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Deterministic and Probabilistic Assessment for Dietary Exposure of Naturally Occurring Formaldehyde in Fresh Foods of Plant Origin in Indonesia

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ABSTRACT

Formaldehyde is known to pose health risks, including carcinogenic effects. Its presence is often associated with the misuse of formalin. Information on formaldehyde in fresh food of plant origin (FFPO) and its effect on public health remains limited. This study assessed formaldehyde levels in FFPO commodities, estimated dietary exposure, and performed risk analysis using deterministic and probabilistic approaches. A total of 138 samples collected from supply chain nodes were analyzed by UV-Vis spectrophotometry using chromotropic acid reagent. Results showed that formaldehyde concentrations varied across commodities, ranging from below the limit of detection to 155.00 mg/kg. National exposure as the estimated daily intake (EDI) was estimated at 0.0012 mg/kg bw/day, while regional analysis across 38 provinces revealed exposure levels between 0.000640 and 0.008227 mg/kg bw/day. Monte Carlo simulation yielded a mean daily exposure of 0.00249 ± 0.00523 mg/kg bw across age groups, substantially lower than the reference total daily intake (TDI) of 0.15 mg/kg bw. Non-carcinogenic risk characterization showed hazard quotient (HQ) values below 1, indicating that the exposure is unlikely to pose a significant health risk. Carcinogenic risk characterization showed cancer risk (CR) values generally within the acceptable range (10-6 to 10-4), although slightly exceeding the upper limit in certain groups. However, as the assessment is based on conservative assumptions without accounting for potential reduction, the actual risk may be lower.

1. INTRODUCTION

Formaldehyde is a simple aldehyde compound that can naturally occur in foods through metabolic processes or component degradation (Rahman *et al*., 2023). It is primarily generated through methanol oxidation resulting from the demethylation of cellular components such as cell wall pectin, as well as DNA, RNA, and proteins (Li *et al*., 2023). In fresh foods of plant origin (FFPO), natural formaldehyde levels vary depending on commodity type and storage conditions, including temperature, storage duration, and maturity stage (Nowshad *et al*., 2018). However, formal-dehyde detection in food products is often linked to the misuse of formalin, an illegal preservative employed to extend shelf life and maintain food quality (Rahman *et al*., 2023).

The International Agency for Research on Cancer (IARC) classifies formaldehyde as a Group 1 carcinogen. Acute exposure may cause irritation of the skin, eyes, and respiratory tract, whereas chronic exposure has been associated with neurotoxicity, reproductive toxicity, genotoxicity, respiratory system damage, and carcinogenic effects (Li *et al*., 2023). The World Health Organization (WHO) has established a tolerable daily intake (TDI) of 0.15 mg·(kg bw)$^{-1}$·(day)$^{-1}$ for oral exposure (EFSA-AFC Panel, 2006). In Indonesia, the use of formalin as a food additive is strictly prohibited under the Regulation of the Ministry of Health No. 33/2012 and NADFC No. 7/2018. Technically, this imposes a strict zero tolerance policy where any detection is legally deemed a violation. However, a critical implementation gap occurs in field surveillance, as standard screening methods were unable to differentiate between exogenous added formalin and naturally occurring endogenous levels. Furthermore, baseline levels for natural formaldehyde are not yet available to serve as a reference for interpreting surveillance results.

Beyond posing regulatory surveillance challenges, formaldehyde in FFPO also represents a potential source of daily dietary exposure. To bridge this critical scientific and regulatory gap, this study provides the first comprehensive, national-level evaluation of dietary exposure and health risks associated with naturally occurring formaldehyde in FFPO. Unlike previous localized or small-scale evaluations (Wihardi *et al.*, 2023), this is the pioneering study to assess dietary exposure and risk characterization across all 38 provinces in Indonesia. This assessment is urgent as FFPO commodities are staples widely consumed by the population, meaning naturally occurring formaldehyde could contribute significantly to long-term dietary exposure even without formalin misuse.

Furthermore, this research represents the first framework in the country to integrate both deterministic and probabilistic approaches for food chemical risk assessment. The deterministic approach generates a single aggregate exposure estimate, whereas the probabilistic approach enables characterization of the population exposure distribution by accounting for data variability and uncertainty (*Pekmezci et al.*, 2025). The resulting data will provide unprecedented scientific evidence for food safety authorities to establish realistic maximum limits of endogenous formaldehyde, support risk-based surveillance, and inform future regulatory considerations. Ultimately, it is hypothesized that while naturally occurring formaldehyde in FFPO is expected to remain below levels of toxicological concern for the general population, high consumption subgroups may exhibit elevated probabilistic risks.

2. MATERIALS AND METHODS

2.1. Materials

Primary data consist of formaldehyde levels in 24 FFPO commodities collected across different supply chain nodes, determined using UV Vis spectrophotometry with chromotropic acid reagent (AOAC 931.08). Secondary data included the 2024 national and regional food consumption data, calculated by the National Food Agency from the National Socio-Economic Survey (SUSENAS) for deterministic assessment, and the 2014 Individual Food Consumption Data (SKMI) obtained from the Ministry of Health for probabilistic assessment.

