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Health risk assessment related to heat-induced contaminants in peanut-based foods consumed in Southern Benin

Christin Sogbossi Gbétokpanou [a,b,c], Herbert Ogouyôm Iko Afé [b], Philippe Szternfeld [d], Georges Scholl [e], Samiha Boutaleb [a], Miriam Porretti [f], Laure Joly [d], Paulin Azokpota [b], Gauthier Eppe [e], Marianne Sindic [c], Marie Louise Scippo [a,*], Yann Emeric Madodé [b], Caroline Douny [a]

[a] Laboratory of Food Analysis, Fundamental and Applied Research for Animals and Health (FARAH), Faculty of Veterinary Medicine, University of Liège, Liège, Belgium
[b] Laboratory of Food Sciences and Technologies, Ecole Doctorale des Sciences Agronomiques et de l'Eau, University of Abomey-Calavi, Abomey-Calavi, Benin
[c] Laboratory of Agro-food Quality and Safety, Axis Chemistry for Sustainable Food and Environmental Systems, Gembloux Agro-Bio Tech, Université de Liège, Passage des Déportés 2, Gembloux B-5030, Belgium
[d] Chemical & Physical Health Risks department, Sciensano, Rue Juliette Wytsman 14, Ixelles 1050, Belgium
[e] Mass Spectrometry Laboratory, MolSys Research Unit, University of Liege, Allée de la Chimie 3, B-6c Sart-Tilman, Liege B-4000, Belgium
[f] University of Messina, Department of Chemical, Biological, Pharmaceutical and Environmental Sciences (CHIBIOFARAM), Messina 98166, Italy

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ABSTRACT

Consumption of peanut-based foods may expose consumers to heat-induced contaminants, including polycyclic aromatic hydrocarbons (PAHs), acrylamide, and furans. This study assessed consumer exposure to heat-induced contaminants in peanut-based foods prepared in Southern Benin. A food consumption survey was conducted in six municipalities of southern Benin, involving 400 adult consumers of *kluiklui* (fried pressed peanut cake) and/or roasted peanut snacks. Contaminant contents were determined in 27 roasted peanut snack and 42 *kluiklui* samples using chromatographic and mass spectrometry based-methods. Daily consumption ranged from 0.4 to 346 g for *kluiklui* and 0.6–284 g for roasted peanut snacks. Benzo[*a*]pyrene levels were below the limit of quantification in roasted peanut snack samples, while ΣPAH4 content ranged from 1.0 to 2.8 μg/kg. The calculated margins of exposure (MOE) for ΣPAH4 were above 10,000, indicating a low concern of cancer risk. Acrylamide contents varied from 34.4 to 282.5 μg/kg in *kluiklui* and from 20.0 to 129 μg/kg in roasted peanut snacks. Based on median and maximum acrylamide contents, 41–72 % of *kluiklui* consumers, 38–78 % of roasted peanut snacks consumers, and 80–92 % of consumers of both products had MOEs below 10,000, suggesting a potential carcinogenic health risk. Furan contents ranged from 2.0 to 11.6 μg/kg in roasted peanut snacks and from 4.0 to 62 μg/kg in *kluiklui*. Furans did not raise concern for non-neoplastic effects (MOE > 100), while there was a risk for neoplastic effects, for 2 % of *kluiklui* consumers. Understanding the impact of specific processing practices (in particular the temperature used during the heat treatment) on contaminant formation is needed for developing risk mitigation strategies related to peanut-based food consumption.

1. Introduction

Peanut (*Arachis hypogaea*) is a legume of considerable economic and nutritional importance, widely consumed due to its availability and accessibility (Arya et al., 2016). A wide variety of peanut-based foods is produced worldwide, particularly in Africa. Peanuts can be consumed roasted as snacks, or boiled, and on various processed forms, including peanut paste, peanut oil, fried pressed-peanut cakes (Adjile et al., 2015; Chang et al., 2013; Variath & Pasupuleti, 2017). However, consuming peanut-based foods may expose to health risks due to hazardous chemical contaminants, particularly those that are formed during processing such as acrylamide, furans, and polycyclic aromatic hydrocarbons, since these foods are predominantly produced using heat processing methods (Koszucka & Nowak, 2019; Liu et al., 2024).

* Correspondence to: University of Liège, Department of Food Sciences, FARAH-VPH (Fundamental and Applied Research for Animal & Health, Veterinary Public Health), Quartier Vallée 2, Avenue de Cureghem 10 (B43b), Liege 4000, Belgium.
E-mail address: mlscippo@uliege.be (M.L. Scippo).

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Acrylamide is a chemical hazard formed in starchy foods during high-temperature treatments such as frying and roasting, at temperatures above 120 °C and under low moisture conditions (Rifai & Saleh, 2020; Tareke et al., 2002). It is mainly formed from reducing sugars (glucose and fructose) and amino acids (mainly asparagine) via the Maillard reaction. Acrylamide has been classified by the International Agency for Research on Cancer (IARC) as “probably carcinogenic to humans” (group 2 A) (IARC, 1994). Acrylamide is rapidly absorbed from the gastrointestinal tract after ingestion, and widely distributed throughout tissues. It is also able to cross the placental barrier. Its metabolism in liver through the Cytochrome P450 (CYP) metabolizing enzymes leads to the formation of an epoxide, named glycidamide. Due to its high toxicity, dietary acrylamide may induce adverse health effects, including genotoxicity, neurotoxicity, hepatotoxicity, carcinogenicity, cardiovascular toxicity, and reproductive toxicity (EFSA, 2015). Benchmark levels for acrylamide are set in certain food products including French fries, potato chips, cookies, wafers, roasted and instant coffee, crackers, soft bread and crisp bread by the EU Regulation 2017/2158 (European Commission, 2017). No values have been set for peanut-derived products.

Furan and alkylfurans formation pathways involve carbohydrate degradation and rearrangement (caramelisation), amino acid degradation, Maillard reaction, and thermal oxidation of ascorbic acid, polyunsaturated fatty acids, and carotenoids (Becalski & Seaman, 2019; Limacher et al., 2007; Limacher et al., 2008; Owczarek-Fendor et al., 2012; Owczarek-Fendor et al., 2010; Perez Locas & Yaylayan, 2004). The IARC has classified furan as “possibly carcinogenic to humans” (group 2B) (IARC, 1995). Once absorbed, furan is metabolised by cytochrome P450 2E1 (CYP2E1) into cis-2-butene-1,4-dial (BDA), a highly reactive metabolite responsible for its toxicity (EFSA, 2017; Moro et al., 2012). *In vivo* studies indicate that furan exhibits multiple toxic effects, including hepatotoxicity, nephrotoxicity, reproductive and developmental toxicity, as well as carcinogenicity and genotoxicity (EFSA, 2017). Alkylfurans, such as 2-methylfuran and 3-methylfuran, co-occur with furan in thermally processed foods and are likely formed through similar mechanisms. These compounds are predicted to be metabolise in a same way to furan and EFSA has considered them in consumer exposure assessments (EFSA, 2017). Currently, there are no legally established maximum levels for furan in food products.

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds formed by the incomplete combustion of organic matter during food processing methods such as smoking, drying, frying, grilling, and roasting (Samarajeewa, 2023; Singh et al., 2016; Taghizadeh et al., 2024). Among the various PAHs, 16 PAHs have been identified as potentially genotoxic and carcinogenic to humans and should therefore be prioritised in risk assessments. These include benz[*a*]anthracene (BaA), benzo[*b*]fluoranthene (BbF), chrysene (CHR), benzo[*j*]fluoranthene (BjF), benzo[*k*]fluoranthene (BkF), benzo[ghi]perylene (BgP), benzo[*a*]pyrene (BaP), cyclopenta[cd]pyrene (CcP), dibenz[*a*,*h*]anthracene (DhA), dibenzo[*a*,*e*]pyrene (DeP), dibenzo[*a*,*h*]pyrene (DhP), dibenzo[*a*,*i*]pyrene (DiP), dibenzo[*a*,*l*]pyrene (DlP), indeno[1,2,3-cd]pyrene (IcP), 5-methylchrysene (5MC) and benzo[*c*]fluorene (BcL) (EFSA, 2008). BaP is classified as “carcinogenic to humans” (group 1); CcP, DhA, and DlP, as “probably carcinogenic to humans” (group 2 A); and BaA, BbF, CHR, BjF, BkF, BgP, DeP, DhP, DaP, IcP and 5MC as “possibly carcinogenic to humans” (group 2B) (IARC, 2010). Although the 16 PAHs were initially prioritised in risk assessments, later, the European Food Safety Authority (EFSA) showed that four PAHs were particularly relevant according to both their occurrence in food and their toxicity, and considered them as suitable indicators for PAH risk assessment in food (EFSA, 2008). This group is named ΣPAH4 in this paper and includes BaA, BaP, BbF, and CHR (EFSA, 2008). BaP, the most carcinogenic, has been used as a marker to evaluate the carcinogenic potential of foods. The maximum limits for BaP and ΣPAH4 have been set out by the EU Regulation 2023/915 on maximum levels for certain contaminants in food (European Commission, 2023). This regulation applies to various products including vegetable oils, smoked products (meat or fish), nuts and oilseeds (e.g., peanuts, walnuts, sesame seeds). The maximum levels set considering oilseeds and vegetable oils are 2 μg/kg for BaP and 10 μg/kg for ΣPAH4.

