
Concentrations of 3-MCPDE and GE in various heat-treated oil-containing foods.

Food Type	N	Fat (%)	3-MCPDE (mg/kg)[a]		GE (mg/kg)[a]	
			Mean ± SD	Min-Max	Mean ± SD	Min-Max
Fried	52	22.3	0.30 ± 0.19	<LOD–0.70	0.21 ± 0.18	<LOD–0.69
Smoked	20	7.0	0.91 ± 0.29	0.38–1.28	0.61 ± 0.30	0.20–1.20
Grilled	14	11.7	0.56 ± 0.32	0.09–0.97	0.47 ± 0.28	0.11–0.82
Baked	14	12.5	0.30 ± 0.43	0.04–1.25	0.21 ± 0.33	<LOD–0.96

[a] The analyses were carried out in duplicates.

Health Organization (WHO) advised that half of the LOD value was used for levels below the LOD when less than 60 % of the samples showed such results (WHO, 1995). Among the four food groups, smoked foods contained the highest mean levels of 3-MCPDE (0.91 mg/kg; ranged from 0.38 to 1.28 mg/kg) and GE (0.61 mg/kg, ranged from 0.2 to 1.2 mg/kg), with all samples having levels above LOD, followed by grilled foods which also showed contamination in all samples, with a mean level of 0.56 mg/kg (range: 0.09–0.97 mg/kg) for 3-MCPDE and 0.47 mg/kg (range: 0.11–0.82 mg/kg) for GE. In the case of fried foods, 92.3 % and 88.5 % of the samples were detected with 3-MCPDE and GE, respectively, whereas 100 % and 85.7 % of baked food samples showed 3-MCPDE and GE levels above LOD, respectively. Notwithstanding, both food groups had similar mean levels of 3-MCPDE (0.31 mg/kg) and GE (0.21 mg/kg). It is obvious from these findings that although there is inadequate data about 3-MCPDE and GE for many foodstuffs, heat-processed oil-based foods serve as significant sources of these contaminants to consumers. This is also evident in an earlier study reported by Chung et al. (2013) on heat-processed foods (fried, baked, and so on) sold in Hong Kong which demonstrated similar levels of 3-MCPDE in pastries (not detected [ND]–1.2 mg/kg), biscuits (0.05–0.86 mg/kg), snacks (0.009–1 mg/kg) and meat, fish and their products (ND-0.28 mg/kg). Another food survey conducted in China reported a wider range of 3-MCPDE levels in fried foods (ND-5.621 mg/kg) and baked foods (ND-2.461 mg/kg) consumed in 31 Chinese provinces (Cui et al., 2021). Meanwhile, in Germany, a study by Ostermeyer et al. (2021) in 2021 revealed a comparatively lower 3-MCPDE (ND-0.034 mg/kg) and GE (ND-0.043 mg/kg) in smoked fishery products. In the same year, Di Campi et al. (2020) conducted a study in Italy indicating that the mean 3-MCPDE contamination in cookies was 0.702 mg/kg, clearly higher than the mean level found in this present study. In the same report, the mean level of 3-MCPDE in bread (0.098 mg/kg) was lower than in this study. The variations in the contaminants' levels could be attributed to different foods in the various food groups. These foods have distinct moisture content, matrixes, chlorine content, and processing conditions. Water promotes the formation of precursors of 3-MCPDE and GE, namely diacylglycerol (DAG) and monoacylglycerol (MAG) from triacylglycerol (TAG) in food (Goh et al., 2021). Similarly, foods with high-fat content, transition metals, and oil-uptaking ability often have increased 3-MCPDE and GE levels after heat-processing (Arisseto et al., 2017; Goh et al., 2021). High-fat products such as food emulsions, margarine, special fats, and shortening that are derived from refined vegetable oils contain 3-MCPDE and GE in high levels (Macmahon et al., 2013; Custodio-Mendoza et al., 2019). Subsequently, these contaminants find their way into various foodstuffs, such as bakery products, which use these high-fat products as primary raw materials. Sodium chloride is used in most cooking applications and, together with organic chloride, facilitates 3-MCPDE generation (Nagy et al., 2011). However, chlorine content does not result in GE formation, which explains the apparent higher concentrations of 3-MCPDE than GE in the various food groups in this study (Table. 1). Lastly, processing conditions (e.g. temperature and time) also influence the formation of 3-MCPDE and GE in food. For instance, Ostermeyer et al. (2021) attributed 3-MCPDE and GE formation in smoked fish products partly to smoking temperature, smoke density, and smoking time. In a study on biscuit baking system, Mogol et al. (2014) demonstrated that baking temperature, particularly between 200 and 220 ℃, coupled with the presence of sodium chloride in the recipe, resulted in the formation of 3-MCPDE in the biscuits. Similarly, the high temperatures used in frying are typically between 120 and 180 ℃ (Oke et al., 2018), and this is comparable to the deodorization temperatures employed during vegetable oil refining, a process responsible for the astronomical rise in 3-MCPDE and GE levels in oils (Cheng et al., 2017). It was, therefore, expected that fried foods would show high contamination of these contaminants in this study. In contrast, a lower level of contamination was observed in fried foods compared to the other food groups. It was earlier suggested by Aniołowska and Kita (2015) that these contaminants may decompose at a typical frying temperature. This phenomenon was observed by Xu et al. (2020), who reported a decrease in 3-MCPDE and GE levels in fish nuggets with frying time. It could also be that, due to the potential health risk of 3-MCPDE and GE exposure, vegetable oil producers in various countries have adopted measures to reduce the generation of these contaminants during the processing of the oils, which ultimately led to safer vegetable oils in the market (Matthäus et al., 2011; Zulkurnain et al., 2013; Cheng et al., 2017).

