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Migration of acrylamide from food contact paper products and preliminary risk assessment

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ABSTRACT

This study focuses on acrylamide migration from food contact paper products, a source of dietary exposure that has received insufficient attention. A total of 270 paper product samples were subjected to migration tests in accordance with Chinese National Food Safety Standards with some modifications, and acrylamide was quantified using ultra performance liquid chromatography tandem mass spectrometry. The results indicated that acrylamide was quantified in at least one food simulant in 61.9 % of the samples. Different food simulants showed varying migration levels. A preliminary risk assessment, based on worst-case tests with consideration of conservative exposure levels, was carried out using the Margin of Exposure method. Upon the application of an allocation factor and factoring in the overall uncertainty, the potential health risk is acceptable. Given the increasing use of food contact paper products, further research on harmonized migration test methods, migration mechanisms and more accurate risk evaluations that consider actual consumption data is essential for better understanding and management of the latent risk from food contact paper products.

1. Introduction

Acrylamide (2-Propenamide) is a low-molecular-weight polar organic compound that belongs to the aliphatic amide class with the chemical formula $C_3H_5NO_2$. It occurs as an odorless, white, crystalline solid or flake-like crystals and is highly soluble in water.

All acrylamide present in the environment is synthetic. It exists in two forms: a monomer and a polymer (Karimi & Rashedinia, 2014). The monomeric form of acrylamide was initially manufactured for commercial use through the reaction of acrylonitrile (CH_2CHCN) with either hydrated sulfuric acid or copper catalysts. This monomer is employed principally as a chemical intermediate in the production of substances known as polyacrylamides (PAM) and acrylamide copolymers. The polymers have a wide range of applications, including the treatment of municipal and industrial effluent, the production of cosmetics and toiletries, the manufacturing of textile, and the processing of crude oil.

People working in these sectors may be at an increased risk of exposure through dermal contact or inhalation during the production or use of PAM, as acrylamide can be released from the polymers into the environment. In addition to occupational exposure, acrylamide can enter the human body through the smoking of tobacco products and consumption of drinking water. In 2002, Swedish researchers discovered that foods cooked at high temperatures and rich in carbohydrates, such as fried potato chips, contain elevated levels of acrylamide (Tareke et al., 2002). This finding suggests that dietary intake is a significant source of exposure to acrylamide for the general population.

Toxicological properties of acrylamide have been investigated extensively. Studies in rodent models have found that acrylamide exposure increases the risk for several types of cancer. In light of these findings, the International Agency for Research on Cancer (IARC) classified acrylamide into group 2 A: potentially carcinogenic agent for humans in 1994 (The International Agency for Research on Cancer, 1994). Subsequently, food safety authorities around the globe, including the Food Agriculture Organization (FAO)/World Health Organization (WHO) Joint Expert Committee on Food Additives (JECFA) (Joint FAO/WHO Expert Committee on Food Additives JECFA, 2011), and

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European Food Safety Authority (EFSA) (EFSA Panel on Contaminants in the Food Chain, 2015), have determined that acrylamide represents a human health concern due to its neurotoxic (Erkekoglu & Baydar, 2014), genotoxic (Guth et al., 2023), reproductive toxic (Hogervorst et al., 2022), and carcinogenic properties (Hölzl-Armstrong et al., 2020).

Currently, there have been extensive studies devoted to the reduction of acrylamide formation during food processing (Baskar & Aiswarya, 2018; Schouten et al., 2020; Maan et al., 2022). Yet, another potential source of dietary exposure, which is often overlooked, is food contact materials, specifically food contact paper and cardboard products. This is because PAM is used as processing aid in the paper and pulp manufacturing, and acrylamide monomers may be present in the final products and can be ingested by humans through migration into food.

PAM is an indispensable additive in the modern paper making industry. Cationic PAMs, serving as retention, fixing, flocculation agents, have multiple functions in pulp processing and products (Semple et al., 2022). They help prevent clumping or loss of additives during drainage, and also provide moisture repellency for the cellulose in the pulp (Debnath et al., 2022).