Peanuts carbohydrate (16 g/100 g) and unsaturated fatty acid (15 g/100 g of polyunsaturated fatty acids) contents (Çiftçi & Suna, 2022), as well as the heat treatments (roasting and frying) applied during their processing, may promote the formation of process contaminants in peanut-based foods. Peanut-based foods consumers are thus potentially exposed to these process contaminants through the ingestion of contaminated foods. Several studies highlighted the occurrence of acrylamide (Esposito et al., 2017; Rifai & Saleh, 2020), furans (Fromberg et al., 2009; Masite et al., 2022), and polycyclic aromatic hydrocarbons (Olabemiwo et al., 2013; Samarajeewa, 2023; Singh et al., 2016), in peanut-based foods. High exposures to acrylamide in Italy (Esposito et al., 2017) and Iran (Nematollahi et al., 2020), to furan in Europe (Fromberg et al., 2009) and to PAHs in China (Liu et al., 2023) were reported due to peanut and peanut-based foods consumption. However, consumer exposure to these process contaminants in peanut-based foods remains poorly assessed, especially in West Africa.

In the context of Benin, to date and to our knowledge, limited studies have evaluated the occurrence of process neo-formed contaminants in peanut foods, as well as peanut food consumption levels for subsequent risk assessment. To address this gap, the present study assessed the chemical risks associated with the consumption of two widely consumed peanut products, roasted peanut snacks and *kluiklui* (fried pressed peanut cake), as commonly available on local market in Benin.

2. Material and methods

2.1. Food consumption data collection

Consumption data were gathered through a food consumption survey conducted in six municipalities of South Benin: Abomey, Aplahoué, Cotonou, Covè, Glazoué, and Ouèssè (Fig. 1). Surveyed locations were selected based on their reputation in peanut farming, processing, or consumption. Covè is known for peanut processing and consumption, particularly *kluiklui* and roasted peanut snacks (Adanguidi, 2019). Aplahoué offers diverse peanut-based food forms, including bracelet-shaped *kluiklui*. In Abomey, roasted peanut snacks are widely consumed (Akissoé, 2021). Cotonou, a cosmopolitan city with high population density and diverse dietary habits, was included due to its major markets which attract nationwide food products. Glazoué host one of Benin’s largest regional markets and serves as a key trade centre for Nigeria, Benin, and Togo. Ouèssè is the municipality where peanut production is the highest in Benin (DSA, 2022).

The survey aimed to assess the daily intake of roasted peanut snacks and *kluiklui*. The number of consumers to be surveyed was determined using the following formula (Dagnelie, 1998).

$$N = \frac{4p \quad (1-p)}{ME^2}$$

Where, N: the total number of consumers to be surveyed for each category of peanut-based food, p: 50 %, ME: margin of error, set at 5 %. The proportion p of 50 % was applied due to the lack of literature data on the consumption of peanuts and peanut-based food products in Benin (Kaur, 2017).

Consumer survey was conducted through interviews of 400 adults (≥18 years) in the six targeted municipalities. Based on sampling rates described by Iko Afé et al. (2020), the number of consumers surveyed in each municipality and district was proportionally distributed according to population densities derived from Benin’s Fourth General Population and Housing Census (RGPH 4). Respectively, 29, 54, 216, 16, 40, and 45 consumers were surveyed in the municipalities of Abomey, Aplahoué, Cotonou, Covè, Glazoué, and Ouèssè. The geographical distribution of

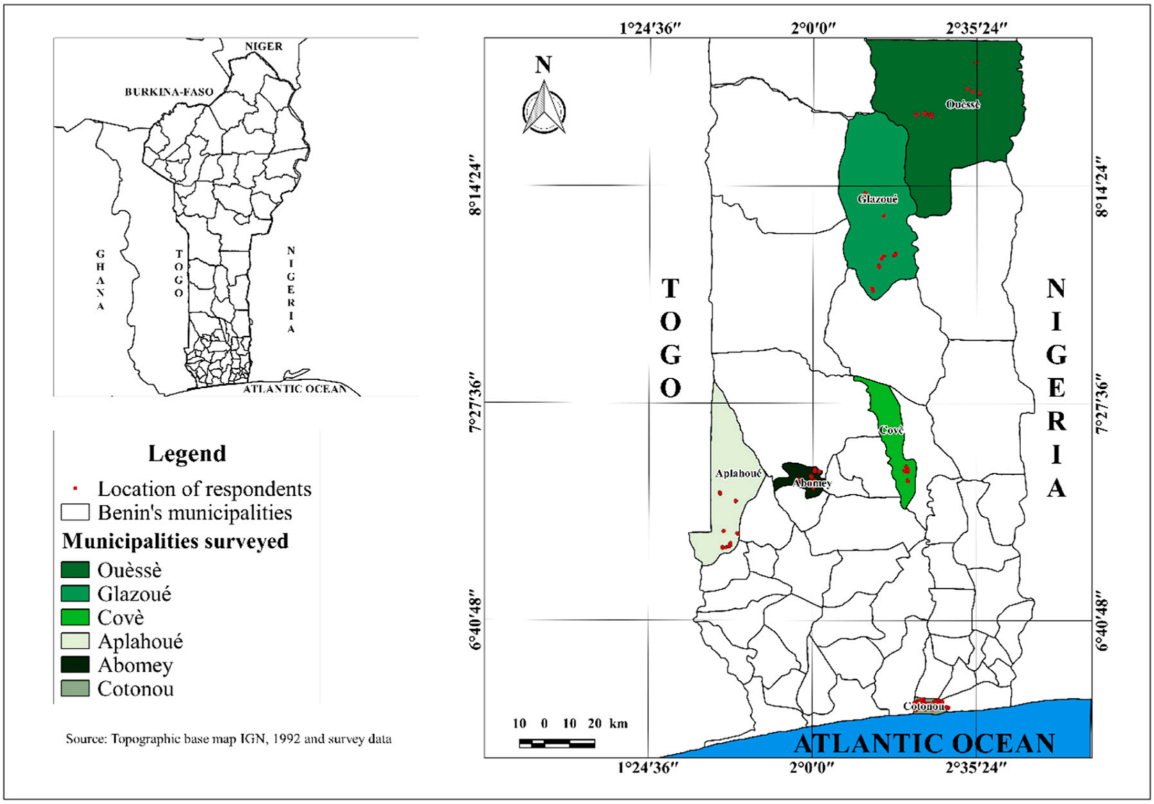

Fig. 1. Study area and geographic distribution of surveyed consumers of kluiklui and/or roasted peanut snacks in Southern Benin.

the 400 consumers of *kluiklui* and/or roasted peanut snacks surveyed, is shown on Fig. 1. A consent form was filled and signed by each participant prior to each interview.

Manual workers (bricklayers, tailors, mechanics, welders, etc.) were interviewed at their workplaces and at production and sale sites (markets, supermarkets, street vendors, roadside stalls). Data collection was performed using a digital survey form developed on *KoboCollect App*. Interviews were conducted in French and local languages (Fon, Mahi, Adja, Nago, Idatcha). Anthropometric and socio-demographic data (name, age, gender, education level) were recorded on basis of consumer assertion while body weight was measured using an electronic scale (Seca LK No. 5158, Germany). The survey also gathered information on consumption patterns, including consumption mode (alone or in combination with other foods), frequency (daily, weekly, monthly), and portion size. Consumption proportions were estimated using product cost data, as described in Iko Afé, Anihouvi, et al. (2020), based on respondents' declarations regarding the cost of peanut-based foods they regularly purchase. An equivalent monetary value of six samples of each peanut-based food product was purchased from various vendors in each district and weighed using a calibrated balance. These measurements were then used to estimate individual daily intake by integrating the average quantity consumed with the consumption frequency reported during the interviews. In case of non-daily consumption, the portion weight was divided by the weekly or monthly declared consumption to estimate a daily consumption. For those cases where the respondent declared that the purchased amount of peanut-based product was to share with the whole family, the intake of the respondent was estimated by dividing the purchased quantity by the number of household members. The detailed recorded raw data as well as the calculated daily consumptions are presented in table S5. Information was also collected about other smoked, roasted or grilled products consumed by the respondents.

2.2. Quantification of PAHs, acrylamide, furan and methylfurans in peanut-based foods

2.2.1. Sampling of peanut-based foods

The samples were collected in the same locations where the food consumption data was collected (Aplahoué, Abomey, Cotonou, Covè, Glazoué, and Ouèssè). A total of 27 roasted peanut snacks and 42 *kluiklui*, were randomly collected from processors, retail outlets, and supermarkets across these municipalities. *Kluiklui* is produced by deep-frying pressed and shaped peanut paste, obtained by grinding slightly roasted peanut seeds (Adjou et al., 2012). The paste is fried using a portion of the peanut oil collected after peanut paste pressing (Tandji, 2014). Roasted peanut snacks, on the other hand, are prepared by pan-roasting pre-cooked peanut seeds (Bankole et al., 2005). Table S1 provides details of the sampling of roasted peanuts and *kluiklui*. Collected samples were stored in sealed containers in a dry and well-ventilated place, protected against humidity and sunlight, until analysis.

2.2.2. Standards and chemicals

Analytical standards and solvents were purchased from various suppliers. PAHs, acrylamide and acrylamide-D3 standards were obtained from Dr Ehrenstorfer GmbH (Augsburg, Germany), while DiP-D14 was purchased from LGC Promochem (France). Standards for furan and methylfurans analysis, were obtained from Sigma-Aldrich (USA), while deuterated furans were sourced from Toronto Research Chemicals (Canada) and Campro Scientific (Germany). HPLC-grade solvents, including methanol, dichloromethane, cyclohexane, and ethyl acetate were supplied by VWR (Belgium), and acetonitrile and n-hexane by Biosolve (The Netherlands). Ethanol and acetone (EMSURE®-grade) were acquired from Merck (Darmstadt, Germany). HPLC-grade methanol was procured from Chem-Lab (Belgium).Formic acid was supplied by Merck (Germany). High-purity distilled water ($<$18 MΩ) was obtained using a Milli-Q system. Bulk PSA, C18, and SPE AccuCAT cartridges were supplied by Agilent Technologies (Santa Clara, USA).

