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Exposure to Methamphetamine in Contaminated Residential Properties: A Cross-Sectional Analysis of Airborne Exposure

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ABSTRACT

Studies of third-hand exposure to methamphetamine from contaminated properties have focused on dermal and oral exposure but have mostly excluded inhalation. Recent literature highlights the need to consider this previously omitted pathway. In this study, we monitored airborne concentrations in properties most likely contaminated via recreational smoking of methamphetamine. The homogeneity of airborne methamphetamine was assessed, along with the correlation between its levels and those measured on different surfaces or in the subsurface material. Airborne methamphetamine concentrations were also compared 'before' and 'after' remediation. Our results suggested airborne methamphetamine contributes as an exposure route for properties contaminated by this drug, although this may only be significant in certain situations. The level of airborne methamphetamine was relatively homogenous among rooms of the same property, and there were correlations between air sampling with wipe ($R^2 = 0.76$) and bulk sampling ($R^2 = 0.94$), but mainly driven by higher contamination levels. This indicates that air sampling could be used as an additional tool to identify the presence of high methamphetamine contamination. The presence of low levels of airborne methamphetamine after remediation of impacted surfaces is additional evidence that airborne sampling is a sensitive method to detect methamphetamine contamination in properties. Further research is needed to establish the relationship between levels of methamphetamine contamination and specific health risks, which can then be used to determine related policy responses and, if necessary, establish evidence-based remediation targets.

1 | Introduction

Methamphetamine is a powerful illegal psychostimulant which is manufactured and used in a number of global regions, including East and Southeast Asia, North and South America, and Oceania, predominately Australia and New Zealand [1, 2]. The manufacture and smoking of methamphetamine can contaminate properties, and methamphetamine manufacture is responsible for higher residue levels and accompanied by toxic chemicals that are absent when methamphetamine is only smoked [3–5]. Personal exposure to methamphetamine in properties contaminated by methamphetamine residues from manufacture or smoking has the potential to be a health risk, which includes neurological, developmental and reproductive effects [6].

Scientific understanding of health risks from exposure to methamphetamine legacy contamination remains surprisingly limited, particularly at lower levels associated with recreational methamphetamine use through smoking [3–8]. To compensate for the absence of scientific evidence, some jurisdictions

have followed strong precautionary approaches [4, 9–15] and adopted conservative safety factors in the derivation of methamphetamine contamination thresholds to help address this uncertainty. In New Zealand and the United States, these strict limits led to significant unintended negative consequences, including tenancy terminations, withdrawal of properties from public housing stock and award of financial reparations to landlords from tenants, with many cases involving vulnerable tenants [5, 16, 17]. In response to public and council concerns [18, 19], a NZ government review in 2018 increased the remediation threshold level from 0.5 μg/100 cm^2 established in 2010 to 15 μg/100 cm^2 (a 30-fold increase) [5, 9].

Currently in Australia, the risk assessment for methamphetamine exposure is based on its contamination levels compared against the national health investigation and clean-up guideline (health investigation level [HIL]) of 0.5 μg methamphetamine per 100 cm^2 of household surface (the same as the 2010 New Zealand threshold level). Below this level, the property is deemed to be safe [20, 21], which makes it the target for remediation activities [22]. However, the derivation of the HIL only took account of ingestion and dermal exposures.

A decade ago, a study of a former clandestine methamphetamine laboratory suggested that inhalation of airborne methamphetamine could be a significant exposure route [23]. A more recent study supported this view, providing additional evidence of the significance of the inhalation route to methamphetamine exposure from two contaminated properties [24]. The authors further proposed that airborne methamphetamine can function as a mechanism for methamphetamine transfer and deposition throughout a property, hence exacerbating exposure from dermal and ingestion exposure routes [24]. Those findings led to a call for more research on airborne methamphetamine in contaminated buildings [25].

Most previous studies investigated airborne methamphetamine levels from suspected or known clandestine methamphetamine laboratories [23–25] which are generally reported to have significantly higher levels of surface contamination than from properties contaminated by smoking methamphetamine (denoted as smokehouse) [26]. Therefore, it is important to investigate inhalation as a potential source of risk in smokehouses. Additionally, measuring airborne methamphetamine in smokehouses may also reveal an advantage of air sampling. Surface sampling by using wipes over a 100 cm^2 area may not always be representative of contamination levels. Sampling technicians may sample areas farther away from the primary smoking source or from porous surfaces rather than impermeable material, both of which can affect the amount of recovered methamphetamine residue [21, 24]. Given the likely relatively homogenous dispersal of airborne contaminants, air sampling could partly overcome the limitations of wipe sampling if a relationship can be established between air and surface contamination. Air measurements may be less warranted for likely manufacture situations due to surface contamination being higher and more extensive and so easier to identify.

This study was aimed at investigating airborne methamphetamine concentrations in a range of properties suspected to be contaminated by methamphetamine smoking, their potential contribution to public health risk, and assessing the continued suitability of the HIL, which is based purely on dermal and ingestion exposure routes. The data collected was expected to reflect realistic third-hand exposure to methamphetamine smoking. Additionally, the correlation between air concentrations and those measured in surface and bulk materials was examined to assess how contamination persists over time.