According to the Chinese National Food Safety Standard-GB 9685 (National Health and Family Planning Commission the People 2016b), the migration of acrylamide from food contact materials should not be detectable, with a maximum detection limit of 0.01 mg/kg. As previous dietary exposure assessments of acrylamide have not considered the potential exposure from food contact materials, this standard should be further evaluated.

In March 2022, members of the United Nations Environment Assembly (UNEA) unanimously endorsed a historic resolution with the ambition of eliminating plastic pollution from the environment. When stakeholders contemplate shifting away from single-use plastic packaging, renewable source products, such as paper and board, are always viewed as optimal alternatives (Herrmann et al., 2022; Zhang et al., 2022). The utilisation of paper-based food contact materials in everyday life is increasing notably in both the number of applications and the frequency of use. It is imperative that, irrespective of whether paper products can serve as a functional substitute for disposable plastics, their safety is guaranteed as a prerequisite.

This article aims to highlight the extensive migration of acrylamide monomer from paper-based products. The study analyzes acrylamide migration levels based on different uses, raw material processes, and experimental conditions. Furthermore, a preliminary risk assessment based on worst-case tests was conducted to evaluate the dietary exposure risk associated with acrylamide from food contact materials. Despite the scarcity of similar studies in the existing literature, it is hoped that the information presented here will attract the attention of regulatory authorities, industry stakeholders, and consumers alike.

2. Material and methods

2.1. Sampling

From April 2022 to September 2023, a total of 270 brand new disposable food contact paper product samples were randomly obtained from super markets, retail shops, e-commerce platforms and fast-food restaurants across five geographical regions in China (Jilin, Gansu, Anhui, Guangdong, and Beijing).

The samples were collected according to their intended use, which included 12 different kinds of paper products: paper plates (45), paper cups (32), baking paper (32), baking cups (29), wrapping paper (27), paper boxes (23), paper straws (16), paper bowls (16), paper doilies (15), popcorn buckets (14), paper bags (12), and takeaway boxes (9). Subsequently, the samples were characterized and categorized according to raw materials and manufacturing processes based on product labels, packaging details, and information supplied by the vendors when available. The expected food contact surfaces of all samples were subjected to Fourier transform infrared spectroscopy (FT-IR) (IRTracer-100, Shimadzu, Japan) test to confirm the presence or absence of polymer coatings, such as polyethylene (PE). Fig. 1 offers a concise overview of the purposes and raw materials of the paper products collected for this research. (Fig. 1).

2.2. Reagents

Acrylamide was purchased from Dr. Ehrenstorfer GmbH (Augsburg, Germany) and isotope-labeled $^{13}C_3$-acrylamide as an internal standard was purchased from Cambridge Isotope Laboratories, Inc. (Andover, MA, U.S.A.). HPLC grade methanol (MeOH), ethanol (EtOH), formic acid and acetic acid were acquired from Anavo (Beijing, China). Ultrapure water was obtained from a Millipore ultrapure water purification system (Milli-Q IQ 7015, Merck KGaA, Darmstadt, Germany).

The standard solutions of acrylamide and $^{13}C_3$-acrylamide were prepared by dissolving a certain amount of the solid neat chemicals in ultrapure water. Food simulants, including 10 % ethanol solution (v/v) as aqueous food (EtOH10), 4 % acetic acid solution (v/v) as acidic food (EcAd04) (PH<4), 95 % ethanol solution (v/v) as oily food (EtOH95), for migration tests were prepared in accordance to Chinese National Food Safety Standards-GB 5009.156 (National Health and Family Planning Commission the People's 2016a).

2.3. Migration tests

Migration tests were carried out in accordance with Chinese National Food Safety Standards- GB 31604.1(National Health Commission of the People's Republic of China, 2023), with some modifications. Briefly, paper product samples were placed in contact with food simulants at 70 ℃ for 2 hours. However, for baking cups and baking papers, given their intended use at higher temperatures, the migration tests were conducted at 70 °C for 4 hours. Given that paper products are disposable, the migration test was carried out once for each sample. The migration level of the sample is calculated as the arithmetic mean of the results obtained from two parallel migration tests.