3.2. Food consumption data

The food consumption data distributions of the study population are summarized in Tables 3 and 4. The data distributions were presented using mode (or modal), median, and 95th percentile estimates to represent the most frequent, medium, and high estimates, respectively. Generally, similarities were observed in the distribution of 3-MCPDE and GE levels for each food group consumed for breakfast, lunch, and supper presented under gender (male and female) and age group, suggesting that the study population consumed the same type of food samples for each meal. Furthermore, in almost all cases, the population was exposed to the highest concentration of contaminants by consuming smoked foods during each meal, as seen in all distribution indices (mode, median, and 95th percentile). Ironically, smoked foods were generally the least consumed by mass across the day among the food groups, which may stem from the high cost and dry nature of foods in this group (mainly fish) which tend to affect the weight of food consumed as well as the purchasing and consumption behavior of the people.

As shown in Table 3, among the most frequently consumed masses of foods in a day, fried foods consumed by males for lunch and females for breakfast were the lowest, with modal masses of 21.15 g and 14.37 g, respectively. Similarly, the highest 95th percentile mass of food was 492.50 g of fried food, consumed in a day by males for supper and females for lunch and supper. When comparing the 95th percentile masses of foods consumed at breakfast, males consumed more grilled foods (294.38 g) than females (220.79 g), whereas females consumed more baked foods (376.48 g) than males (312.12). Likewise, most males consumed more smoked foods (105.76 g) at lunch than females (17.15 g). Also, the median masses of fried foods consumed at lunch (male: 98.48 g; female: 73.50 g) and supper (male: 73.50 g; female: 68.31 g) suggest a higher consumption behavior among male consumers. Notwithstanding, largely, the study showed that both males and females consumed comparable masses of foods in the four food groups across the day. On the contrary, Altissimi et al. (2017), in an earlier food consumption study conducted in Italy, observed that the male population consumed distinctively more masses of foods than females. This trend was also observed by Siaw et al. (2018) in their consumption studies conducted in Ghana. The body weights of consumers involved in Siaw et al. (2018)'s study and this present study are also similar, with male consumers having a slightly upper edge over their female counterparts.

Table 3
Statistical distribution of elements of daily exposures in male and female respondents.

			Male			Female		
	Variables	Food type	Mode	Median	95th P	Mode	Median	95th P
	BW (kg)		79.40	73.50	93.50	73.80	68.60	91.40
Breakfast	3-MCPDE (mg/kg)	Fried	0.01	0.21	0.51	0.01	0.19	0.51
		Smoked	0.38	0.66	1.29	0.38	0.66	1.25
		Grilled	0.09	0.09	0.49	0.09	0.09	0.49
		Baked	0.04	0.05	1.25	0.04	0.05	0.36
	GE (mg/kg)	Fried	0.01	0.14	0.62	0.01	0.07	0.62
		Smoked	0.30	0.36	0.88	0.30	0.36	0.88
		Grilled	0.11	0.11	0.61	0.11	0.11	0.61
		Baked	0.01	0.03	0.96	0.01	0.03	0.19
	Mass of food (g)	Fried	21.56	68.31	175.65	14.37	68.31	175.65
		Smoked	32.12	68.60	159.30	31.73	68.60	159.30
		Grilled	44.16	147.19	294.38	44.16	147.19	220.79
		Baked	39.02	151.76	312.12	39.02	151.76	376.48
Lunch	3-MCPDE (mg/kg)	Fried	0.01	0.29	0.52	0.01	0.39	0.52
		Smoked	0.38	0.38	1.25	0.38	0.38	1.25
		Grilled	0.09	0.09	0.49	0.09	0.09	0.49
	GE (mg/kg)	Fried	0.01	0.14	0.40	0.01	0.11	0.61
		Smoked	0.30	0.30	0.88	0.30	0.30	0.75
		Grilled	0.11	0.11	0.61	0.11	0.28	0.40
	Mass of food (g)	Fried	21.15	98.48	394.00	21.15	73.50	492.50
		Smoked	105.76	49.78	85.76	17.15	49.78	85.76
		Grilled	22.08	73.60	164.51	22.08	73.60	147.19
Supper	3-MCPDE (mg/kg)	Fried	0.01	0.29	0.70	0.01	0.29	0.70
		Smoked	0.38	0.38	1.24	0.38	0.66	1.25
		Grilled	0.09	0.09	0.49	0.09	0.09	0.49
		Baked	0.04	0.05	0.36	0.04	0.05	1.25
	GE (mg/kg)	Fried	0.01	0.11	0.69	0.01	0.09	0.69
		Smoked	0.20	0.30	0.88	0.20	0.30	0.88
		Grilled	0.11	0.11	0.61	0.11	0.11	0.61
		Baked	0.01	0.01	0.19	0.01	0.03	0.96
	Mass of food (g)	Fried	27.66	73.50	492.50	21.15	68.31	492.50
		Smoked	36.43	85.76	144.36	42.30	80.30	155.59
		Grilled	73.60	220.79	367.98	58.88	220.79	294.38
		Baked	55.22	186.88	379.40	55.22	156.06	379.40