Although a ten-year gap exists between these datasets, their combined use is justified due to national data availability constraints, as SKMI 2014 remains the most recent official registry providing the individual level consumption and body weight distributions necessary for probabilistic modeling. Furthermore, while SUSENAS 2024 captures contemporary macro level regional intake, the utilization of SKMI 2014 provides the essential granular variability required for Monte Carlo simulations, assuming dietary patterns for core FFPO commodities have remained relatively stable over decade.

2.2. Methods

2.2.1. Sampling of FFPO

A purposive approach was applied to collect 24 FFPO commodities (fruits, vegetables, tubers, and mushrooms) across four Indonesian provinces: DKI Jakarta, West Java, Banten, and Lampung. This selection is justified as these provinces constitute the primary national food supply chain hub. Furthermore, the markets within this trading corridor act as critical consolidation nodes that produce, receive, distribute, and consume FFPO commodities sourced nationwide, thereby serving as a reliable proxy for national-level exposure. Therefore, selected sampling locations were considered appropriate to represent heterogeneous exposure conditions within national FFPO distribution network.

The selection of commodities was conducted purposively based on three main considerations: (1) level of public consumption, (2) potential for endogenous formaldehyde formation reported in previous studies, and (3) representation of major FFPO commodity groups to ensure diversity across food categories. Practical constraints, including seasonal availability, limited market access, and logistical considerations during sampling period also influenced commodity inclusion.

Sampling was conducted in May 2025, capturing harvest period during transition to dry season. For each commodity, 200 g samples were collected independently from 6 to 7 distinct sampling points, vacuum sealed and coded on site to maintain integrity, prevent contamination, and enhance traceability throughout the analysis. This sample size was optimized for laboratory quantification while minimizing moisture loss and volatile degradation. By analyzing these points, the study was able to capture intra supply chain variability and heterogeneity among distribution nodes that are essential for the subsequent probabilistic risk simulation.

2.2.2. Determination of Formaldehyde Content

Formaldehyde content was quantified following AOAC Official Method 931.08 (AOAC International, 2023). Homogenized samples (5 g) were extracted in 50 mL distilled water at 80 °C for 30 minutes, centrifuged at 3000 rpm for 20 minutes to obtain clear supernatants. Aliquots of the supernatant were reacted with sulfuric acid and chromotropic acid in a water bath at 95–100 °C for 15 minutes until a purple-colored complex developed. Absorbance was measured using UV–Vis spectrophotometry at 570 nm and formaldehyde concentrations were determined against a standard calibration curve. Method validation was performed to ensure analytical reliability, yielding a limit of detection (LOD) of 0.0858 mg/kg and a limit of quantification (LOQ) of 0.2145 mg/kg.

2.2.3. Statistical Data Analysis

Initially, One-Way Analysis of Variance (ANOVA) was considered to evaluate mean differences among groups, provided that the primary numerical variables satisfy the assumption of normality. However, if exploratory data analysis reveals significant normality violations, high variability, or extreme outliers, the non-parametric Kruskal–Wallis test will be employed as a robust alternative to compare median rank distributions across provinces and supply chain points. Accordingly, the choice of post-hoc procedures depends on the primary test outcome. If ANOVA assumptions are met, Tukey's HSD test will be applied for pairwise comparisons. Otherwise, following a significant Kruskal–Wallis result, Dunn's post-hoc test with adjusted *p*-values will be performed. This conditional approach ensures controlled Type I error and maintains statistical validity across multiple comparisons.

2.2.4. Estimation of Formaldehyde Exposure (EFSA, 2011)

The Estimated Daily Intake (EDI) for the general population was determined by combining formaldehyde levels in food with consumption rates, which was subsequently normalized against average body weight (Equation 1). To represent a conservative worst-case scenario, calculation was done using formaldehyde levels measured in raw FFPO samples from supply chain points, rather than in cooked or processed forms.

$$\mathrm{EDI} = \frac{\mathrm{I} \times \mathrm{C}}{\mathrm{bw} \times 1000} \tag{1}$$

where EDI (estimated daily intake) is presented in mg·(kg bw)$^{-1}$·(day)$^{-1}$, I is daily consumption (g/day), C is formaldehyde level (mg/kg), and bw is body weight (kg).

2.2.5. Health Risk Characterization (WHO, 2021)

Effect of formaldehyde exposure on health was evaluated for both non carcinogenic and carcinogenic effects. Non carcinogenic risk was determined from the Hazard Quotient (HQ) value, which was estimated by comparing the EDI with toxicological reference point (Equation 2). HQ above 1 indicates potential adverse health risks.

$$\mathrm{HQ} = \frac{\mathrm{EDI}}{\mathrm{TDI}} \tag{2}$$

where HQ is hazard quotient, a dimensionless value for risk characterization, and TDI is WHO tolerable daily intake of 0.15 mg·(kg bw)$^{-1}$·(day)$^{-1}$ (EFSA-AFC Panel, 2006).