2.2.3. Quantification of PAHs

PAHs determination was carried out on roasted peanut snacks samples only. Indeed, according to EFSA (2008) and Rose et al. (2015), domestic roasting and frying practices do not significantly contribute to PAH formation. In the process of *kluiklui* production, the roasting is very mild, and during *kluiklui* frying, the product is immersed in oil, so there is no direct contact with combustion smoke as it is separated by the frying pan and oil. Extracted peanut oil is used for frying during *kluiklui* production. According to Ingenbleek et al. (2019), mean concentrations of BaP (0.4 μg/kg) and PAH4 (3.1 μg/kg) were reported to be relatively low in peanut oil samples from southern Benin. Furthermore, typical domestic frying temperatures (approximately 180 °C) observed in open-air frying (Tandji, 2014) are insufficient to induce significant PAH formation (Balbino et al., 2020; Purcaro et al., 2006; Rose et al., 2015). In addition, Zhao et al. (2017) observed very low BaP concentrations (0.11 ± 0.01 μg/kg) in peanuts fried at 170 °C for 4 min, even after using the frying oil for 12 h, further confirming the limited impact of household thermal processing on PAH contamination levels. Therefore, the determination of PAHs in *kluiklui* samples, which were expected to remain below the maximum regulatory limits set by the European Union (European Commission, 2023), was not considered relevant for risk assessment purposes, contrary to roasted peanuts.

The analysis of PAHs was performed on roasted peanut snack samples following the procedure described by Iko Afé, Saegerman, et al. (2020). PAHs were extracted from 1 g of sample using a hexane/acetone mixture (50:50, v/v) in an accelerated solvent extractor (ASE 200, Dionex Corporation). The extract was evaporated under a nitrogen stream to a final volume of 1 mL and subsequently reconstituted with 5 mL of cyclohexane. The reconstituted extract was purified using an EnviChrom P column (Macherey-Nagel Chromabond), which was preconditioned with 15 mL of ethyl acetate followed by 10 mL of cyclohexane. After loading the sample extract, the column was washed with 6 mL of a cyclohexane/ethanol mixture (70:30, v/v), and the PAHs were eluted using 12 mL of a cyclohexane/ethyl acetate mixture (40:60, v/v) as described by Veyrand et al. (2007). The eluate was evaporated to dryness, and the residue was reconstituted with 90 μl of acetonitrile. Finally, 10 μl of deuterated DiP (injection standard) was added to the reconstituted sample, and transferred into a vial for ultra-performance liquid chromatography-fluorescence detection (UPLC-FLD) analysis using Waters Acquity UPLC system. Table S2 provides information on the performance of the method used for PAHs determination. A limit of quantification of 0.25 ng/g was obtained for BaP, BaA, BbF and CHR, with respective recovery rates of 85 %, 81 %, 91 % and 102 %. Commission Regulation (EU) No 836/2011 sets out the strict requirements that analytical methods must comply with in order to ensure control laboratories use comparable performance level procedures. LOQ values below 0.9 μg/kg and recovery rates ranging from 50 % to 120 % are required for BaP, BaA, BbF and CHR (European Commission, 2011). The LOQ and recovery rates obtained for these four compounds in this study meet the European Commission's requirements. The performance levels of the method used in our study are also similar to those reported in previous studies, as shown in Table S3 (Belo et al., 2017; Ingenbleek et al., 2019; Mahmoudpour et al., 2017; Muntean et al., 2013; Suchanová et al., 2008).

2.2.4. Quantification of acrylamide

The acrylamide content in *kluiklui* and roasted peanut snack samples was determined using liquid chromatography tandem mass spectrometry (LC-MS/MS), following the method described by Szternfeld et al. (2025). This method has been validated for linearity, recovery, limit of detection (LOD) and limit of quantification (LOQ) based on Regulation (EU) 2017/2158 (European Commission, 2017). Initially, 25 μL of acrylamide-D3 (10 μg mL^{-1}) was added to 1 g of the homogenised sample. A QuEChERS extraction was then performed by adding 5 mL of hexane, 10 mL of Milli-Q water, 10 mL of acetonitrile, 0.5 g of sodium chloride (NaCl), and 4 g of magnesium sulphate ($MgSO_4$) to the sample. The mixture was shaken manually for 1 min and subsequently centrifuged. A 5 mL aliquot of the supernatant was cleaned using dispersive solid-phase extraction (d-SPE) containing 150 mg of PSA and C18. The cleaned supernatant was evaporated under a nitrogen stream to a volume of 500 μL, and the final volume was adjusted to 2 mL with Milli-Q water. Subsequently, 500 μL of this solution was filtered through a 0.2 μm PVDF auto-filtering vial prior to LC-MS/MS analysis. The LC-MS/MS analyses were conducted using an Ultra-Performance Liquid Chromatography system (Acquity Ultra Performance IKA®) coupled to a Xevo TQ mass spectrometer (Waters, Milford, MA, USA) controlled by LC® v4.2 software. Information on method linearity and range is presented in Table S4. Performance details of other published analytical methods used for acrylamide determination are presented in Table S5. A comparison between the results obtained using the method applied in this study and those reported in the litterature demonstrated the excellent performance of the present method, including an acceptable LOQ, a high coefficient of determination (R^2), and a high recovery rate, as well as its suitability for peanut-based foods.

2.2.5. Quantification of furan and methylfurans

Furan and methylfurans were quantified using the method described by Alsafra et al. (2023). Stock solutions of furan, methylfurans, and internal standard solutions containing deuterated-labelled furans were initially prepared by pipetting and weighing 10 μL of each analytical standard into a 20 mL airtight vial completely filled with methanol. From these stock solutions, working solutions of furans and deuterated furans were prepared daily. Precisely 1 g of ground and homogenised *kluiklui* and roasted peanut snack samples, as well as 5 mL of brine, were placed in a 20 mL headspace vial sealed with a PTFE/silicone septa. Subsequently, 150 μL of each deuterated-labelled furan standard was added to the headspace vial via the septa. The mixture was homogenised for 2 min using a vortex mixer prior to extraction. The headspace vials containing the solid samples were stored at 4 °C and analysed by headspace solid-phase microextraction coupled to gas chromatography–mass spectrometry (HS-SPME-GC-MS) within 24 h. Volatile compounds were extracted by HS-SPME using a fibre coated with 50/30 μm of DVB/CAR/PDMS (Supelco, St. Louis, MO, USA). The HS-SPME process was automated on a CTC Combi-Pal autosampler (CTC Analytics AG, Zwingen, Switzerland). Gas chromatography separation was carried out using a Trace-GC 2000 oven (Thermo Scientific, Waltham, MA, USA) and Mass spectrometry (MS) detection was performed using a PolarisQ ion-trap mass spectrometer (Thermo Scientific, Waltham, MA, USA). This analytical method was validated in accordance with the European Commission Decision No. 2002/657/EC (European Commission, 2002) and the European Commission Recommendation on the monitoring of furan and alkyl furans (European Commission, 2022). Details on method parameters and performance are summarised in Table S6. Comparisons between the results obtained using the analytical method applied in this study (Table S6) and those reported in the itterature (Table S7) confirm the good performance of the proposed method (LOQ and recovery) and its suitability for the analysed products.

2.3. Exposure estimation and health risk assessment

2.3.1. Exposure estimation

The estimated daily intake (EDI) of PAHs, acrylamide, furan and total furans (sum of furan, 2-methylfuran and 3-methylfuran) was assessed, using a deterministic approach, to calculate roasted peanut snacks and *kluiklui* consumers dietary exposure. The 400 consumers were clustered into three categories: consumers of roasted peanut snacks only, consumers of *kluiklui* only, and consumers of both *kluiklui* and roasted peanut snacks. Median and maximum contaminant concentrations were used. For each consumer, the EDI was calculated by multiplying individual daily consumption data of roasted peanut snacks and/

or *kluiklui* by the corresponding median and maximum concentrations of contaminants (PAHs, acrylamide, furan, and total furans), and then dividing the result by the individual's body weight.

$$\textbf{Estimated daily intake}\,(\textbf{EDI}) = \frac{Contamination\ level * Daily\ consumption}{Body\ weight(kg/person)}$$

- Estimated daily intake: The estimated quantity of PAHs, acrylamide, furan, or total furans ingested daily (μg/kg bw per day).
- Contamination level: The median or maximum concentration of PAHs, acrylamide, furan, or total furans (μg/kg).
- Daily consumption: The quantity of roasted peanut snacks and/or *kluiklui* consumed on a daily basis (kg per day). The supplementary information (Table S5) presents an overview of the detailed consumption data and the method used to determine the daily consumption.

2.3.2. Risk characterization

The margin of exposure (MOE) approach was used to assess the health risk associated with each process contaminant (PAHs, acrylamide, furan, and total furans). For each consumer, the MOE was determined by dividing the Benchmark Dose Lower Confidence Limit (BMDL10) of each contaminant by the EDI, according to the expression:

$$Margin\ of\ exposure = \frac{BMDL_{10}}{EDI}$$

The BMDL10 values used for risk characterisation are coming from EFSA opinions. For ΣPAH4, the BMDL10 (10 % increase risk of cancer) is 0.34 mg/kg bw per day (EFSA, 2008). MOE below 10,000 are indicative of potential health concern for the consumer.