While the present study found the respective median and 95th percentile ages of males to be 73.5 kg and 93.5 kg and that of females to be 68.6 kg and 91.4 kg, Siaw et al. (2018) reported 68 kg and 94 kg as the respective median and 95th percentile ages for males and 63 kg and 91 kg as that for females.

Table 4 shows the consumption patterns of the study population, categorized into age groups: 3–9 years, 10–17 years, 18–64 years, and 65–74 years. The masses of foods consumed by each age group during lunch were the lowest compared to the masses consumed for breakfast and supper. This observation agrees with the findings of Siaw et al. (2018)'s study, in which the authors reported heavy consumption during breakfast and supper and the least consumption occurring during lunch. The authors attributed the low patronage of lunch meals to short break periods of 10 to 30 min, usually granted to the study population. Whilst this reason could also hold for this study considering the similarity in the demography of the two study populations (pupils, students, and formal and non-formal workers), there could be other reasons such as health, high cost of lunch meals, poverty, busy work schedules, and mistrust for quality and safety of vended foods (Bae et al., 2008; Rheinländer et al., 2008; Pfeiffer et al., 2017). Children between the ages 3–9 years recorded the lowest modal mass of food consumed for breakfast (21.56–44.16 g), lunch (16.06–22.08 g), and supper (21.15–75.88 g), with adults in the 65–74 years age group recording the highest. Similar to the findings made in this study, children aged 2–11 years recorded the lowest food intake in the National Nutrition Survey (NNS) conducted by the Australian Bureau of Statistics (1999); however, the highest intake in the country was recorded for young adults (25–29 years).

3.3. *Exposure assessment*

The dietary intakes of 3-MCPDE and GE from heat-processed oil-based foods of the study population aged 3 years and above are shown in Tables 5–8. Generally, the most frequent dietary intake of 3-MCPDE and GE ranged from 0.01 to 1.18 μg/kg bw/day and 0.01 to 0.8 μg/kg bw/day, respectively. The 95th percentile intakes range from 0.14 to 37.03 μg/kg bw/day and 0.11 to 13.05 μg/kg bw/day for 3-MCPDE and GE, respectively. These intakes compare favorably with estimated intakes reported in previous studies. In China, Cui et al. (2021) reported that exposure of consumers of edible oils and oil-containing foods in the 95th percentile ranged from 1.511 to 4.027 μg/kg bw/day, whereas average consumers ranged from 0.586 t0 1.539 μg/kg bw/day. Similarly, the estimated 3-MCPDE exposures of average and high consumption of heat-processed foods in Hong Kong were 0.2 and 0.58 μg/kg bw/day, respectively (Chung et al., 2013). Also, per the JECFA (2017)'s report, international estimates of mean dietary exposure to total 3-MCPD (predominately 3-MCPDE) ranged from 0.2 μg/kg bw/day for countries in cluster G14 (Fiji, Papua New Guinea, Comoros, Kiribati, Solomon Islands, Vanuatu, Sri Lanka) to 1.7 μg/kg bw/day for countries in cluster G11 (the Netherlands, Belgium). Those of GE were in a similar range of between 0.2 and 1.0 μg/kg bw/day. The 90th percentile exposures were estimated to range from 0.4 to 3.4 μg/kg bw/day for 3-MCPD and 0.3 to 2.1 μg/kg bw/day for GE. In effect, it can be deduced from the aforementioned studies and this present study that high consumers of heat-processed oil-based foods consume significantly more of the contaminants.