The carcinogenic risk (CR) was calculated using the EDI and a cancer slope factor (SF) as in Equation (3) (OEHHA, 2011), with SF of 0.021 per mg·(kg bw)$^{-1}$·(day)$^{-1}$. The estimated results were evaluated against the acceptable incremental lifetime cancer risk range of 1×10^{-6} to 1×10^{-4} (U.S. EPA, 2023).

$$\mathrm{CR} = \mathrm{EDI} \times \mathrm{SF} \tag{3}$$

2.2.6. Modelling and Data Analysis

The formaldehyde concentration data was fitted with probabilistic distributions using @RISK add-in for Excel version 8.12. The selected distribution was evaluated based on the Akaike Information Criteria (AIC) and conformity to data characteristics. Simulations were run for 50,000 iterations using Monte Carlo Sampling in combination with a Mersenne twister random number generator and a fixed seed value of 1.

3. RESULTS AND DISCUSSION

3.1. Formaldehyde Concentration in Fresh Foods of Plant Origin (FFPO)

Formaldehyde was detected in most fresh food of plant origin (FFPO) samples, with concentrations ranging from below the limit of detection (<LOD) to 155.00 mg/kg. In general, the observed values remained within the ranges previously reported in the literature (Table 1). However, when compared with narrower literature ranges, pear, ajwa dates, banana, fuji apple, cabbage, wood ear mushroom, and fresh shiitake mushroom showed higher maximum concentrations. This indicates that quantified concentrations do not directly correlate to the misuse of formalin, as all detected levels relatively align with documented endogenous baselines.

The selection of these specific samples was based on high national consumption, potential for natural formaldehyde formation, representativeness across diverse food groups, and relevance to public exposure, ensuring the analysis targets key risk contributors. Variability among samples may be attributed to commodity characteristics as well as storage conditions, including temperature, storage duration, and maturity level (Nowshad *et al*., 2018). Meanwhile, values below LOD or limit of quantification (LOQ) were substituted with LOD/2 or LOQ/2 as an estimation approach in data analysis, particularly when the proportion of non-detect data was relatively low (EFSA, 2010).

Formaldehyde concentrations in fruits ranged from below the limit of detection (<LOD) to 5.21 mg/kg, with the highest level observed in Barangan bananas. The endogenous formation of formaldehyde in fruits may occur naturally during ripening and is associated with metabolic processes as well as methanol oxidation derived from pectin components (Nowshad *et al*., 2018; Sun *et al*., 2025). A unique statistical outcome of this approach is observed in green tomatoes, where the minimum, maximum, and mean concentrations are reported as <LOD, <LOD, and 0.043 mg/kg, respectively. Since 100% of the samples for this commodity fell below the detection threshold, the calculated mean was entirely driven by the substituted value of LOD/2 (0.0858 mg/kg/2 ≈ 0.043 mg/kg), consequently yielding a standard deviation of zero. Meanwhile, vegetables generally showed lower concentrations, with most mean values below 0.3 mg/kg, except for the maximum value in cabbage (2.07 mg/kg). This may be related to the lower postharvest metabolic activity of vegetables and the ability of plants to degrade formaldehyde through enzymatic detoxification mechanisms involving formaldehyde dehydrogenase in plant tissues (He *et al*., 2020).

The mushroom group exhibited species-specific variations in formaldehyde levels. Shiitake mushroom (*Lentinus edodes*), both in fresh and dried forms, showed the highest concentration compared to wood ear and enoki mushrooms. The elevated levels in shiitake are naturally occurring and linked to enzymatic processes involving the degradation of lentinic acid. This reaction pathway, catalyzed by γ glutamyl transpeptidase and lyase enzymes, simultaneously generates formaldehyde and volatile compounds such as lenthionine (Li *et al*., 2023). The difference in formaldehyde levels between dried and fresh shiitake mushrooms is primarily attributed to the reduction of moisture content and the consequent concentration of soluble compounds (Chaipoot *et al.*, 2023), as well as increased enzymatic activity of GGT and C-S lyase under drying temperatures above 45 °C (Xu *et al.*, 2019).

To enable a proportional comparison in the exposure assessment, dried samples were converted to a fresh-weight basis. This normalization was performed using a dry matter fraction conversion approach, assuming moisture contents of 13% (w/w) for dried shiitake (CXS 39 1981) and 90% (w/w) for fresh samples (Duan *et al*., 2025). Based on this conversion, the measured concentration of 153.05 mg/kg in dried shiitake corresponds to approximately 17.6 mg/kg on a fresh weight basis, enabling a more representative exposure evaluation aligned with actual consumption patterns. Notably, the unadjusted concentration of 153.05 mg/kg in dried samples closely approaches lower bound of documented endogenous range reported by Huynh *et al.* (2024), which spans from 169.1 to 402.5 mg/kg for dried shiitake mushrooms. This confirms that the observed level reflects natural biogenic occurrence rather than exogenous adulteration.