Initially, the paper product samples were exposed to food simulants in the way they contact with real food, such as filling (e.g., paper cups), single-sided contact (e.g., wrapping paper with a grease and water repellent surface), and total immersion (e.g., paper straws). However,

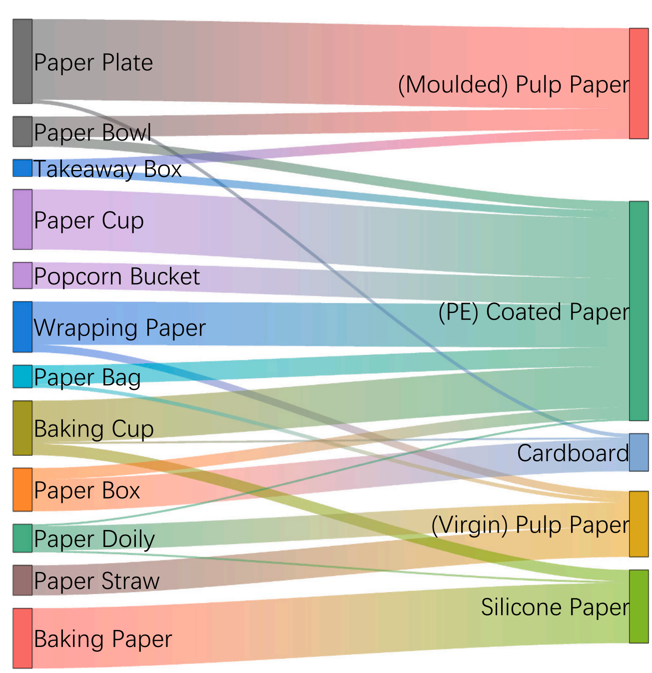

Fig. 1. Usage and material of food contact paper products.

preliminary experiments showed that, with the exception of the EtOH10 filling in paper cups, most samples were unable to withstand the aforementioned test conditions and experienced issues such as deformation, leakage during non-immersion contact, leading to physical structure damage. To avoid the unnecessary expenditure of samples, reagents and time, all subsequent migration tests were carried out using the contact type of total immersion.

For total immersion, paper product samples were cut into pieces of approximately 1–2 cm^2 with scissors, while paper straws were cut into pieces of approximately 1–2 cm. Subsequently, each sample was transferred into a wide mouth Erlenmeyer flask before a certain amount of food simulants was introduced. The volume of the added food simulants was recorded with the contact area of each sample to calculate the surface to volume ratio (S/V). The flask was sealed with aluminum foil and then placed in the oven. Food simulant solvents were pre-heated to 70 °C before the tests.

After migration tests, 1 mL of food simulants was transferred to a 2 mL Eppendorf tube and internal standard (20 ng) was added before vortexing for 30 seconds. For EtOH10 and EcAd04, the mixed solution was filtered through a 0.22 µm PTFE filter (Anavo, Beijing, China) before the instrumental analysis. In the case of EtOH95, the mixture was evaporated to near dryness at 35 °C under a gentle stream of nitrogen and then reconstituted in 1 mL of ultrapure water. The reconstituted solution was filtered prior to instrumental analysis.

2.4. Instrumentation

The determination of acrylamide from food simulants was performed on Ultra Performance Liquid Chromatography Tandem Mass Spectrometry (UPLC-MS/MS, ACQUITY, TQD, Waters Corporation, Milford, MA, USA) with an ACQUITY HSS C18 SB column (2.1 mm × 100 mm, 1.8 µm particle size) coupled to a ACQUITY HSS C18 SB VanGuard precolumn (2.1 mm × 5 mm, 1.8 µm particle size) from Waters Corporation (Milford, MA USA).

The mobile phase was a solution of MeOH (A) and formic acid (0.1 %, v/v) (B) at a flow rate of 0.2 mL min^{-1}. The gradient was as follows: initial 5 % of A during 0.1 min, increasing to 100 % A at 6 min, kept constant at 100 % A for 1 min and decreasing to 5 % at 7.1 min, re-equilibrate for 3 min for the next injection. The sample injection volume was 5 µL.