For acrylamide, a BMDL10 of 0.17 mg/kg bw per day was used to assess neoplastic effects (i.e. inducing Harderian gland adenomas and adenocarcinomas in mice), and a BMDL10 of 0.43 mg/kg bw per day was applied for neurotoxic effects (i.e. inducing peripheral nerve (sciatic) axonal degeneration in rats) (EFSA, 2015). According to EFSA (2015), MOEs below 10,000 for neoplastic effects and below 125 for neurotoxic effects are indicative of a potential health concern.

For the neoplastic effects of furan (EFSA, 2017), a BMDL10 of 1.31 mg/kg bw per day was selected, based on the induction of hepatocellular adenomas and carcinomas in mice. For the non-neoplastic effects of furan or the sum of furan, 2-methylfuran, and 3-methylfuran, a BMDL10 of 0.064 mg/kg bw per day was used, reflecting their ability to induce cholangiofibrosis in rats. This value was selected based on the dose-additive hepatotoxicity observed in rats from the combined effects of furan, 2-methylfuran, and 3-methylfuran. MOEs below 10,000 for neoplastic effects and below 100 for neurotoxic effects are indicative of potential health concern for the consumer (EFSA, 2017).

2.4. Statistical analysis

Descriptive statistical analyses were performed using Microsoft Excel 2019. Data were analysed using R version 4.4.2 software. All contamination data were expressed on a wet weight basis. All calculations were carried out using upper bound (UB) contamination data, i.e. concentrations below the limit of quantification (LOQ) were replaced by the LOQ value. Since acrylamide, furan, 2-methylfuran and 3-methylfuran contents did not follow a normal distribution, the significance of the differences between mean contents of acrylamide, furan, 2-methylfuran and 3-methylfuran in roasted peanut snacks and in *kluiklui* was analysed using Mann-Whitney U nonparametric independent sample test. Since acrylamide and furans are both generated during thermal processing, and mitigation strategies may affect their formation simultaneously, a Spearman's correlation analysis was performed using the **Hmisc** package to assess the relationships between acrylamide, furan, 2-methylfuran, and 3-methylfuran. This approach aimed to determine whether these compounds are formed independently, as previously reported by Lipinski et al. (2024) and Alsafra et al. (2023). Correlograms were then generated, with the package **corrplot**. Results with $p < 0.05$ were considered statistically significant.

3. Results and discussion

3.1. Consumption of roasted peanut snacks and kluiklui in Southern Benin

3.1.1. Socio-demographic characteristics of consumers interviewed in Southern Benin

The majority of respondents (61 %) were men. The distribution of ages and weights of the surveyed consumers is presented on Fig. 2. Most of the surveyed consumers were aged between 18 and 40 years old (82 %, n = 327) (Fig. 2a). Their body weights predominantly ranged between 52 kg and 74 kg (67 %, n = 266) (Fig. 2b). Socio-demographic data of all interviewed consumers are provided in the supplementary information (Table S8).

3.1.2. Consumption level of kluiklui and roasted peanut snacks

Among the 400 surveyed consumers, 350 persons consumed kluiklui (regardless of roasted peanut snacks consumption), and 283 individuals consumed roasted peanut snacks (regardless of kluiklui consumption). Table 1 (and S8 for individual data) shows the level of consumption of kluiklui and roasted peanut snacks by respondents.

Kluiklui is predominantly consumed with *gari* (fermented and dehydrated cassava pulp) as the main side-dish for the majority of *kluiklui* consumers (95 % of *kluiklui* consumers, n = 333) (Fig. 3). Daily consumption of *kluiklui* and roasted peanut snacks ranged respectively from 0.4 to 346 g, and from 0.6 to 284 g (Table 1). There is a significant difference between *kluiklui* and roasted peanut snacks daily consumption (p-value = 5.309e-09). Roasted peanut snacks are mainly consumed with *gari* (63 % of roasted peanut snack consumers, n = 179) and porridge (35 % of roasted peanut snacks consumers, n = 98) (Fig. 3).

The Food and Agriculture Organization of the United Nations (FAO) reports an average daily consumption of 11 g of peanut-based foods among adult Beninese consumers (FAO/WHO, 2012), which is comparable to the median consumption rate of *kluiklui* or roasted peanut snacks observed in this study. The median amount of roasted peanut snacks daily consumed by the respondents (9.5 g) is lower than the daily recommended intake of nuts and seeds set by the European Commission for various countries, such as Belgium (15–25 g per day), Denmark (30 g per day) and Germany (25 g per day) (European Commission, 2025). However, the 90th and 95th percentiles, as well as the maximum daily intake by the respondents, are 2–14 times higher than the recommended daily intake for European countries. There is no significant difference between roasted peanut snacks (p-value = 0.91) and *kluiklui* (p-value = 0.44) consumption levels neither among age groups, nor among weight groups. It is also important to notice that consumer gender appears to influence *kluiklui* daily consumption rate (-value = 0.004083), whereas roasted peanut snacks daily intake remains unaffected (p-value = 0.6969). Men are the highest *kluiklui* consumers; with respective median intakes of 19.2 and 10.8 g for men and women. Videgla et al. (2016) reported that *kluiklui* is mainly purchased by men, with students and manual workers identified as the main consumers. These consumer groups often seek ready-to-eat products (Videgla et al., 2016) or affordable, energy-dense foods (Mwale, 2023), such as *gari*, which is the main accompaniment to *kluiklui*. This may explain the higher level of *kluiklui* consumption observed among men in this study.

3.2. Occurrence of PAHs in roasted peanut snacks and associated health risk

3.2.1. Concentration of PAHs in roasted peanut snack samples

The concentrations of PAHs in roasted peanut snack samples are

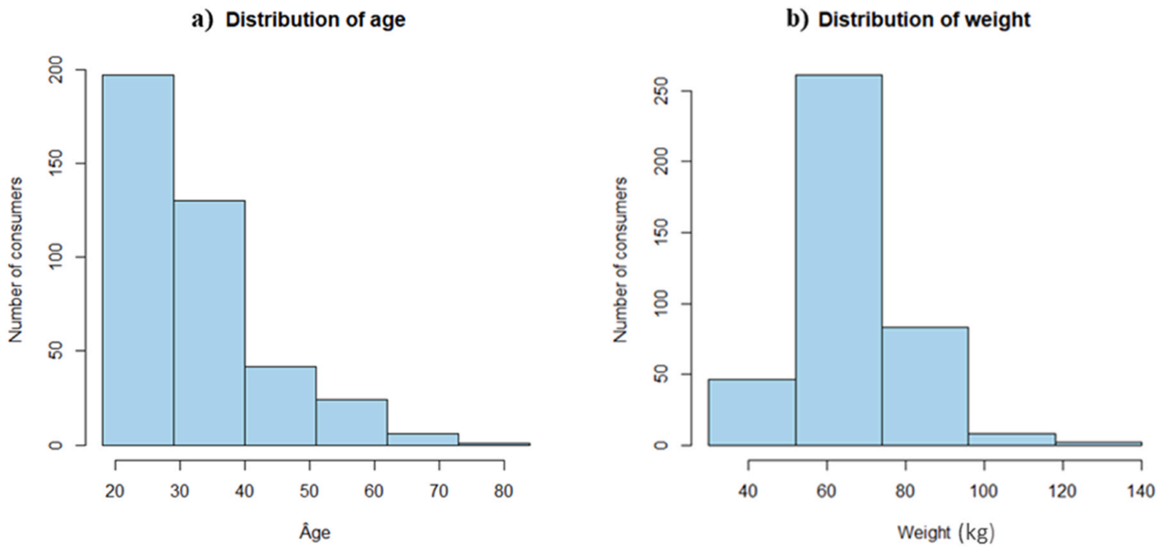

Fig. 2. Age (a) and weight (b) distributions of surveyed consumers of main peanut- based foods in Southern Benin (n = 400).

Table 1
Daily consumption of main peanut- based foods (g per day).

Descriptive level	*Kluiklui (n = 350)*	*Roasted peanut snacks (n = 283)*
Mean±SD	25.8 ± 33.0	17.6 ± 26.0
Min	0.4	0.6
P50	14.4	9.5
P90	57.6	37.9
P95	82.1	56.8
Max	345.6	284.0

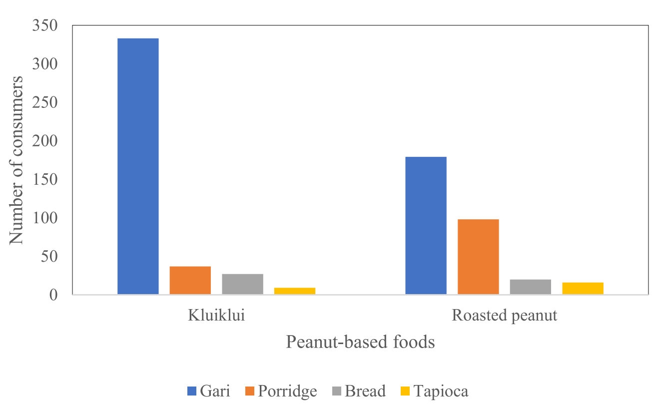

Fig. 3. Main side dishes consumed together with peanut-based foods in Southern Benin.