Table 1. Formaldehyde content in FFPO

No.	Food Commodities	Formaldehyde Concentration (mg/kg)				
		Minimum	Maximum	Mean ± SD	Literature 1[a]	Literature 2[b]
1.	Green grape	< LOD*	1.78	0.370 ± 0.697	0.22 – 0.80	22.40
2.	Red grape	< LOD*	0.43	0.189 ± 0.164	0.22 – 0.80	22.40
3.	Black grape	< LOD*	1.11	0.359 ± 0.403	0.22 – 0.80	22.40
4.	Green pear	1.46	2.37	1.988 ± 0.356	0.04 – 1.71	38.70 – 60.00
5.	Yellow pear	0.69	2.31	1.288 ± 0.588	0.04 – 1.71	38.70 – 60.00
6.	Honey pear (singo)	0.88	2.41	1.575 ± 0.584	0.04 – 1.71	38.70 – 60.00
7.	Sukkari dates	0.46	1.59	0.865 ± 0.486	0.04 – 1.71	-
8.	Ajwa dates	1.46	3.05	2.198 ± 0.598	0.04 – 1.71	-
9.	Lady finger banana (mas)	< LOD*	2.84	0.734 ± 1.062	0.15 – 0.55	16.30
10.	Cavendish banana (ambon)	< LOD*	2.39	0.495 ± 0.940	0.15 – 0.55	16.30
11.	Barangan banana	< LOD*	5.21	1.075 ± 2.045	0.15 – 0.55	16.30
12.	Malang apple	< LOD*	0.39	0.247 ± 0.135	0.26 – 0.75	6.30 – 22.30
13.	Fuji apple	< LOD*	2.17	0.609 ± 0.789	0.26 – 0.75	6.30 – 22.30
14.	Red apple	0.11	0.73	0.436 ± 0.221	0.26 – 0.75	6.30 – 22.30
15.	Green tomato	< LOD*	< LOD*	0.043 ± 0.000	0.27 – 0.47	5.70 – 13.30
16.	Red tomato	< LOD*	0.14	0.059 ± 0.040	0.27 – 0.47	5.70 – 13.30
17.	Cabbage	0.24	2.07	1.037 ± 0.612	0.30 – 1.06	5.30
18.	Local carrot	< LOD*	0.72	0.235 ± 0.261	0.09 – 0.49	6.70 – 10.00
19.	Large potato	< LOD*	0.17	0.064 ± 0.052	0.20 – 0.49	19.50
20.	Cauliflower	< LOD*	0.55	0.127 ± 0.207	0.06 – 0.46	26.90
21.	Fresh shiitake mushroom	11.88	50.81	32.387 ± 19.548	3.70 – 25.64	6.00 – 54.40
22.	Dried shiitake mushroom	151.17	155.00	153.053 ± 1.916	3.70 – 25.64	100 – 406
23.	Wood ear mushroom	0.20	2.40	0.905 ± 0.791	0.06 – 1.06	-
24.	Enoki mushroom	< LOD*	< LOQ**	0.054 ± 0.026	0.36 – 0.66	-

Notes: *LOD: 0.0858 mg/kg; **LOQ: 0.2145 mg/kg. Data represent 6–7 distinct sampling points per commodity. Minimum and maximum reflect absolute range across individual points. Mean ± SD indicates average and standard deviation, incorporating substituted values for non-detectable or non-quantifiable data. Source: a. Lee *et al*. (2024); b. Centre for Food Safety (2009)

3.1.1. Formaldehyde Levels by Province of Origin

While median formaldehyde levels in this study remained low (<2 mg/kg) across four provinces, actual background concentrations can vary significantly across food commodities due to matrix-specific pathways of endogenous generation (Li *et al*., 2023). Banten exhibited a relatively higher median and narrow interquartile range (IQR), whereas DKI Jakarta and West Java showed wider variability, characterized by larger IQRs and multiple outliers (Figure 1).

Kruskal–Wallis test demonstrated a statistically significant overall difference in formaldehyde concentrations among provinces (p = 0.0457). However, subsequent Dunn's post-hoc analysis did not identify statistically significant differences between any individual province pairs after adjustment for multiple comparisons (all adjusted p > 0.05). This discrepancy stems from two statistical limitations. First, the stringent p-value adjustments in Dunn's post-hoc test

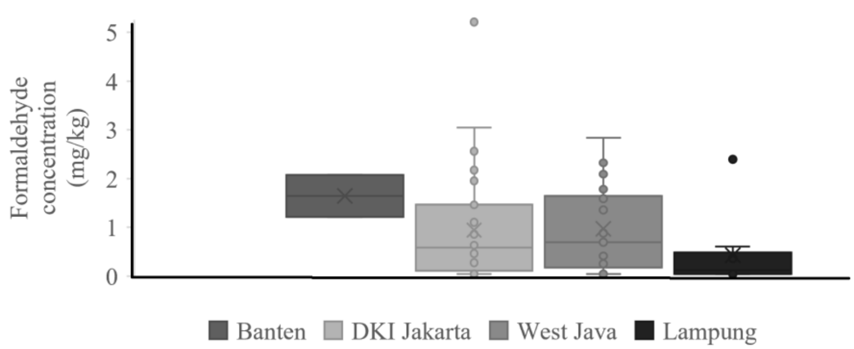

Figure 1. Formaldehyde levels by province of origin

drastically reduced statistical power compared to the global Kruskal–Wallis test. Second, high variability, unequal dispersion (particularly in DKI Jakarta and West Java), and extreme outliers increased rank variance, obscuring localized provincial differences.