The analyte was detected by tandem mass spectrometry in multiple reactions monitoring (MRM) mode, using positive the electrospray ionization (ESI+) source. Nitrogen and argon were used as the nebulizer and collision gas, respectively. The quantitative transitions monitored for acrylamide was m/z 72 > 55 at 8 V, and for $^{13}C_3$-acrylamide was m/z 75 > 58 at 8 V. Automatic dwell times were used. Data acquisition and processing were completed by MassLynx software version 4.1(Waters, Manchester, UK).

2.5. Method validation

The method was validated for acrylamide in three types of food simulants in terms of linearity, limit of detection and quantification (LOD and LOQ), relative recovery, and precision. Quantitation of migrating acrylamide was based on matrix-matched calibration curves constructed by plotting the peak area ratio between the target ions of acrylamide and the internal standard $^{13}C_3$-acrylamide against the concentrations of acrylamide. Calibration curves were prepared at six different concentration levels in three different food simulant solutions. Linear regression analysis was applied, and the results were assessed using correlation coefficient (R^2) that should not be below 0.995. The LOD and LOQ were determined as the concentrations at which the signal-to-noise (S/N) ratio was three and ten, respectively. These values were derived from the examination of the lowest calibrated level. Blank food simulant samples were spiked at three different levels (low, medium, high) with six replicates to evaluate the relative recoveries. Precision, expressed as the relative standard deviation (RSD) in %, was calculated from the results generated by the repeatability of recovery tests.

2.6. Migration data

In this manuscript, the acrylamide migration data utilized for both statistical analysis and risk assessment are presented in units of micrograms (µg). The calculation procedures are as follows:

$$MD_N = IMR_N \times V_N$$

Here, MD_N represents the migration data (µg) of test sample N, IMR_N stands for the acrylamide migrating level in food simulant derived from test sample N, and V_N indicates the volume of food simulant solvent used in the migration test of sample N. This unit signifies the absolute quantity of acrylamide that has leached from a single piece of paper product sample, rather than its concentration in the food simulant solutions. In the case of samples packaged in rolls, such as baking paper, the migration levels are adjusted to reflect the area of a single sheet of wrapping paper (25 cm × 25 cm). For left-censored results, where the initial migration levels fall below the LOD, a value of zero is assigned.

2.7. Risk assessment

A preliminary risk assessment was performed on two age groups: children aged 3–14 years with an average weight of 27.4 kg (Zhang et al., 2023) and adults aged above 18 years with an average weight of 65.8 kg (Chen et al., 2023). This assessment utilized the Margin of Exposure (MOE) approach recommended by the EFSA (EFSA Panel on Contaminants in the Food Chain, 2015).

$$MOE = \frac{BMDL}{Estimated\ Exposure\ Dose}$$

The Benchmark Dose Lower Bound (BMDL) is a reference value derived from the Benchmark Dose (BMD), which expands the use of response data from animal studies. For genotoxic and carcinogenic compounds, an MOE of ≥ 10,000 would be considered to pose a low risk from a public health perspective.

Based on EFSA's report, the value of 0.17 mg/kg b.w. per day, derived as the lowest $BMDL_{10}$ from data on incidences of Harderian gland adenomas and adenocarcinomas in male B6C3F1 mice exposed to acrylamide for two years, was selected for MOE calculation.

The primary source of human dietary acrylamide exposure is from processed foods, as acrylamide forms when carbohydrate-rich foods are cooked at high temperatures for extended periods (The International Agency for Research on Cancer, 2019,). As suggested by EFSA, if it is known that a significant portion of exposure to a substance is not due to its migration from food contact materials, an allocation factor may be used to attribute only a fraction of the toxicologically tolerable amount to exposure from FCM (Fürst et al., 2019). Therefore, the reference point value used to calculate the MOE in this study was set at 20 % of $BMDL_{10}$, i.e. 0.034 mg/kg b.w. per day.

$$MOE = \frac{0.034\ mg/kg\ b.w.\ per\ day}{Estimated\ Exposure\ Dose}$$

Due to the lack of survey data on actual consumption, Estimated Exposure Dose was calculated based on multiple hypotheses. A) The frequency of daily usage of various functional paper products by consumers was estimated based on research conducted by Di Mario et al. (Di Mario et al., 2023) with some modifications; B) It was assumed that every time a consumer eats food contained in paper packaging, the acrylamide that has migrated from the paper product is also entirely consumed, which represents the worst-case scenario; C) It was supposed that the migrated amount of acrylamide for each type of paper product is equal to the average migration level found in the present study for that specific category of paper product.