In Tables 5 and 6, the exposure levels of both male and female populations were investigated. It was found that females generally had higher exposure levels than males at the 95th percentile. The only departure from this trend occurred at exposure levels for fried food at

Table 4
Statistical distribution of elements of daily exposures for various age groups.

			3 –9 years			10–17 years		
	Variables	Food type	Mode	Median	95th P	Mode	Median	95th P
	BW (kg)		10.27	21.20	32.40	28.47	39.10	68.40
Breakfast	3-MCPDE (mg/kg)	Fried	0.01	0.01	0.44	0.01	0.01	0.52
		Smoked	0.38	0.66	1.24	0.38	0.66	1.24
		Grilled	0.09	0.09	0.09	0.09	0.09	0.09
		Baked	0.05	0.05	1.25	0.05	0.10	0.36
	GE (mg/kg)	Fried	0.01	0.01	0.32	0.01	0.01	0.40
		Smoked	0.30	0.36	0.75	0.30	0.36	0.75
		Grilled	0.11	0.11	0.11	0.11	0.11	0.11
		Baked	0.01	0.01	0.96	0.01	0.08	0.19
	Mass of food (g)	Fried	21.56	58.55	80.52	24.50	52.56	246.25
		Smoked	32.12	59.74	99.56	32.12	59.74	137.21
		Grilled	44.16	73.60	147.19	73.60	147.19	294.38
		Baked	39.02	78.03	151.76	78.03	151.76	303.52
Lunch	3-MCPDE (mg/kg)	Fried	0.01	0.29	0.70	0.01	0.29	0.52
		Smoked	0.38	0.66	1.24	0.38	0.38	1.24
		Grilled	0.09	0.09	0.09	0.09	0.09	0.49
	GE (mg/kg)	Fried	0.01	0.09	0.69	0.01	0.09	0.40
		Smoked	0.30	0.36	0.75	0.30	0.30	0.75
		Grilled	0.11	0.11	0.11	0.11	0.11	0.61
	Mass of food (g)	Fried	21.15	41.71	197.00	27.66	73.50	344.75
		Smoked	16.06	29.87	68.60	49.78	49.78	68.60
		Grilled	22.08	36.80	73.60	36.80	73.60	110.39
Supper	3-MCPDE (mg/kg)	Fried	0.01	0.29	0.70	0.01	0.29	0.70
		Smoked	0.38	0.38	1.24	0.38	0.38	1.10
		Grilled	0.09	0.09	0.49	0.09	0.09	0.49
		Baked	0.05	0.05	0.36	0.05	0.05	1.25
	GE (mg/kg)	Fried	0.01	0.09	0.69	0.01	0.09	0.69
		Smoked	0.29	0.30	0.88	0.29	0.30	1.20
		Grilled	0.11	0.11	0.61	0.11	0.11	0.61
		Baked	0.01	0.01	0.19	0.01	0.03	0.96
	Mass of food (g)	Fried	21.15	64.00	295.50	42.30	61.55	394.00
		Smoked	33.21	59.74	102.91	59.74	66.42	171.51
		Grilled	58.88	73.60	147.19	73.60	132.47	294.38
		Baked	75.88	78.03	188.24	78.03	141.04	227.64
	BW (kg)		72.60	76.90	97.20	81.40	67.30	87.60
Breakfast	3-MCPDE (mg/kg)	Fried	0.01	0.22	0.51	0.20	0.21	0.51
		Smoked	0.38	0.66	1.29	0.38	0.79	1.29
		Grilled	0.09	0.09	0.49	0.09	0.09	0.09
		Baked	0.04	0.05	0.36	0.04	0.04	0.10
	GE (mg/kg)	Fried	0.01	0.14	0.62	0.20	0.19	0.62
		Smoked	0.30	0.36	0.88	0.30	0.46	0.75
		Grilled	0.11	0.11	0.61	0.11	0.11	0.11
		Baked	0.01	0.03	0.19	0.03	0.03	0.08
	Mass of food (g)	Fried	24.50	68.31	175.65	64.08	66.68	114.96
		Smoked	18.22	68.60	171.51	55.40	59.74	199.12
		Grilled	73.60	147.19	257.58	147.19	147.19	294.38
		Baked	55.22	156.06	376.48	55.22	110.44	156.06
Lunch	3-MCPDE (mg/kg)	Fried	0.01	0.52	0.52	0.19	0.19	0.52
		Smoked	0.38	0.66	1.25	0.38	0.38	1.25
		Grilled	0.09	0.09	0.49	0.09	0.09	0.09
	GE (mg/kg)	Fried	0.01	0.40	0.40	0.14	0.14	0.40
		Smoked	0.30	0.36	0.88	0.30	0.30	0.75
		Grilled	0.11	0.11	0.61	0.11	0.11	0.11
	Mass of food (g)	Fried	24.62	197.15	492.50	51.27	81.59	197.00
		Smoked	17.15	49.78	99.56	49.78	49.78	99.56
		Grilled	41.13	73.60	183.99	73.60	73.60	147.19
Supper	3-MCPDE (mg/kg)	Fried	0.01	0.29	0.70	0.70	0.22	0.70
		Smoked	0.38	0.38	1.25	0.38	0.38	1.25
		Grilled	0.09	0.09	0.49	0.09	0.09	0.09
		Baked	0.04	0.05	1.25	0.04	0.04	0.10
	GE (mg/kg)	Fried	0.01	0.10	0.69	0.69	0.11	0.69
		Smoked	0.20	0.30	0.88	0.20	0.30	0.75
		Grilled	0.11	0.11	0.61	0.11	0.11	0.11
		Baked	0.01	0.03	0.96	0.01	0.03	0.08
	Mass of food (g)	Fried	27.66	83.42	492.50	75.20	83.42	394.00
		Smoked	36.43	99.56	159.30	99.56	80.30	99.56
		Grilled	147.19	257.58	367.98	147.19	220.79	294.38
		Baked	55.22	195.08	379.40	156.06	151.76	390.15