3.1.2. Formaldehyde Levels by Supply Chain Point

Median formaldehyde concentrations across all supply chain nodes remained low (<2 mg/kg), although variations in levels can still be influenced by external factors such as storage conditions, temperature, storage duration, and maturity level (Nowshad *et al*., 2018). Traditional markets and importers exhibited the highest variability, whereas farmers/farmer groups and modern retail showed lower medians and narrower distributions (Figure 2). The Kruskal–Wallis test indicated a significant difference in formaldehyde levels based on the supply chain node (p = 0.0098). However, subsequent Dunn's post-hoc test revealed that this significant difference existed solely between samples from importers and farmers/farmer groups (p = 0.0052), while no other pairwise comparisons showed significant differences.

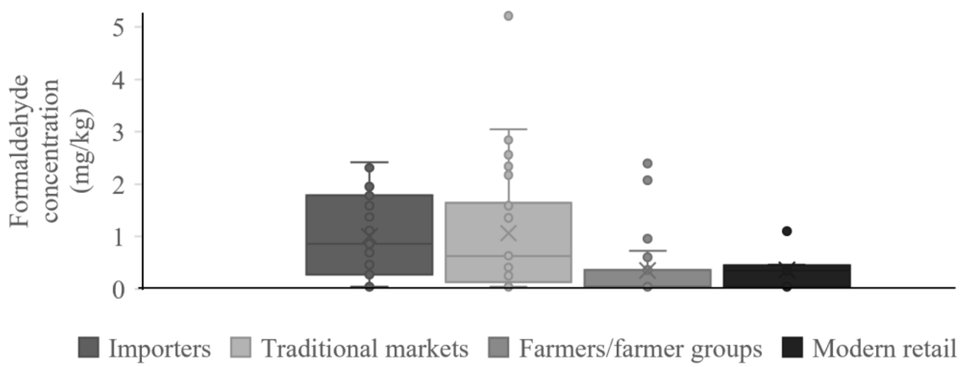

Figure 2. Formaldehyde levels by supply chain point

3.2. Exposure Assessment using Deterministic Approach

Formaldehyde exposure for the Indonesian population was estimated by integrating FFPO concentration data with the consumption data processed from the 2024 SUSENAS survey. This approach identifies the relative contribution of each food group under actual dietary conditions. As detailed in Table 2, the consumption data were derived directly from national food consumption figures per SUSENAS category, while the formaldehyde concentrations represent the compiled values obtained from laboratory testing of specific representative commodities within each group.

Table 2. FFPO commodities with the highest contribution to EDI

SUSENAS category	Food commodity (lab testing)	Formaldehyde (mg/kg)	Consumption (g/day)	EDI*	Share (%)
Apple	Malang apple, fuji apple, red apple	0.4303	2.0203	0.0000145	1.20
Ambon banana	Cavendish banana (ambon)	0.4953	5.2940	0.0000437	3.61
Other bananas	Lady finger banana (mas), barangan banana	0.7680	12.3640	0.0001583	13.08
Cabbage	Cabbage	1.0367	4.0584	0.0000701	5.79
Carrot	Local carrot	0.2348	3.3598	0.0000131	1.09
Potato	Large potato	0.0641	6.9076	0.0000074	0.61
Tomato	Green tomato, red tomato	0.3796	5.7802	0.0000366	3.02
Other vegetables	Cauliflower, shiitake mushroom, wood ear mushroom, enoki mushroom	6.5189	6.1718	0.0006706	55.41
Other fruits	Green grape, red grape, black grape, green pear, yellow pear, honey pear (singo), sukkari dates, ajwa dates	1.1042	10.6422	0.0001959	16.19

Note: Data represents deterministic point estimates. Consumption values were processed from 2024 SUSENAS database, and formaldehyde concentrations were compiled from laboratory testing. The unit of EDI is (mg·(kg bw)$^{-1}$·(day)$^{-1}$

Results show a total Estimated Daily Intake (EDI) of 0.0012 mg·(kg bw)$^{-1}$·(day)$^{-1}$ for an adult with an average body weight of 60 kg. This value is significantly lower than the tolerable limit of 0.15 mg·(kg bw)$^{-1}$·(day)$^{-1}$ (EFSA-AFC Panel, 2006). Table 2 highlights that the other vegetables group was the primary contributor, representing 55.41% of the total intake, followed by other fruits at 16.19% and other bananas at 13.08%. These findings confirm that formaldehyde exposure is determined not only by consumption volume but also by its concentration in food, meaning that commodities with lower consumption rates can still contribute substantially to the total exposure (EFSA, 2014; Hoque *et al*., 2018).