The Estimated Exposure Dose of acrylamide from paper product origin was calculated using the following equation.

$$EED_g = \frac{1}{BW_g} \sum M_x FR_x$$

where EED_g represents the estimated exposure dose (mg/kg b.w. per day) to acrylamide for the studied population g (children and adults), BW_g indicates the mean body weight of the studied population g (27.4 kg and 65.8 kg), x indicates the category of the food contact paper product, M_x (μg) is the mean of the absolute quantity of acrylamide migration from food contact paper product category x, and FR_x stands for the consumption frequency of food contact paper product category x.

Additionally, in risk assessment, the data used are the average values of the migration levels from three types of food simulants. It should be noted that for paper bags, paper boxes, paper plates, baking paper, muffin cups, wrapping paper, and paper doilies, which are usually used for the packaging of foods with free fats on the surface, the acrylamide migration values in food simulant EtOH95 were set at one-third of the detected values, according to GB 31604.1(National Health Commission of the People's Republic of China, 2023). The remaining studied samples were not adjusted, as they could potentially serve as containers for liquid foods.

2.8. Statistical analysis

Data normality of acrylamide migration levels from different food simulants was evaluated using the Shapiro-Wilk test. If a skewed distribution was observed, a non-parametric Friedman test was employed to compare the differences. A post-hoc pairwise analysis was conducted if a significant difference was identified. The threshold for statistical significance was set at 0.05.

3. Results and discussion

3.1. Method performance and quality control

The performance of the proposed analytical method was assessed in terms of recovery, precision (RSD), linearity (correlation coefficient, R^2), LOD and LOQ. The validation parameters are shown in Table 1.

3.2. Acrylamide in the food simulants

Of the 270 paper products tested, 167 samples (61.9 %) had acrylamide quantified (>LOQ) in at least one of their food simulants (Supplementary Material), and 7.5 % of the samples exceeded the migration limit for acrylamide.

From the perspective of food simulants, the average migration of acrylamide in EtOH10 from 270 samples was 0.687 μg, with 125 samples detected above the LOQ. The quantifiable range was 0.026–68.623 μg, and the average quantified value was 1.483 μg. In EcAd04, the overall average migration of acrylamide was 1.396 μg, with 103 samples quantified, showing a measurable range of 0.028–201.678 μg and an average quantified value of 3.660 μg. For EtOH95, the average migration level was 3.044 μg, with 153 positive samples out of 270. The quantifiable range was 0.028–377.749 μg, with an average value of 5.373 μg.

A total of 79 samples showed measurable levels of acrylamide in all three kinds of food simulants. Among these, the average quantified values were 2.204 μg in EtOH10, 4.719 μg in EcAd04, and 9.661 μg in EtOH95.

The migration levels of acrylamide in the three food simulants did not show a normal distribution. A Friedman's test indicated that statistically significant differences exist among the three groups. Subsequently, a paired post-hoc test revealed that, overall, the migration level of acrylamide in EtOH95 was higher than in the other two groups.

In practical applications, paper products made from different materials and processes may serve the same purpose. For instance, both molded pulp products and PE laminated paper products can be used for takeaway boxes. On the contrary, paper products designed for various uses may also be made from the same materials and processes. For example, PE laminated paper can be employed in the production of paper cups or takeaway boxes.

From the perspective of paper products usage, the quantitative rate of paper straws is the highest at 93.8 %. Out of 16 paper straw samples, only one did not show quantifiable levels of acrylamide migration. This is followed by wrapping paper and paper plates, with quantitative rates of 88.9 % and 86.7 %, respectively. The quantitative rates for paper bags and paper boxes also exceed 80 %. Baking paper has the lowest quantitative rate at only 6.3 %. The results of Friedman's test that compared the migration levels from different food simulant solution when grouped by application were not consistent with the results of the overall sample, possibly due to the sample size.