presented in Table 2. Individual results for each roasted peanut snack sample analysed are provided in the supplementary information (Table S9). BaP levels were below the quantification limit (0.25 μg/kg) in all samples. Among the PAH4, BaA was found in 9 samples of roasted peanut snacks out of 27, while BbF and CHR were found in only 2 and 1 samples, respectively. The concentrations of ΣPAH4 ranged between 1.0, and 2.8 μg/kg. European regulation does not specify limits for BaP or ΣPAH4 levels in roasted peanut snacks. However, limits of 2 μg/kg for BaP and 10 μg/kg for PAH4 were established for peanut oil (European Commission, 2023) produced from roasted peanut snacks via grinding and manual pressing. PAH concentrations in roasted peanut snacks samples are well below these regulatory thresholds for peanut oil. The mean total PAH content (ΣPAH15) of roasted peanut snack samples was 5.6 ± 1.4 μg/kg. Olabemiwo et al. (2013) reported similar mean total PAHs content of 3.34 ± 0.01 μg/kg for roasted peanut snacks prepared using a roasting pot in Nigeria. These mean total PAH contents are relatively low compared to the limit set for 4PAHs. However, the list of PAHs determined by these authors is different from the ones in this study. Besides BaA, CHR, BkF, BbF, BaP, IcP, DhA, and BgP, which are common to both studies, Olabemiwo et al. (2013) analysed naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, and pyrene. Most of them were below the detection limit, except pyrene. According with Olabemiwo et al. (2013), roasted peanut snacks were prepared using a roasting pot, and in Benin, it is known that roasting is predominantly conducted in concave-bottomed pans (IFDC-ACMA2, 2020). The low levels of PAHs observed in both studies may be explained by the lack of direct contact between grains and heat source, due to the shape of the roasting pot or a pan used. This may have reduced polycyclic aromatic hydrocarbon formation.

3.2.2. Dietary exposure to PAHs after roasted peanut snacks consumption and risk characterisation

As no BaP was quantified in roasted peanut snack samples, a risk assessment was performed for PAH4 only. The dietary exposure to ΣPAH4 through roasted peanut snacks consumption and consumers margins of exposure (MOE) are shown in Table 3. The estimated daily intake of ΣPAH4 was calculated based on median (scenario 1) and maximum (scenario 2) ΣPAH4 concentrations. For scenario 1, the median and maximum ΣPAH4 daily intakes were 0.00016, and 0.003 μg per kilogram of body weight per day (μg/kg bw per day), respectively. For scenario 2, these intakes were 0.0004, and 0.008 μg/kg bw per day.

The margin of exposure (MOE) for ΣPAH4, ranged from 50,497,849–118,666 under scenario 1, and from 18,085,556–42,500 under scenario 2. For roasted peanut snack consumers, all MOEs were far above 10,000, indicating a low concern of cancer risk.

However, Beninese consumers could be exposed to PAH from other dietary sources. Besides peanut products, the survey showed that 99 % of surveyed consumers also consume other roasted, grilled, or smoked foods, including smoked fish (81 %, n = 229), grilled maize (81 %, n = 227), smoked meats (62 %, n = 175), and roasted cashew nuts (28 %, n = 80) (Fig. 4). In Benin, previous studies have reported maximum exposures to ΣPAH4 of 13,627 μg/kg bw per day for smoked dried fish consumers (Iko Afé et al., 2021), and 1321 μg/kg bw per day for grilled pork consumers (Iko Afé, Saegerman, et al., 2020). Although PAH exposure from roasted peanut snacks consumption appears low, the combined intake of these products, along with roasted peanut snacks, may increase overall PAH exposure and associated health risks.

Table 2
Concentrations of PAHs (μg/kg) in roasted peanut snacks samples (n = 27).

PAHs	LOQ	Samples > LOQ	Min*	Mean ± SD*	P50*	P95*	Max*
BcL	0.25	15 (55.6 %)	0.25	0.66 ± 0.5	0.7	1.46	1.8
BaA	**0.25**	**9 (33.3 %)**	**0.25**	**0.65 ± 0.6**	**0.25**	**1.77**	**2.0**
CHR	**0.25**	**1 (3.7 %)**	**0.25**	**0.27 ± 0.1**	**0.25**	**0.25**	**0.8**
5MC	0.25	0	0.25	0.25 ± 0.0	0.25	0.25	0.25
BjF	0.25	3 (11.1 %)	0.25	0.51 ± 0.8	0.25	2.25	3.9
BbF	**0.25**	**2 (7.4 %)**	**0.25**	**0.27 ± 0.1**	**0.25**	**0.46**	**0.6**
BkF	0.25	0	0.25	0.25 ± 0.0	0.25	0.25	0.25
BaP	**0.25**	**0**	**0.25**	**0.25 ± 0.0**	**0.25**	**0.25**	**0.25**
DlP	0.25	0	0.25	0.25 ± 0.0	0.25	0.25	0.25
DhA	0.25	0	0.25	0.25 ± 0.0	0.25	0.25	0.25
BgP	0.25	0	0.25	0.25 ± 0.0	0.25	0.25	0.25
IcP	1.0	0	1.0	1.0 ± 0.0	1.0	1.0	1.0
DeP	0.25	0	0.25	0.25 ± 0.0	0.25	0.25	0.25
DiP	0.25	0	0.25	0.25 ± 0.0	0.25	0.25	0.25
DhP	0.25	0	0.25	0.25 ± 0.0	0.25	0.25	0.25
ΣPAH4**			1.0	1.4 ± 0.7	1.0	2.7	2.8
ΣPAH15			4.4	5.6 ± 1.4	5.1	7.3	11.1

**PAH4: Sum of BaA, Chr, BbF, and BaP.
* Upper bound values: concentrations below the limit of quantification (LOQ) were replaced by the LOQ value. benz[*a*]anthracene (BaA), benzo[*b*]fluoranthene (BbF), benzo[*c*]fluorene (BcL), chrysene (CHR), benzo[*j*]fluoranthene (BjF), benzo[*k*]fluoranthene (BkF), benzo[ghi]perylene (BgP), benzo[*a*]pyrene (BaP), dibenz[*a*,*h*]anthracene (DhA), dibenzo[*a*,*e*]pyrene (DeP), dibenzo[*a*,*h*]pyrene (DhP), dibenzo[*a*,*i*]pyrene (DaP), dibenzo[*a*,*l*]pyrene (DlP), indeno[1,2,3-cd]pyrene (IcP) and 5-methylchrysene (5MC).

Table 3
Estimation of dietary exposure to ΣPAH4 through roasted peanut snacks consumption and margins of exposure (MOE).

Descriptive level	Dietary exposure to ΣPAH4 (μg/kg bw per day)		MOE $BMDL_{10}$* = 0.34 mg/kg bw per day	
	Scenario 1 (median contamination level)	*Scenario 2 (maximum contamination level)*	*Scenario 1*	*Scenario 2*
Min	0.000007	0.00002	50,497,849	18,085,556
P50	0.00016	0.0004	2134,617	764,503
P95	0.0009	0.003	363,546	130,202
Max	0.003	0.008	118,666	42,500

* EFSA, 2018

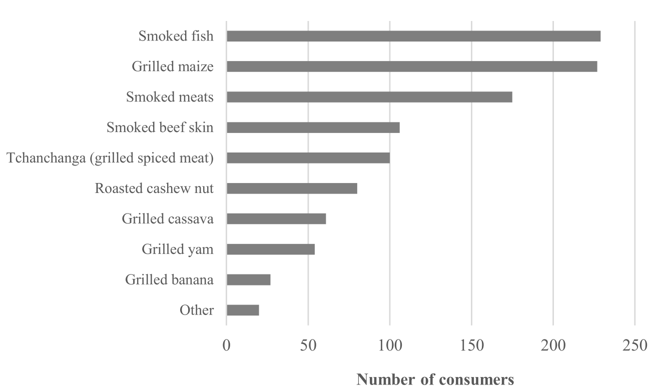

Fig. 4. Other smoked or grilled products consumed by surveyed roasted peanut snack consumers.

3.3. Acrylamide content of peanut-based foods and health risk assessment

3.3.1. Acrylamide content of kluiklui and roasted peanut snack samples

Fig. 5 shows acrylamide concentrations in peanut-based food samples. All individual acrylamide contents of *kluiklui* and roasted peanut snack samples are presented in Table S10 of the supplementary information. Acrylamide was quantified in 100 % of *kluiklui* and 85.2 % of roasted peanut snack samples. For *kluiklui*, the minimum, median, and maximum acrylamide contents were 34 μg/kg, 124 μg/kg, and 283 μg/kg, respectively, while they were 20 μg/kg (=LOQ), 52 μg/kg, and 129 μg/kg, respectively, for roasted peanut snacks. The acrylamide contents were significantly higher in *kluiklui* than in roasted peanut snacks (p-value = 4.924e-07). There is no specific acrylamide benchmark level set for peanut-based foods by EU Regulation 2017/2158, which establishes mitigation measures and benchmark levels to reduce the presence of acrylamide in foodstuffs like French fries, biscuits and wafers, crispbread and rusks for infants and young children (European Commission, 2017). In 2015, the acrylamide surveillance study conducted by the United States Food and Drug Administration (FDA) reported acrylamide contents of 50 μg/kg in roasted peanut snack samples (FDA, 2015), which corresponds to the median acrylamide level observed in this study for the same product (52 μg/kg). For roasted peanut snacks, authors from Iran reported an average acrylamide content of 131 μg/kg (Nematollahi et al., 2020), which is higher than the mean acrylamide contents reported in this study. In comparative studies carried out in other countries, the levels of acrylamide detected in roasted peanut snacks were generally lower than those observed in the present study. For instance, De Paola et al. (2017) reported concentrations ranging from 6.16 to 42.86 μg/kg in samples from Israel and Egypt, while Esposito et al. (2017) reported a value of 21 μg/kg in samples from Italy. No publication was found reporting acrylamide contamination levels in *kluiklui*. In light of the concentrations observed in roasted peanuts and *kluiklui*, it appears necessary to implement targeted actions to reduce acrylamide formation during their production.