While national exposure remains low and well below safe toxicological limits, this deterministic assessment only represents the mean consumption of general population. Exposure may vary among population groups with different consumption characteristics and could be further analyzed using a probabilistic approach (Putri *et al*., 2018). Furthermore, since exposure levels under the conservative scenario remain within safe limits, actual exposure following processing or metabolism is expected to be even lower (Sun *et al*., 2025).

Exposure analysis at the regional level based on the 2024 SUSENAS regional consumption showed spatial variations in exposure driven by the diverse dietary characteristics in Indonesia (Figure 3). Estimated exposure ranged from 0.000640 to 0.008227 mg·(kg bw)$^{-1}$·(day)$^{-1}$, with the lowest exposure (0.000640 mg·(kg bw)$^{-1}$·(day)$^{-1}$ found in Riau Province, 0.000709 mg·(kg bw)$^{-1}$·(day)$^{-1}$ in Gorontalo, and 0.000709 mg·(kg bw)$^{-1}$·(day)$^{-1}$ in Aceh. Meanwhile, the highest exposure was observed in Highland Papua Province (0.008227 mg·(kg bw)$^{-1}$·(day)$^{-1}$), Central Papua (0.003274 mg·(kg bw)$^{-1}$·(day)$^{-1}$), and West Nusa Tenggara (0.002736 mg·(kg bw)$^{-1}$·(day)$^{-1}$). The exposure value across all provinces remains well below the TDI, thereby indicating no significant health risk for general consumption.

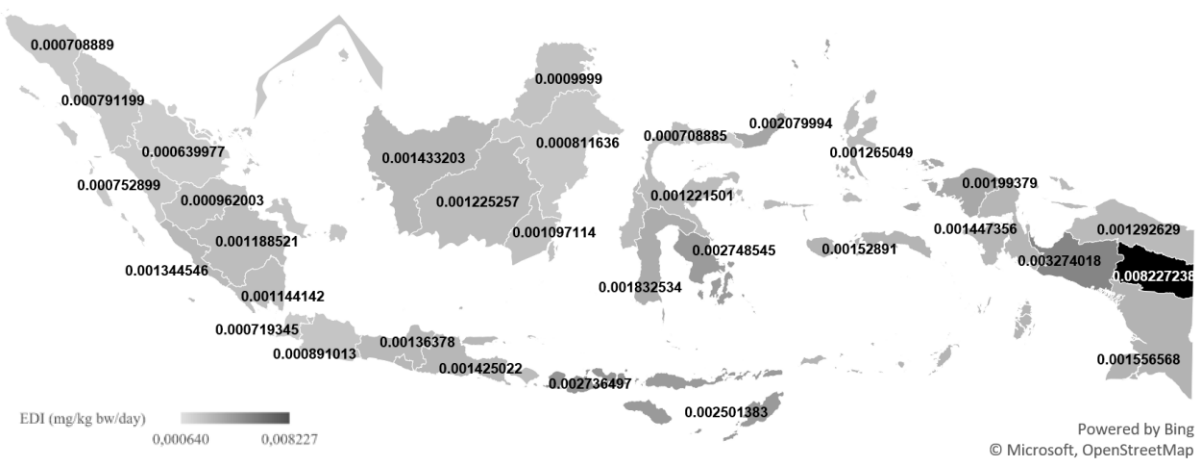

Figure 3. Distribution of estimated daily intake across Indonesian provinces

3.3. Risk Characterization using Deterministic Approach

At the national level, with an EDI of 0.0012 mg·(kg bw)$^{-1}$·(day)$^{-1}$ and a TDI of 0.15 mg·(kg bw)$^{-1}$·(day)$^{-1}$, an HQ of 0.0081 was obtained. At the regional level, HQ values ranged from 0.0043 to 0.0548. This variation indicates differences in consumption patterns across regions. Since all calculated HQ values remain significantly below safety threshold (HQ < 1), formaldehyde exposure from FFPO does not pose a significant non-carcinogenic health risk to Indonesian population at either national or regional scale (WHO, 2021). Consequently, while formaldehyde is present in food, intake remains within levels considered tolerable without causing adverse effects. These results align with findings that dietary exposure to natural formaldehyde stays below TDI value and generally does not pose a significant health risk (Lee *et al*., 2024).

For carcinogenic risk evaluation, this study applied linear extrapolation using an oral slope factor (SF) of 0.021 (mg/kg bw/day)$^{-1}$. At the national level, a Cancer Risk (CR) of 2.54×10^{-5} was obtained, whereas regional estimates ranged from 1.34×10^{-5} in Riau to 1.73×10^{-4} in Highland Papua. These values lie within to slightly exceeding the upper boundary of the generally acceptable risk range of 10^{-6} and 10^{-4} (U.S. EPA, 2023). Nevertheless, these outcomes should be interpreted with caution and tend to be conservative because the calculations do not account for the potential reduction of formaldehyde during food processing, as well as its rapid physiological turnover, where endogenous and absorbed formaldehyde is efficiently oxidized to formate by ADH5 and ALDH2 enzymes and subsequently excreted or utilized in purine synthesis (Sun *et al.*, 2025; Pietzke *et al.*, 2019). Therefore, the CR values in this study reflect a precautionary approach for screening level purposes rather than an actual risk estimation under real consumption conditions.