PAM is used as a flocculant in the paper and pulp industry; hence, raw material and manufacturing processes could be one of the major factors influencing the level of acrylamide migration. In terms of materials and processes, the highest frequencies of acrylamide quantification were found in cardboard and molded pulp paper products, at 90.0 % and 86.4 %, respectively. Following these were the virgin paper pulp product at 62.9 % and PE-laminated paper product at 60.7 %. In contrast, the quantitative rate for silicone paper is relatively low, at 12.8 %.

Table 1
The validation parameters of the determination method.

Food Simulant	Spiked Level (μg /L)	Recovery (%)	RSD (%)	LOQ (μg /L)	LOD (μg /L)	R^2
EtOH10	0.5	89.4	6.5	0.1	0.03	> 0.998
	10	92.3	3.9			
	100	97.8	2.1			
EcAd04	0.5	93.2	4.2	0.1	0.03	> 0.998
	10	89.5	4.4			
	100	103.2	6.1			
EtOH95	0.5	95.1	10.0	0.1	0.03	> 0.996
	10	88.7	4.5			
	100	91.0	5.9			

3.3. Polymer barrier

It should be noted that the paper-based samples included in this study do not include multi-layer composite materials with a metal layer. These investigated specimens are generally considered to lack an efficient barrier. Samples such as paper cups, popcorn buckets, and takeaway boxes feature an inner surface coated with a PE film. In the initial migration tests, the filling method, which involved contact with the inner surface, was employed for a select number of paper cup samples with EtOH10 as the food simulant. No migration of acrylamide was observed in the food simulant solution. However, when the full immersion method, which involved cutting the sample into small pieces, was later applied, acrylamide migration was detected. The process of migration from fibre-based materials differs significantly from that occurring in plastics, such as PE. Paper and board materials are heterogeneous, open and porous structures comprising cellulosic fibres and air pores (Poças et al., 2011). Previous research shows that PE lamination is not completely effective in preventing the migration of substances such as phthalates, benzophenones, or mineral oil from paper products (Song et al., 2003; Ewender et al., 2013). Nevertheless, it does offer a certain degree of barrier against the migration of acrylamide monomer.

3.4. Time, temperature and migration

Three different paper products made of various materials - specifically, paper box of cardboard, paper bowl of molded pulp paper and paper straw of virgin pulp paper - were selected from all samples that had previously tested positive for acrylamide migration for a series of further migration tests to investigate the relationship between temperature, contact duration, and levels of acrylamide migration. Simply, test samples were subjected to five test conditions. The contact time ranged from 15 min to 120 min. The contact temperature for the first test was at room temperature (RT), and for the remaining tests, it was 70 °C. The contact method of the five tests was total immersion.

Overall, the acrylamide migration in the different food simulants for these three types of samples exhibited a similar pattern. The migration levels increased as the contact time and temperature rose, as depicted in Fig. 2.

This trend is consistent with the findings of previous studies. For example, a study by Han et al. indicated that the migration of photoinitiators from food-grade kraft paper into EtOH95 was facilitated at high temperatures (Han et al., 2016). Zabaleta et al. reported that, when using EtOH95 as a simulant, higher migration rates of long carbon chain PFAS and their precursors were observed at 60°C compared to those at room temperature (Zabaleta et al., 2020). Another research conducted by Blanco-Zubiaguirre et al. suggested that contact time had a positive effect on the migration of photoinitiators, phthalates and plasticizers from paper and cardboard materials into ethanol-based simulants (Blanco-Zubiaguirre et al., 2021).