Table 5
3-MCPDE exposure (µg/kg bw/day) among respondents by gender.

		Male			Female		
	Food type	Mode	Median	95th P	Mode	Median	95th P
Breakfast	Fried	0.02	0.23	1.32	0.01	0.05	5.30
	Smoked	0.36	0.72	3.15	0.33	0.68	3.72
	Grilled	0.17	0.22	0.74	0.17	0.22	0.82
	Baked	0.09	0.18	1.37	0.10	0.19	1.61
Lunch	Fried	0.10	0.63	4.01	0.12	0.54	4.22
	Smoked	0.25	0.37	1.68	0.30	0.42	1.90
	Grilled	0.10	0.14	0.50	0.05	0.13	0.56
Supper	Fried	0.07	0.43	3.07	0.14	0.41	2.85
	Smoked	0.12	0.21	0.83	0.45	0.71	3.61
	Grilled	0.24	0.33	1.22	0.18	0.33	1.30
	Baked	0.08	0.19	1.64	0.09	0.22	2.67

Table 6
GE exposure (µg/kg bw/day) among respondents by gender.

		Male			Female		
	Food type	Mode	Median	95th P	Mode	Median	95th P
Breakfast	Fried	0.01	0.05	5.88	0.01	0.04	2.75
	Smoked	0.29	0.45	1.97	0.25	0.46	2.07
	Grilled	0.22	0.27	0.95	0.24	0.29	1.06
	Baked	0.02	0.06	1.22	0.03	0.07	1.56
Lunch	Fried	0.03	0.41	2.90	0.04	0.37	3.16
	Smoked	0.17	0.26	1.13	0.21	0.29	1.24
	Grilled	0.13	0.18	0.63	0.07	0.16	0.68
Supper	Fried	0.08	0.42	3.01	0.02	0.22	2.03
	Smoked	0.08	0.14	0.60	0.28	0.50	2.56
	Grilled	0.26	0.41	1.49	0.29	0.41	1.60
	Baked	0.03	0.06	1.02	0.27	0.50	2.57

supper and fried food at breakfast (GE only). In an earlier study by Li et al. (2015), the authors also investigated Chinese male and female dietary exposure to 3-MCPDE from edible oils and fats by categorizing the study population into age groups. With the exception of the 18 to 49 years group, higher 95th percentile exposure levels were observed for females across the age groups. In this study, the higher exposures observed for the females may be attributed to their relatively lower body weights than the males, as discussed earlier.