3.4. Exposure Assessment using Probabilistic Approach

Formaldehyde exposure was estimated using the 2014 SKMI data categorized by age groups to account for population variability and enable consumption and risk analysis across various subpopulations through probabilistic assessment (Stefano *et al.*, 2025). Distribution fitting results showed that body weight and consumption across all groups tended to follow a lognormal distribution. This aligns with standard practices in probabilistic modeling, where the lognormal distribution is commonly assumed to represent body weight (Dominguez *et al.,* 2024) and food consumption rates (Paoli *et al.,* 2025), as illustrated in probabilistic dietary exposure models. To avoid unrealistic negative values, the distribution was truncated at a minimum value of 0.043 mg/kg, which represents half of the LOD.

Formaldehyde exposure at the national level showed that both the mean values and the 95th percentiles across all age groups remained below the TDI, with an overall average of 0.00249±0.00523 mg·(kg bw)$^{-1}$·(day)$^{-1}$. This outcome is consistent with earlier risk assessment studies indicating that dietary exposure to formaldehyde contributes less than 1% relative to endogenous levels and is thus considered negligible (Rietjens *et al.*, 2022). Toddlers aged 6 to 59 months exhibited the highest mean exposure (0.00809±0.01356 mg·(kg bw)$^{-1}$·(day)$^{-1}$), whereas adults aged 19 to 55 years showed the lowest exposure (Table 3). Younger age groups tend to exhibit higher EDI values compared to older age groups, a trend driven by their greater ratio of food consumption to body weight (Milićević *et al*., 2021).

Table 3. Formaldehyde exposure from FFPO consumption across different age groups

Age group	EDI (mg/kg bw/day)					
	Mean ± SD	P-5	P-25	P-50	P-75	P-95
6 – 59 months	0.00809 ± 0.01356	0.000250	0.001410	0.003790	0.009240	0.029370
5 – 12 years	0.00420 ± 0.00720	0.000131	0.000710	0.001940	0.004720	0.015470
13 – 18 years	0.00247 ± 0.00410	0.000079	0.000438	0.001180	0.002850	0.009040
19 – 55 years	0.00193 ± 0.00308	0.000068	0.000362	0.000944	0.002253	0.006899
> 55 years	0.00230 ± 0.00406	0.000074	0.000400	0.001070	0.002610	0.008390
All ages	0.00249 ± 0.00523	0.000084	0.000423	0.001110	0.002700	0.009130

Note: Values were simulated using Monte Carlo software (50,000 iterations). Consumption inputs were derived from 2014 SKMI database, and formaldehyde levels inputs were obtained from laboratory testing.

Across all age groups, the mean consumption of the general population resulted in an exposure value of 0.00249 mg·(kg bw)$^{-1}$·(day)$^{-1}$, which is equivalent to 1.66% of the TDI. This value is higher than deterministic estimate (0.0012 mg·(kg bw)$^{-1}$·(day)$^{-1}$) due to methodological differences. While the deterministic approach uses a fixed single-point average, the probabilistic model captures the full data spectrum via Monte Carlo simulation. Given that national consumption data follow right-skewed lognormal distribution, integration of high-end consumers mathematically pulls the probabilistic mean upward, thereby offering a more realistic representation of population exposure.

This outcome is consistent with the study reported by Lee *et al*. (2024), where formaldehyde exposure from the consumption of agricultural products in the South Korean population was estimated at 127.5 µg/day or 0.002125 mg·(kg bw)$^{-1}$·(day)$^{-1}$, equivalent to 1.4% of the TDI. Similarly, a study on fish consumption in Bangladesh reported an average formaldehyde exposure of 7.73×10^{-3} mg·(kg bw)$^{-1}$·(day)$^{-1}$, or equivalent to 3.9% of the toxicological reference value of 0.2 mg·(kg bw)$^{-1}$·(day)$^{-1}$, which also remains below the acceptable daily intake value (Hoque *et al*., 2016).

3.5. Risk Characterization using Probabilistic Approach

The results showed that both the mean and 95th percentile HQ values across all age groups remained below 1 (Table 4), with an overall average of 0.01660±0.03490. This confirms that formaldehyde exposure from the consumption of FFPO does not pose a significant non-carcinogenic health risk (WHO, 2021). Even under the high exposure scenario (P-95), the HQ value was 0.06090, which also does not exceed the safe threshold. Toddlers aged 6 to 59 months exhibited the highest mean HQ (0.05390±0.09040), reflecting a relatively higher exposure per unit of body weight.