3.3.2. Dietary exposure to acrylamide and risk characterisation

The daily acrylamide intake of consumers of kluiklui only, roasted peanut snacks only, and both products is presented in Table 4. Based on the median concentrations of acrylamide (scenario 1), the median and maximum daily intakes were 0.02 and 0.2 μg/kg bw per day, respectively, for consumers of kluiklui; 0.01 and 0.15 μg/kg bw per day for consumers of roasted peanut snacks; and 0.04, and 0.5 μg/kg bw per day for consumers of both products. According to scenario 2, based on the maximum acrylamide concentrations, median and maximum daily intakes were 0.04 and 0.5 μg/kg bw per day, respectively, for consumers of kluiklui; 0.03, and 0.4 μg/kg bw per day for consumers of roasted peanut snacks; and 0.08 and 1.0 μg/kg bw per day for consumers of both products.

Considering the risk of neoplastic effects, based on median (scenario 1) and maximal (scenario 2) acrylamide contents, MOE (at the 50th

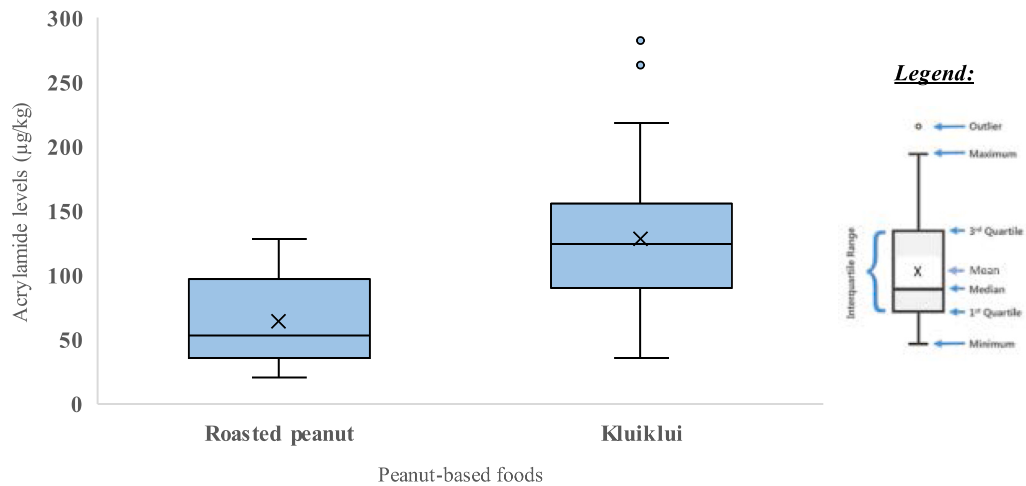

Fig. 5. Acrylamide contents of roasted peanut snacks (n = 27) and kluiklui samples (n = 42). *LOQ (limit of quantification): 20 µg/kg. For roasted peanut snack samples, upper bound concentrations are presented (data below the LOQ were replaced by the LOQ value).*

Table 4
Estimation of dietary exposure to acrylamide through peanut-based food consumption and margins of exposure (MOE).

Consumer category	Descriptive level	Dietary exposure to acrylamide (µg/kg bw per day)		MOE (neoplastic effects) BMDL$_{10}$* = 0.17 mg/kg bw per day		MOE (non-neoplastic effects) BMDL$_{10}$* = 0.43 mg/kg bw per day	
		Scenario 1	*Scenario 2*	*Scenario 1*	*Scenario 2*	*Scenario 1*	*Scenario 2*
Consumer of roasted peanut snacks only							
n = 50	Min	0.001	0.003	132,472	53,991	335,076	136,565
	P50	0.01	0.03	12,799	5217	32,375	13,195
	P95	0.05	0.13	3120	1272	7891	3216
	Max	0.15	0.4	1125	459	2845	1160
Consumer of *kluiklui* only							
n = 117	Min	0.001	0.003	151,187	61,618	382,414	155,858
	P50	0.02	0.04	11,011	4488	27,851	11,351
	P95	0.06	0.15	2838	1157	7178	2925
	Max	0.2	0.5	826	337	2090	852
Consumer of both roasted peanut snacks and *kluiklui*							
n = 283	Min	0.002	0.004	100,564	48,322	254,367	122,226
	P50	0.04	0.08	4119	2098	10,420	5307
	P95	0.2	0.3	933	492	2361	1245
	Max	0.5	1.0	339	177	858	447

* EFSA, 2015. For neoplastic effects, a MOE above 10,000 or above 125 means a low health concern, for neoplastic and non-neoplastic effects, respectively. Scenario 1: Calculation of dietary exposure using the median contamination data of roasted peanut snacks and kluiklui. Scenario 2: Calculation of dietary exposure using the maximum contamination data of roasted peanut snacks and kluiklui.

percentile) were 11,011 and 4488 for *kluiklui* consumers, 12,799 and 5216 for roasted peanut snack consumers, and 4119 and 2098 for consumers of both *kluiklui* and roasted peanut snacks (Table 4). Margin of exposures were below 10,000 for 38 % (Fig. 6a) and 78 % (Fig. 6b) of roasted peanut snack consumers, according to scenario 1 and scenario 2, respectively, and for 41 % (Fig. 6c) and 72 % (Fig. 6d) of *kluiklui* consumers, and 80 % (Fig. 6e) and 92 % (Fig. 6f) of consumers of both *kluiklui* and roasted peanut snacks. These MOE below 10,000 mean a potential health concern for these consumers. For neurotoxicity, all MOEs were above the threshold of 125 (Table 4), suggesting no concern for neurotoxicity among consumers of *kluiklui*, roasted peanut snacks, or both *kluiklui* and roasted peanut snacks.

In Italy, Esposito et al. (2017) reported a maximum exposure to acrylamide from roasted peanut snacks consumption of 0.008 µg/kg bw per day, based on the consumption of roasted peanut snacks containing 21 µg acrylamide per kg. This is lower than median and maximum acrylamide exposures observed in this study for consumers of peanut-based foods in southern Benin. In Iran, Nematollahi et al. (2020) estimated mean exposure levels of 0.01 µg/kg bw per day for consumers of roasted nuts and seeds, displaying an average contamination level of 131 µg/kg. This is comparable to the median exposure for roasted peanut snacks consumers in this study under scenario 1, but exceeds the median acrylamide exposure of *kluiklui* consumers and of those consuming both products. Although the median acrylamide concentration in roasted peanut snacks samples analysed in this study (52 µg/kg) was more than two times lower than that reported by Nematollahi et al. (2020), the higher consumption level of roasted peanut snacks by Beninese consumers (median intake of 9.5 g per day) compared to Iranian consumers (4.12 g per day) may explain the similar exposure levels observed.

3.4. Furan and methylfurans contents of peanut-based foods, and health risk assessment

3.4.1. Concentrations of furan, 2-methylfuran and 3-methylfuran in kluiklui and roasted peanut snacks

Furan, 2-methylfuran (2-MF) and 3-methylfuran (3-MF) contents of roasted peanut snacks and *kluiklui* samples are presented in Table 5. All individual results are provided in Table S11 of the supplementary information. Among the analysed samples, furan and 2-methylfuran were