Detailed studies of dietary exposure assessments conducted by previous researchers and international organizations have revealed a common trend: the high percentile (95th) exposure estimates are higher for younger than older age groups. Notably, in the EFSA (2018) report, high exposure levels of 3-MCPDE for younger age groups ranged from 1.1 to 2.6 µg/kg bw/day and that of adolescents and adults from 0.3 to 1.3 µg/kg bw/day across the dietary surveys. Similarly, according to JECFA 2017, the national high percentile (90th, 95th) estimates of dietary exposure to GE for adults in Japan and the USA were between 0.2 and 0.8 µg/kg bw/day. In contrast, children and adolescents had higher exposures between 0.4 and 2.1 µg/kg bw/day. Li et al. (2015) estimated the 95th percentile exposure to 3-MCPDE from edible oils and fats for Chinese children aged 7 to 10 years to be 3.81–3.86 µg/kg bw/day in comparison to 2.01–3.04 µg/kg bw/day for those aged 11 years and above. This study observed a similar trend among the medium and high exposure estimates across the age groups (Tables 7 and 8). For the younger aged group (3–9 years), the medium and high 3-MCPDE exposure levels ranged from 0.07–1.73 µg/kg bw/day and 0.35–37.03 µg/kg bw/day, respectively, that of GE ranged from 0.06–1.23 µg/kg bw/day and 0.44–13.05 µg/kg bw/day respectively. In the case of the older aged groups (10 years and above), lower estimates were recorded for medium and high exposures to 3-MCPDE (0.04–0.95 and 0.14–3.45 µg/kg bw/day, respectively) and GE (0.04–0.65 and 0.11–2.48 µg/kg bw/day respectively). This trend arises primarily from variations in consumption data and body weight: younger groups have lower body weights, which translates into higher consumption per kilogram of body weight.

3.4. Risk assessment

The JECFA (2016) and EFSA (2018) have established the PMTDI of 4 µg/kg bw per day and TDI of 2 µg/kg bw per day, respectively, to serve as health guidance value in risk assessment. The different guidance values are attributed to the differences in methods employed in applying the benchmark dose (BMD) approach. JECFA and EFSA used the same data set on male rat kidney hyperplasia during the BMD analyses. However, EFSA applied an overall uncertainty factor to a selected reference point to compensate for interspecies and intraspecies variations. Regardless, the established guidance values did not sufficiently

Table 7
3-MCPDE exposure (µg/kg bw/day) among respondents by age group.

		3–9 years			10–17 years		
	Food type	Mode	Median	95th P	Mode	Median	95th P
Breakfast	Fried	0.02	0.07	1.24	0.01	0.04	1.38
	Smoked	1.03	1.73	6.08	0.50	0.85	3.45
	Grilled	0.29	0.39	0.92	0.24	0.32	0.59
	Baked	0.19	0.33	1.33	0.15	0.24	1.26
Lunch	Fried	0.11	0.51	2.53	0.09	0.51	2.98
	Smoked	0.57	1.04	3.70	0.43	0.58	1.15
	Grilled	0.10	0.14	0.35	0.15	0.20	0.40
Supper	Fried	0.03	0.17	37.03	0.13	0.52	2.24
	Smoked	1.18	1.73	5.57	0.73	0.95	2.59
	Grilled	0.34	0.43	0.93	0.22	0.33	1.23
	Baked	0.28	0.45	1.54	0.12	0.21	1.91
		18–64 years			65–74 years		
Breakfast	Fried	0.03	0.21	0.91	0.20	0.25	0.57
	Smoked	0.50	0.65	1.76	0.41	0.66	2.24
	Grilled	0.18	0.19	0.33	0.17	0.20	0.44
	Baked	0.10	0.14	1.68	0.07	0.07	0.14
Lunch	Fried	0.18	0.77	2.82	0.14	0.21	0.92
	Smoked	0.27	0.34	0.94	0.29	0.38	1.08
	Grilled	0.11	0.14	0.29	0.08	0.10	0.25
Supper	Fried	0.18	0.39	2.16	0.29	0.38	2.33
	Smoked	0.58	0.70	1.93	0.48	0.59	1.62
	Grilled	0.36	0.35	0.65	0.25	0.28	0.45
	Baked	0.13	0.21	1.89	0.09	0.10	0.21

Table 8
GE exposure (µg/kg bw/day) among respondents by age group.

		3–9 years			10–17 years		
	Food type	Mode	Median	95th P	Mode	Median	95th P
Breakfast	Fried	0.03	0.06	0.72	0.01	0.04	0.79
	Smoked	0.73	1.18	3.24	0.37	0.57	1.76
	Grilled	0.36	0.49	1.17	0.32	0.41	0.75
	Baked	0.04	0.09	1.06	0.03	0.09	2.48
Lunch	Fried	0.05	0.27	1.76	0.07	0.35	2.36
	Smoked	0.43	0.72	2.13	0.22	0.23	0.41
	Grilled	0.14	0.18	0.44	0.20	0.25	0.51
Supper	Fried	0.03	0.14	13.05	0.02	0.26	1.74
	Smoked	0.83	1.23	4.03	0.44	0.65	1.95
	Grilled	0.41	0.54	0.93	0.27	0.40	1.47
	Baked	0.06	0.13	1.54	0.03	0.08	1.56
		18–64 years			65—74 years		
Breakfast	Fried	0.01	0.13	0.71	0.12	0.16	0.63
	Smoked	0.27	0.33	0.80	0.25	0.42	1.36
	Grilled	0.23	0.25	0.41	0.20	0.26	0.56
	Baked	0.03	0.05	1.09	0.03	0.04	0.11
Lunch	Fried	0.07	0.43	2.20	0.12	0.16	0.69
	Smoked	0.19	0.24	0.61	0.23	0.28	0.76
	Grilled	0.13	0.17	0.35	0.10	0.13	0.32
Supper	Fried	0.03	0.22	1.75	0.01	0.19	1.68
	Smoked	0.40	0.49	1.39	0.23	0.32	1.15
	Grilled	0.42	0.44	0.77	0.35	0.36	0.57
	Baked	0.03	0.07	1.31	0.03	0.04	0.22