Table 4. Non-carcinogenic risk levels by age group

Age group	*Hazard quotient*					
	Mean ± SD	**P-5**	**P-25**	**P-50**	**P-75**	**P-95**
6 – 59 months	0.05390±0.09040	0.00167	0.00939	0.02530	0.06160	0.19580
5 – 12 years	0.02800±0.04800	0.00088	0.00473	0.01290	0.03150	0.10320
13 – 18 years	0.01649±0.02735	0.00053	0.00292	0.00786	0.01900	0.06027
19 – 55 years	0.01284±0.02055	0.00046	0.00241	0.00629	0.01502	0.04600
> 55 years	0.01536±0.02707	0.00049	0.00267	0.00716	0.01738	0.05592
All ages	0.01660±0.03490	0.00056	0.00282	0.00741	0.01800	0.06090

Note: Risk values were calculated probabilistically via Monte Carlo simulation based on exposure data from 2014 SKMI database and laboratory testing. HQ values are based on the TDI 0.15 mg/kg bw/day.

The U.S. EPA (2023) defines the generally acceptable cancer risk range as 1×10^{-6} to 1×10^{-4}. Based on Table 5, the mean CR values across all age groups generally remain within this range, with an overall average value of 5.24×10^{-5}. However, in the age group of 6 to 59 months, the value slightly exceeds the upper boundary, reaching 1.70×10^{-4}. This pattern indicates that toddlers tend to face a relatively higher risk compared to adults due to their higher ratio of consumption rate to body weight (Milićević *et al*., 2021). Nevertheless, estimates in this study are based on conservative assumptions of maximum exposure without accounting for formaldehyde reduction during food processing and metabolism within the body (Sun *et al*., 2025; EFSA, 2014), meaning actual risk is expected to be lower.

Table 5. Carcinogenic risk levels by age group

Age group	*Cancer risk*					
	Mean ± SD	**P-5**	**P-25**	**P-50**	**P-75**	**P-95**
6 – 59 months	$1.70\times10^{-4} \pm 2.85\times10^{-4}$	5.26×10^{-6}	2.96×10^{-5}	7.96×10^{-5}	1.94×10^{-4}	6.17×10^{-4}
5 – 12 years	$8.82\times10^{-5} \pm 1.51\times10^{-4}$	2.76×10^{-6}	1.49×10^{-5}	4.07×10^{-5}	9.92×10^{-5}	3.25×10^{-4}
13 – 18 years	$5.20\times10^{-5} \pm 8.62\times10^{-5}$	1.66×10^{-6}	9.21×10^{-6}	2.48×10^{-5}	5.99×10^{-5}	1.90×10^{-4}
19 – 55 years	$4.04\times10^{-5} \pm 6.48\times10^{-5}$	1.43×10^{-6}	7.60×10^{-6}	1.98×10^{-5}	4.73×10^{-5}	1.45×10^{-4}
> 55 years	$4.84\times10^{-5} \pm 8.53\times10^{-5}$	1.55×10^{-6}	8.40×10^{-6}	2.26×10^{-5}	5.48×10^{-5}	1.76×10^{-4}
All ages	$5.24\times10^{-5} \pm 1.10\times10^{-4}$	1.76×10^{-6}	8.88×10^{-6}	2.33×10^{-5}	5.68×10^{-5}	1.92×10^{-4}

Note: Risk values were calculated probabilistically via Monte Carlo simulation based on exposure data from 2014 SKMI and laboratory testing. CR values based on oral slope factor of 0.021 $(mg/kg\ bw/day)^{-1}$

4. CONCLUSIONS

This study confirms the presence of formaldehyde in FFPO in Indonesia, with concentrations ranging from <LOD to 155.00 mg/kg. The national deterministic exposure was estimated at 0.0012 $mg\cdot(kg\ bw)^{-1}\cdot(day)^{-1}$, whereas regional exposure levels across 38 provinces ranged from 0.000640 to 0.008227 $mg\cdot(kg\ bw)^{-1}\cdot(day)^{-1}$. Furthermore, the probabilistic assessment yielded a mean exposure of 0.00249±0.00523 $mg\cdot(kg\ bw)^{-1}\cdot(day)^{-1}$ for the general population, which remains substantially lower than the oral TDI of 0.15 mg/kg bw/day. Non-carcinogenic risk characterization across all age groups and regions consistently resulted in HQ values below 1, specifically 0.0081 from the deterministic approach and 0.01660±0.03490 from probabilistic approach, indicating no significant non-carcinogenic health risk. Regarding cancer risk, while CR estimates at both national and regional levels generally remain within the acceptable risk range, specific regions and age groups slightly exceed upper boundary. Consequently, these outcomes require cautious interpretation under conservative screening-level assumptions. Nevertheless, because these estimates are based on a maximum exposure scenario that does not account for formaldehyde reduction during food processing or its rapid physiological metabolism, the actual risk under real consumption conditions is expected to be lower.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION

During the preparation of this work, the authors used Microsoft Copilot and Google Gemini to improve the language, readability, and structural flow of the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published work.

AUTHOR CONTRIBUTIONS

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
MAR	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	
FK	✓	✓		✓				✓		✓		✓		
DCA	✓	✓	✓	✓				✓		✓		✓		
YE	✓	✓			✓	✓	✓	✓				✓	✓	✓

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	P: Project Administration
M: Methodology	I: Investigation	E: Writing - Review & Editing	Fu: Funding Acquisition
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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