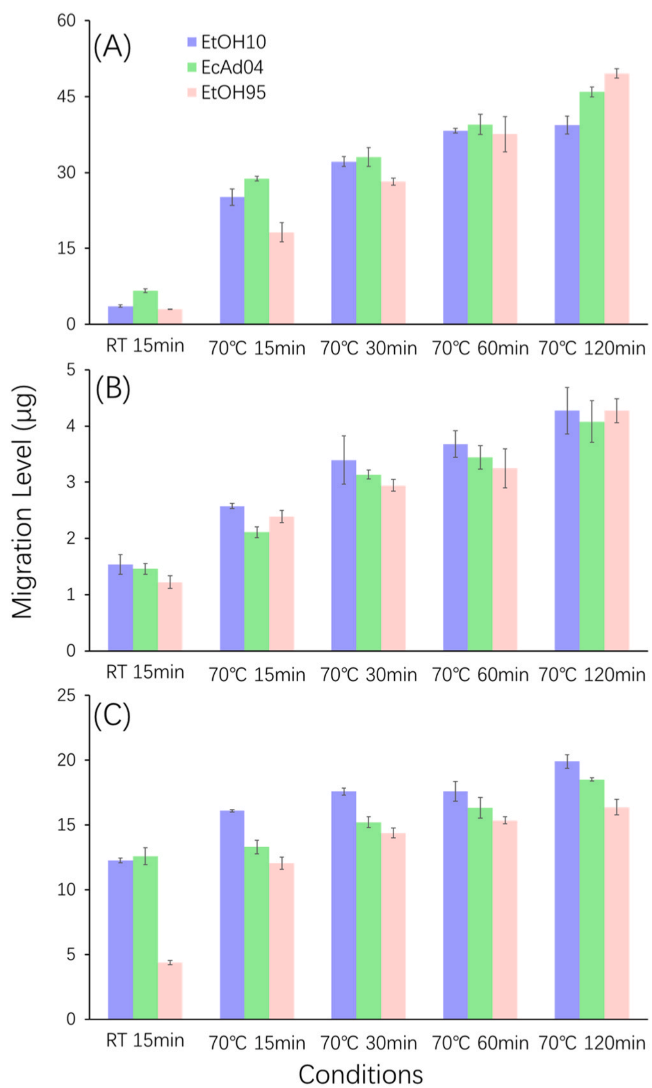

Fig. 2. The influence of time and temperature on the acrylamide migration of paper products - (a) cardboard paper box, (b) molded pulp paper bowl and (c) virgin pulp paper straw.

For paper bowls and paper boxes, using the total immersion method is a very strict approach that can overestimate the actual migration levels of acrylamide. However, in the case of paper straws, the actual application scenario closely resembles total immersion. Even after 15 minutes of contact at room temperature, acrylamide migration can be detected in different aqueous-based food simulants, which is a potential health concern that needs to be further monitored.

3.5. Migration conditions related to paper products

The results of migration tests are directly related to the scientific accuracy of the risk assessment for paper products. Compared with plastic products, research on migration tests for paper products is more complex. The test conditions reported in the literature are inconsistent. Most of the food simulants used were originally designed for plastic products and may not be fully compatible with paper products (Nerin et al., 2025). As this study has shown, these plastic-product-oriented simulants can cause deformation and structural damage to certain paper products. In many studies, including the present one, paper products are cut into pieces and immersed in simulant solutions. Although the cutting sizes vary, predominantly ranging from 1 cm^2 to 10 cm^2 (Trier et al., 2011; Lerch et al., 2022; Sonego et al., 2023; Chen et al., 2024; Di Mario et al., 2024), for most paper products types, this method deviates from their original usage scenarios. Meanwhile, it is likely to inflate the migration level.

Numerous studies have employed Tenax® as a simulant for dry food, as recommended by EU (Störmer et al., 2024). Nevertheless, some food contact material regulatory authorities including the US and China have not incorporated Tenax® into the migration test guideline (Nerin et al., 2025). This is probably because the experimental results in the literature indicate that Tenax® may result in either overestimation or underestimation of migration levels (Zurfluh et al., 2013; Zabaleta et al., 2020; Baele et al., 2020). Other studies have attempted to use real-world foods (Lerch et al., 2023). However, as is widely recognized, real foods exhibit a matrix that is significantly more complex than that of food simulants. Consequently, unpredictable interfering substances can pose substantial difficulties in the accurate interpretation of test data (Fengler & Gruber, 2020). Moreover, given the significant disparities in dietary structures across the globe, reaching a consensus on these food choices remains an arduous task.