cover male fertility and reproductive toxicity parameters, which often resulted in an underestimation of 3-MCPDE-associated risk. Therefore, to err on the side of caution, this study compared the estimated intakes of 3-MCPDE to the two guidance values to ascertain if there is a possible health risk related to 3-MCPDE dietary exposure. As seen in Table 5, only the 95th percentile group of both male and female consumers of fried foods at lunch showed exposure levels (male: 4.01 µg/kg bw per day; female: 4.22 µg/kg bw per day) marginally exceeding the health-based guidance value established by JECFA 2016. The modal and median male and female consumers did not show risk from 3-MCPDE exposure, as the intake values for the various food groups across the day were less than 4 µg/kg bw per day. When the intakes were compared to EFSA's TDI, the most unsafe exposures (higher than 2 µg/kg bw per day) occurred at supper followed by lunch, with the 95th percentile female group presenting higher risk possibilities (55 %) compared to their male counterparts (27 %). This is a significant concern due to the tendency of females to pass the contaminant on to fetuses in their wombs or babies through breast milk (Zelinková et al., 2008). Among the food groups, fried foods presented the most danger of 3-MCPDE exposure for the 95th percentile male and female consumers, with intake values ranging from 2.85 to 4.22 µg/kg bw per day. This stems from the 95th percentile mass of fried foods both genders consume.

In Table 6, the estimated 95th percentile intakes of 3-MCPDE for smoked foods during breakfast (6.08 µg/kg bw per day) and fried and smoked foods during supper (37.03 and 5.57 µg/kg bw per day, respectively) by the 3–9 years age group exceeded JECFA's PMTDI, suggesting a potential health risk. No health risk was observed among the remaining age groups as they had 3-MCPDE intakes lower than 4 µg/kg bw per day. However, when compared to EFSA's TDI, an appreciable percentage of the 95th percentile intakes of the consumers aged 3–9 years (45 %), 10–17 years (36 %), 18–64 years (18 %), and 65–74 years (18 %) were above the safe limit of 2 µg/kg bw per day. The food groups that contributed to these unsafe exposures were fried (46 %) and smoked (54 %) foods. In Li et al. (2015)'s study, all the 95th percentile intakes of 3-MCPDE by all ages were above the TDI of 2 µg/kg bw per day, whereas children aged 3 to 12 years were the only category that had intakes above the TDI at the 95th percentile in Cui et al. (2021)'s. The latter, however, reported intakes surpassing the TDI at the 99th percentile for all age groups (Cui et al., 2021). Both studies found children having the highest 95th percentile 3-MCPDE intake, which was also observed in this study. The estimated results of the aforementioned studies and this present study have pointed to two common conclusions: (1) high food consumers are at risk of 3-MCPDE-related health complications; (2) children are at higher risk than adolescents and adults.

It is worth noting that the contribution of smoked foods, the most contaminated food group in this study, to the overall risk of 3-MCPDE exposures, became conspicuous when the consumers were categorized into age groups. When the assessment was done gender-wise, their importance to 3-MCPDE exposure among the population was not noticeable. This underscores the importance of approaching risk assessment based on smaller population clusters, such as age and body weight. The lower the age and body weight, the more crucial it is not to exceed the health guidance values.

This study used The MoE approach for the risk characterization of GE. The calculated MoEs ranged from 1735 to 17,000 for male consumers' 95th percentile exposure estimates, while those for females ranged from 3709 to 15,000 (Table 9). Since these MoE values are less than 25,000, they are considered a health concern (EFSA, 2016). Similarly, 36 % and 45 % of the median MoEs of male and female consumers, respectively, across the day were lower than the 25,000 reference value. However, the modal MoE estimates for both genders were above 25,000, suggesting a low health concern for male and female consumers from the most frequent dietary exposure to GE.