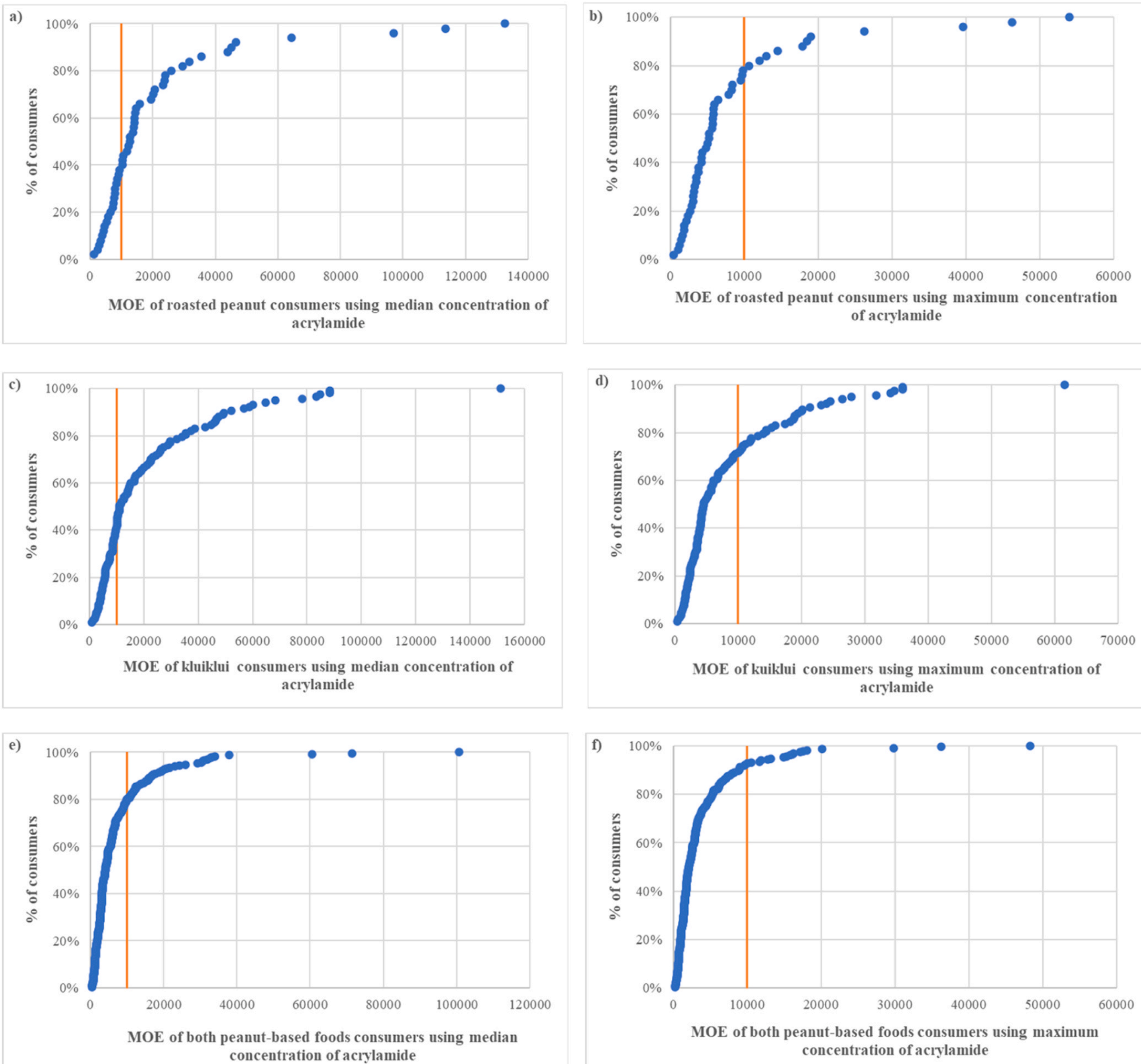

Fig. 6. Margins of exposure (MOE) to acrylamide, for neoplastic effects, based on median (a, c, e) and maximum (b, d, f) concentrations, for consumers of roasted peanut snacks only (a, b), kluiklui only (c, d), and both peanut-based foods (e, f).

the predominant compounds. All *kluiklui* and roasted peanut snacks samples showed furan concentrations above the limit of quantification (LOQ). 2-methylfuran was detected above the LOQ in all *kluiklui* samples and in 92.6 % of roasted peanut snacks samples. 3-methylfuran levels exceeded the LOQ in 100 % of *kluiklui* samples and 96.3 % of roasted peanut snack samples. Average furan, 2-methylfuran, 3-methylfuran and total furans contents were significantly higher for *kluiklui* (13.6 ± 9.1, 12.3 ± 9.8, 5.5 ± 4.0 and 31.4 ± 22.8 μg/kg, respectively) than for roasted peanut snacks (5.1 ± 2.7, 7.2 ± 5.3, 2.7 ± 0.9 and 14.9 ± 8.4 μg/kg respectively). In South Africa, a mean furan contents of 24 μg/kg has been reported in roasted peanut snacks (Masite et al., 2022), which is lower that the furan levels observed in this study. In USA, FDA (2017) reported furan contents of 2.1–7.5 μg/kg in peanut butter. The minimum furan content of *kluiklui* (4.01 μg/kg) observed in this study falls within the FDA range.

EFSA (2017) reported higher furan concentrations compared to 2-methylfuran in most food samples analysed. However, in certain products, such as coffee, canned tomatoes, salmon, and tuna, comparable or higher contents of 2-methylfuran relative to furan are reported. A similar trend was observed in peanut-based food in this study.

3.4.2. Dietary exposure to furan and total furans, and risk characterisation

The dietary exposure to furan and total furans (sum of furan, 2-methylfuran and 3-methylfuran) among the surveyed consumers is presented in Table 6.

The maximum daily intakes of furan, for consumers of *kluiklui*, under scenario 1 and scenario 2 were 0.02 and 0.24 μg/kg bw per day, respectively. For consumers of roasted peanut snacks, these figures were 0.003, and 0.03 μg/kg bw per day, respectively. For consumers of both products, the corresponding maximum daily intakes were 0.05 and 0.22 μg/kg bw per day (Table 6). Regarding dietary exposure to total furans, under scenarios 1 and 2, maximum daily intakes were as follows: 0.1 and 0.6 μg/kg bw per day, respectively, for consumers of *kluiklui*; 0.03 and 0.1 μg/kg bw per day, for consumers of roasted peanut snacks

Table 5
Concentrations of furan, 2-methylfuran and 3-methylfuran (μg/kg) in roasted peanut snack and kluiklui samples.

Products	Statistics	Furan	2-Methylfuran	3-Methylfuran	Total Furans*
Roasted peanut snacks	Mean ± SD	5.1 ± 2.7[a]	7.2 ± 5.3[a]	2.7 ± 0.9[a]	14.9 ± 8.4[a]
(n = 27)	Min	2.01	2.10	1.40	5.63
	P50	3.98	4.99	2.58	11.26
	P95	10.32	18.25	4.08	32.42
	Max	11.63	19.71	4.26	34.41
Kluiklui	Mean ± SD	13.6 ± 9.1[b]	12.3 ± 9.8[b]	5.5 ± 4.0[b]	31.4 ± 22.8[b]
(n = 42)	Min	4.01	4.13	2.15	10.28
	P50	11.90	10.15	4.59	26.36
	P95	23.57	24.83	10.17	58.25
	Max	61.96	64.61	26.89	153.47

LOQ (limit of quantification): Furan = 0.4 μg/kg; 2-methylfuran = 2.1 μg/kg; 3-methylfuran = 1.4 μg/kg, Results are presented as upper bound concentrations (data below the LOQ were replaced by the LOQ value).
[a,b] The mean concentrations of furan (p = 4.665e-09), 2-methylfuran (p = 0.001146) and 3-methylfuran (p = 1.736e-07) were significantly higher in kluiklui than in roasted peanut snacks.
*Total furans: Sum of furan, 2-methylfuran and 3-methylfuran.

Table 6
Dietary exposure to furan and total furans through peanut-based food consumption and margins of exposure (MOE).

Consumer category	Descriptive level	Dietary exposure to furan (μg/kg bw per day)		MOE (neoplastic effects) BMDL$_{10}$** = 1.31 mg/kg bw per day		MOE (non-neoplastic effects) BMDL$_{10}$* = 0.064 mg/kg bw per day		Dietary exposure to total furans (μg/kg bw per day)		MOE (non-neoplastic effects) BMDL$_{10}$* = 0.064 mg/kg bw per day	
		Scenario 1	*Scenario 2*	*Scenario 1*	*Scenario 2*	*Scenario 1*	*Scenario 2*	*Scenario 1*	*Scenario 2*	*Scenario 1*	*Scenario 2*
Consumer of roasted peanut snacks only											
n = 50	Min	0.0001	0.0003	13,447,378	4599,243	656,971	224,696	0.0003	0.0008	232,055	75,915
	P50	0.001	0.003	1299,264	444,371	63,476	21,710	0.003	0.009	22,421	7335
	P95	0.004	0.01	316,702	108,318	15,473	5292	0.01	0.04	5465	1788
	Max	0.01	0.03	114,188	39,054	5579	1908	0.03	0.1	1970	645
Consumer of *kluiklui* only											
n = 117	Min	0.0003	0.0013	5129,193	984,889	250,587	48,117	0.0006	0.003	113,121	19,426
	P50	0.004	0.02	373,551	71,728	18,250	3504	0.008	0.05	8238	1415
	P95	0.01	0.07	96,275	18,486	4704	903	0.03	0.18	2123	365
	Max	0.05	0.24	28,037	5384	1370	263	0.1	0.6	618	106
Consumer of roasted peanut snacks and *kluiklui*											
n = 233	Min	0.0001	0.0006	8903,904	2070,444	435,000	101,152	0.0003	0.001	250,968	47,690
	P50	0.004	0.02	347,472	75,796	16,976	3703	0.005	0.04	12,894	1452
	P95	0.02	0.09	76,367	15,270	3731	746	0.03	0.25	1925	261
	Max	0.05	0.22	28,460	5939	1390	290	0.08	0.6	807	108

Scenario 1: Calculation of dietary exposure using the median contamination data of roasted peanut snacks and kluiklui.
Scenario 2: Calculation of dietary exposure using the maximum contamination data of roasted peanut snacks and kluiklui (worst-case scenario).
Total furans: Sum of furan, 2-methylfuran and 3-methylfuran
* EFSA et al., 2017. For neoplastic effects, a MOE above 10,000 or above 100 means a low health concern, for neoplastic and non-neoplastic effects, respectively.

only, and 0.08 and 0.6 μg/kg bw per day for consumers of both products (Table 6). The comparison of consumer exposures to furan and total furans revealed a significant contribution of methylfurans to the overall exposure ($p < 0.001$).

For neoplastic effects (hepatocellular adenomas), the risk characterisation was performed for furan only, as it was not confirmed that alkylfurans induce hepatocellular carcinoma (EFSA, 2017). The MOE were above 10,000 for all consumers under scenario 1 (using median furan concentrations) (Table 6), while using maximum furan concentrations (scenario 2), the MOE was below 10,000 for 2 % of *kluiklui* consumers, and for 1 % of both products consumers, indicating a potential health concern for these consumers.

For the development of cholangiofibrosis (non-neoplastic effects), the MOE were above 100 for all consumers, taking into account either furan only, or total furans (Table 6) indicating low health concern for these consumers.

Fromberg et al. (2009) reported furan exposure in European adult peanut consumers ranging from 0.002 to 0.009 μg/kg bw per day, through a daily consumption of 1 g of peanuts containing 2.9 μg/kg of furan. The median and maximum exposures of *kluiklui* consumers and both products consumers, as well as the maximum exposure of roasted peanut snacks consumers in southern Benin (this study) exceeded the reported exposure levels of European peanut consumers. These higher exposure levels may be attributed to the greater daily intake of roasted peanut snacks (median: 9.5 g per day), combined with higher furan concentrations in the samples analysed (mean: 5.1 ± 2.7 μg/kg), which together likely contribute to the higher dietary exposure to furan of the Beninese population compared to the exposure of the European population.