3.6. Preliminary risk assessment

Many studies have conducted risk assessments on the chemical migrating substances in paper products. There is also a substantial amount of literature evaluating the health risks posed by acrylamide in processed foods. However, to date, there has been few publications addressing the risk associated with acrylamide migration from food contact paper products.

In the current study, the estimated exposure dose of acrylamide from the migration of paper-based food contact materials was calculated under a series of hypothetical scenarios and based on the results obtained from migration experiments conducted with different food simulants. The exposure levels for children and adults were 0.0041 and 0.0028 μg/kg b.w. per day, respectively (Supplementary Material). When assessing with MOE, it was found that the MOE values for children (9861) fell slightly below the threshold of 10,000, indicating a potential health concern could not be completely ruled out and requires further validation. Within the framework of the dietary pattern hypothesized in the present study, the predominant contributing factor could be attributed to the exposure resulting from the use of paper boxes. Nevertheless, considering the multiple conservative assumptions, the risk was deemed acceptable. For adults (MOE = 11,250), the associated risk from such exposure may be considered insignificant.

Several countries and authoritative food safety bodies have carried out dietary exposure assessment regarding acrylamide. The average dietary intake levels of acrylamide across various age groups have been estimated to range from 0.046 to 3 μg/kg b.w. per day, as reported in literature (Abt et al., 2022). The acrylamide exposure due to the migration of paper products within the two age groups under study was determined to be markedly lower than the previously documented dietary exposure levels of acrylamide for the Chinese population, which was 0.319 μg/kg b.w. per day (Gao et al., 2016). It is worth noting that the prior dietary exposure assessment did not take into account the contribution from the migration of paper-based food contact materials. Given the advancements in acrylamide reduction methodologies within the food processing industry and the escalating prevalence of paper-based food contact materials, future risk evaluations ought to incorporate the exposure originating from food contact materials.

4. Limitations and uncertainty

The main uncertainty in this study is that the migration test conditions used for paper products were based on the worst-case scenario, such as cutting into small pieces and fully immersing them in food simulant solutions. Therefore, it could have led to an overestimation of acrylamide exposure and a rather conservative result. However, it should be noted that such conditions are not uncommon and have been routinely employed in prior investigations concerning paper product contaminants (Sonego et al., 2023; Chen et al., 2024; Di Mario et al., 2024). Additionally, the consumption data of paper products come from the literature and certain assumptions, and all of these might tend to magnify the potential risk.

5. Conclusions

This article reports on the widespread detection of acrylamide monomer in various food simulants of food contact paper product. Although the migration test conditions employed by the researchers are quite strict for some types of paper product samples, it does not rule out the possibility that acrylamide could migrate from paper products into food items that come into contact with or are packaged in them during real-life use. Future research can focus on migration conditions (including food simulant) and mechanisms.

The estimated exposure dose of acrylamide from paper product origin, calculated based on multiple assumptions, was significantly lower than that of food sources. The MOE value for children, derived by applying an allocation factor of 20 % to the BMDL, is marginally lower than 10,000, which means that the potential health concern associated with acrylamide migration is worthy of attention. However, based on the overall uncertainty of migration and risk assessment, the overall risk is acceptable. Once more accurate consumption data and harmonized migration test methods for food contact paper products are available, the results of the risk assessments will be more dependable. To provide regulators with more scientific and precise data to support regulatory action, it is recommended that more comprehensive assessments be conducted. Meanwhile, industries should optimize their manufacturing processes so as to deliver safer products to consumers.

CRediT authorship contribution statement

Wei Liu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dajin Yang:** Supervision, Project administration, Funding acquisition. **Ziyi Wang:** Formal analysis, Data curation. **Rong Zhao:** Writing – review & editing, Supervision, Resources. **Sai Fan:** Resources, Investigation, Formal analysis. **Rui Yuan:** Investigation, Formal analysis, Data curation. **Ruiying Tu:** Formal analysis, Data curation. **Daoyuan Yang:** Writing – review & editing, Data curation. **Jie Gao:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Haixia Sui:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization.

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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.fpsl.2025.101527.

Data Availability

Data will be made available on request.

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