Regarding age groups (Table 10), 91 % of the estimated MoEs at the 95th percentile level were below 25,000, indicating health concerns for heavy consumers in all age groups. This agrees with Jiang et al. (2021)'s findings which associated health concerns with the 95th percentile dietary exposure to GE. In their study, however, a lower-aged population (school children aged 2 to 3 years in China) was considered, which resulted in lower MoEs (5332–5854) than the MoEs estimated in this present study. The present study also showed that young children (3–9 years) are the most vulnerable to GE-related health concerns, as indicated by 36 % of their modal MoEs (12,289–24,878) being lower than 25,000 as against none for the 10–17 and 65–74 years groups and only 9 % for the 18–64 years group (24,286). Also, as high as 45 % of the median MoEs (8293–20,816) for the 3–9 years group were below the GE risk threshold compared to 18 %, 27 % and 9 % of median MoEs for 10–17, 18–64 and 65–74 years groups respectively.

Table 9
Margin of Exposure (MoE) distribution among respondents by gender.

		Male			Female		
	Food type	Mode	Median	95th P	Mode	Median	95th P
Breakfast	Fried	1,020,000	204,000	1735	1,020,000	255,000	3709
	Smoked	35,172	22,667	5178	40,800	22,174	4928
	Grilled	46,364	37,778	10,737	42,500	35,172	9623
	Baked	510,000	170,000	8361	340,000	145,714	6538
Lunch	Fried	340,000	24,878	3517	255,000	27,568	3228
	Smoked	60,000	39,231	9027	48,571	35,172	8226
	Grilled	78,462	56,667	16,190	145,714	63,750	15,000
Supper	Fried	127,500	24,286	3389	510,000	46,364	5025
	Smoked	127,500	72,857	17,000	36,429	20,400	3984
	Grilled	39,231	24,878	6846	35,172	24,878	6375
	Baked	340,000	170,000	10,000	37,778	20,400	3969

Table 10
Margin of Exposure (MoE) distribution among respondents by age group.

		3–9 years			10–17 years		
	Food type	Mode	Median	95th P	Mode	Median	95th P
Breakfast	Fried	340,000	170,000	14,167	1,020,000	255,000	12,911
	Smoked	13,973	8644	3148	27,568	17,895	5795
	Grilled	28,333	20,816	8718	31,875	24,878	13,600
	Baked	255,000	113,333	9623	340,000	113,333	4113
Lunch	Fried	204,000	37,778	5795	145,714	29,143	4322
	Smoked	23,721	14,167	4789	46,364	44,348	24,878
	Grilled	72,857	56,667	23,182	51,000	40,800	20,000
Supper	Fried	340,000	72,857	782	510,000	39,231	5862
	Smoked	12,289	8293	2531	23,182	15,692	5231
	Grilled	24,878	18,889	10,968	37,778	25,500	6939
	Baked	170,000	78,462	6623	340,000	127,500	6538
		18–64 years			65–74 years		
Breakfast	Fried	1,020,000	78,462	14,366	85,000	63,750	16,190
	Smoked	37,778	30,909	12,750	40,800	24,286	7500
	Grilled	44,348	40,800	24,878	51,000	39,231	18,214
	Baked	340,000	204,000	9358	340,000	255,000	92,727
Lunch	Fried	145,714	23,721	4636	85,000	63,750	14,783
	Smoked	53,684	42,500	16,721	44,348	36,429	13,421
	Grilled	78,462	60,000	29,143	102,000	78,462	31,875
Supper	Fried	340,000	46,364	5829	1,020,000	53,684	6071
	Smoked	25,500	20,816	7338	44,348	31,875	8870
	Grilled	24,286	23,182	13,247	29,143	28,333	17,895
	Baked	340,000	145,714	7786	340,000	255,000	46,364

4. Conclusion

In summary, this study revealed that 3-MCPDE and GE were present in various levels in more than 85 % of the sampled foods, with smoked foods having the highest mean concentrations of both contaminants. The daily exposure levels to these contaminants were higher for female consumers than male consumers at the 95th percentile estimate and for younger consumers than older consumers. The health risk assessment showed that 95th percentile female and 95th percentile consumers aged 3–9 years exceeded the health guidance values for 3-MCPDE and had low GE exposure margins, indicating a potential health concern. The main factors influencing the health risk were body weight and consuming fried and smoked foods. Therefore, reducing the levels of 3-MCPDE and GE in these foods and promoting healthy dietary habits are the key strategies to minimize the health risk for heavy consumers of these foods.

Ethical statement

Dietary studies in this article were performed with human participants. Verbal and written informed consent was sought from the participants for their anonymized information to be published in this article.

CRediT authorship contribution statement

Daniel Sitsofe Yabani: Writing – original draft, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Isaac Williams Ofosu:** Writing – review & editing, Supervision. **Gloria Mathanda Ankar-Brewoo:** Writing – review & editing, Supervision, Resources. **Herman Erick Lutterodt:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

I have shared the link to my data at the attached file step 3-Monochloropropandiol and Glycidyl Esters in Heat-Processed Oil-Based Food Products: Exposure and Risk (Original data) (Zenodo).

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