3.5. Correlation between acrylamide and furan content of main peanut-based foods

Fig. 7 illustrates the correlation between acrylamide, furan, 2-methylfuran, and 3-methylfuran contents in roasted peanut snacks (Fig. 7a) and in *kluiklui* (Fig. 7b). The circles represent the degree of correlation between variables, with colour intensity and circle size proportional to the correlation coefficient. An asterisk (*) indicates significant correlations (p-value < 0.05). Details of the correlation matrix are presented in Tables S12 and S13 of the supplementary information.

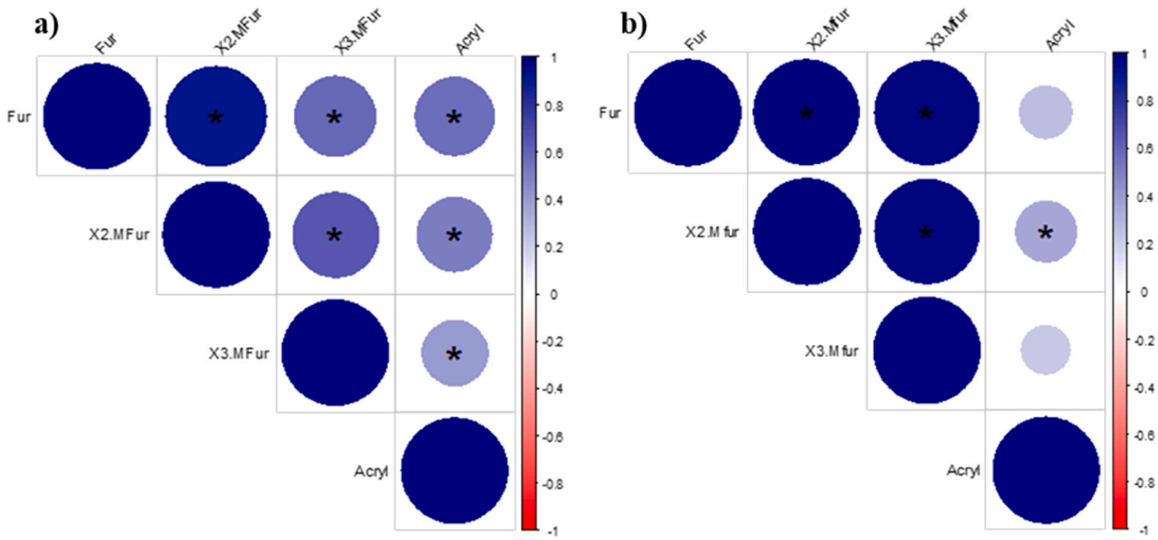

Fig. 7. Correlograms of Pearson correlation coefficient matrix between acrylamide and furan contents of roasted peanut snacks (a) and kluiklui (b) samples. *The colour bar on the side represents the scale of Spearman correlation coefficients. The blue colour represents positive correlation and the red colour negative correlation.*

For roasted peanut snacks samples (Fig. 7a), a strong positive correlation was observed between furan and 2-methylfuran ($r = 0.9$, p-value < 0.0001). Moderate positive correlations were identified between furan and 3-methylfuran ($r = 0.58$, p-value $= 0.001$), furan and acrylamide ($r = 0.56$, p-value $= 0.002$), 2-methylfuran and 3-methylfuran ($r = 0.65$, p-value $= 0.0002$), and 2-methylfuran and acrylamide ($r = 0.5$, p-value $= 0.008$). A weak positive correlation was found between 3-methylfuran and acrylamide ($r = 0.22$, p-value $= 0.04$). For *kluiklui* samples (Fig. 7b), strong positive correlations were observed between furan and 2-methylfuran ($r = 0.98$, p-value < 0.0001), furan and 3-methylfuran ($r = 0.97$, $p < 0.0001$), and 2-methylfuran and 3-methylfuran ($r = 0.97$, p-value < 0.0001). A weak positive correlation was observed between 2-methylfuran and acrylamide ($r = 0.34$, p-value $= 0.03$).

Similarly, Alsafra et al. (2023) reported a significant positive correlation between furan and its derivatives in coffee. However, they observed a negative correlation between acrylamide and furans, which is not observed in the present study. On the contrary and as noted in this study for *kluiklui* and roasted peanut snacks, a positive correlation between furan and acrylamide levels has been reported in extruded cereals and puffed wheat products (Lipinski et al., 2024). Since acrylamide and furans are formed via the Maillard reaction, it seems necessary to quantify reducing sugars and amino acids present in peanut and peanut-based foods in order to understand the formation of these contaminants.

3.6. Study implications and limitations

This study contributes to fill gaps in knowledge about consumer exposure to heat-induced contaminants present in major peanut-based foods consumed in Benin. It shows that consumption practices adopted in surveyed municipalities, together with the contamination levels of roasted peanut snacks and *kluiklui*, results in exposure to acrylamide which is of potential concern. Furthermore, the consumption of roasted peanuts contribute to polycyclic aromatic hydrocarbons (PAHs) intake and other smoked and/or grilled foods could further increase this exposure. These outcomes are consistent with previous research and extend existing knowledge on the health risks associated with peanut-based foods consumption. Importantly, the results are directly relevant for consumers, peanut processors, policymakers, and researchers, and can inform the development of more effective food safety policies and improved processing practices.

Although the study was comprehensively designed, several limitations must be acknowledged. First, the sample size was relatively small (27 samples for roasted peanut snacks and 42 for *kluiklui*), which may limit the robustness and generalisability of the findings. Second, the study relied on data from six municipalities in Southern Benin and therefore may not fully represent the national context of consumer exposure to heat-induced contaminants through peanut-based foods. Third, the lack of detailed information on the processing conditions of the collected samples, together with the absence of data on sugars (fructose and glucose), amino acids, and other precursors of acrylamide and furans, did not allow for a more comprehensive understanding of the co-occurrence of these two process contaminants in *kluiklui* and roasted peanut snacks through correlation analysis. Future assessments would therefore benefit from a more in-depth investigation of *kluiklui* and roasted peanut processing practices in Southern Benin, combined with the analysis of these precursors, in order to refine exposure estimates and better characterise the formation mechanisms of these contaminants.

4. Conclusions

This study evaluated consumer health risks associated with exposure to process contaminants in roasted peanut snacks and *kluiklui* marketed in southern Benin. Reported consumption levels of *kluiklui* and roasted peanut snacks reaching up to 346 g and 284 g, respectively. In addition to both peanut-based foods, surveyed consumers also consume other roasted, grilled, or smoked foods. Roasted peanut snacks samples contained polycyclic aromatic hydrocarbons (PAHs) concentrations below the European maximal limits of 2 μg/kg for BaP and 10 μg/kg for PAH4, defined for peanut oil. The combination of consumption levels and PAHs concentrations in roasted peanut snacks did not pose health risks. However, when considering combined intake from roasted peanut snacks and other thermally processed foods, overall PAH exposure and associated health risks may be elevated. Acrylamide contents were higher in *kluiklui* than in roasted peanut snacks. *Kluiklui* and roasted peanut snacks consumption levels and acrylamide contents induce exposure levels of potential concern. Risk characterization for neoplastic effects, based on median concentration of acrylamide revealed that consumers consuming roasted peanut snacks only were less exposed than those consuming *kluiklui* only or both peanut-based foods. No concern for neurotoxicity was identified among consumers of either of both products. Given the levels of exposure observed, it is recommended that daily co-consumption of both peanut-based products be avoided in order to minimize acrylamide intake. Furan and total furans levels were also higher in *kluiklui* compared to roasted peanut snacks. There is no risk of hepatocellular adenomas or cholangiofibrosis development for all peanut-based food consumers, when furan exposure is calculated using median furan concentrations. The significant differences in acrylamide and furan contents between *kluiklui* and roasted peanut snacks, and the distinct furan profiles (with 2-methylfuran predominating in roasted peanut snacks and furan in *kluiklui*), may be attributed to variations in thermal processing methods and in precursors present in the raw materials. As the analysed samples were randomly sourced from markets, information on raw materials and processing methods could not be collected, limiting insight into the presence of contaminants. However, given the widespread consumption of peanut-based foods across West Africa, and the relative similarity of traditional processing methods in Togo, Benin and Nigeria, the findings of this study may be extrapolated to broader regional contexts. Future studies should focus on characterizing the influence of traditional peanut processing techniques on the formation of process-related contaminants in both roasted peanut snacks and *kluiklui*.

CRediT authorship contribution statement

Yann Emeric Madodé: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Marie Louise Scippo:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Marianne Sindic:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Gauthier Eppe:** Writing – review & editing, Validation, Resources. **Paulin Azokpota:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Laure Joly:** Writing – review & editing, Validation, Resources, Data curation. **Miriam Porretti:** Formal analysis. **Samiha Boutaleb:** Formal analysis. **Georges Scholl:** Writing – review & editing, Validation, Supervision, Resources, Formal analysis, Data curation. **Philippe Szternfeld:** Writing – review & editing, Validation, Resources, Formal analysis, Data curation. **Herbert Ogouyôm Iko Afé:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Christin Sogbossi Gbétokpanou:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Caroline Douny:** Writing – review & editing, Validation, Supervision, Resources, Investigation.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jfca.2025.108525.

Data availability

Data will be made available on request.

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