2 | Materials and Methods

2.1 | Reagents, Chemicals and Apparatus

Methamphetamine D-9 and LiChrosolv Methanol gradient grade for liquid chromatography was purchased from Supelco (Bellefonte, United States). Formic acid was provided by Fisher Scientific (United States). Milli-Q system (Millipore, 0.22-μm filter, 18.2 M Ωcm^{-1}) produced the ultrapure water.

2.2 | Sampling at Contaminated Properties

Properties that were originally suspected to be contaminated via recreational smoking from 2022 to 2024 in Queensland and Northern New South Wales were chosen for this study. After sampling occurred, two properties were confirmed to be contaminated due to manufacture. All other properties were likely to be contaminated through smoking alone. In each property, up to four different types of sampling were conducted: air, surface wipe, carpet and bulk.

2.2.1 | Air Sampling

Air samples were conducted in 42 residential rooms and were collected consistently as possible as follows. Briefly, air samples were collected with OVS XAD-2 Tube (purchased from Sigma Aldrich) using AirChek Essential Model 220-3000 air sampling pumps (purchased from SKC). The OVS XAD-2 tubes incorporate a front quartz fibre filter to retain particulate-bound methamphetamine, followed by a downstream XAD-2 resin bed, where vapour-phase methamphetamine is adsorbed. This design is used for the active sampling of semivolatile organic compounds and provides an integrated measure of total airborne methamphetamine irrespective of phase. The air sampling frequency was set at a sampling rate of 2.5 L/min and operated for a minimum of 60 min. Before each sampling campaign, the flow rate was calibrated with an air flow calibrator. Detailed information of air sample duration is listed in Table S1.

For bathroom and kitchens, active air samplers were placed on benches and/or countertops. For bedrooms, samplers were placed on windowsills. If the above were not possible or if sampling occurred in the garage/hall area, air samplers were placed on the floor. Ventilation was achieved by opening at least one, but not all, windows in the house (e.g., through the sliding screen door and front screen door, if present). All room doors remained open for the entire duration. This is not a 'full' or 'active' ventilation. Temperature and humidity were not recorded during sampling time.

In selected properties, samples were taken before and after remediation to evaluate the effectiveness of the remediation.

2.2.2 | Surface Wipe Sampling

For surface wipe sampling, the procedure and analysis were based on the NIOSH 9111 method, which is the accepted approach in Australia. Alcohol wipes with 70% isopropyl alcohol and 30% water were used to sample a 100 cm^2 area (mostly walls or timber surfaces) using a standard disposable template. Rooms included kitchens, bedrooms, living rooms, bathrooms, laundries, and garages.

2.2.3 | Bulk Sampling

For bulk samples, a section of wall surface (around 200 cm^2) was removed from a property, and thin strips of paint layers were scratched and placed in a collection tube in the laboratory. All samples were stored in a 4°C fridge until extraction of methamphetamine commenced.

2.2.4 | Carpet Sampling

Carpet contamination samples were collected using a clean, detachable nylon sampling sock from Allied Filter Fabrics, installed in a high-power vacuum. The collection area was standardised (1×1 m), and either bedrooms or living spaces (closest to the kitchen) were targeted. The methamphetamine collected in this manner likely represented material most accessible for human exposure, although not the total amount of contamination.

Only a few rooms had carpeted floors in the same compartment where air sampling occurred ($n = 11$). There were 22 locations where both bulk and air sampling were conducted as permission to do bulk sampling was not granted in other properties. Similarly, wipe and air sampling were done in 25 locations as surface wipes were not permitted in other properties due to the risk of surface damage (alcohol wipes can strip the paint layer off surfaces). Only one room had wipe and bulk sampling done without air sampling.

2.3 | LC-MS Analysis

2.3.1 | Methamphetamine Extraction

Prior to methamphetamine extraction, all samples were spiked with an internal standard (0.5 ppm methamphetamine D-9) and desorption solution (MeOH:MQ adjusted to pH = 2, 1:1, v/v) in a 1:100 ratio (IS: desorption solution) (i.e. air samples: 50 μL of 0.5 ppm Meth D-9 was added to 5 mL of MeOH:MQ, pH = 2, and wipe samples: 200 μL of 0.5 ppm meth D-9 was added to 20 mL of MeOH:MQ, pH = 2). Samples were then sonicated for 20 min with an ultrasonic cleaner, Soniclean, and filtered through an RC filter and transferred to an LC vial for analysis.

2.3.2 | Instrumental Analysis

Methamphetamine levels in all sample extracts were quantified using liquid chromatography coupled with mass spectrometry. SCIEX 6500+ QTRAP and SCIE 5500 (Ontario, Canada) with an electrospray ionisation interface were used with a Shimadzu Nexera HPLC system (Kyoto, Japan). Hydro-RP polar C18 column (Phenomenex, $150 \times 3\,mm^2$, 3 μm) was used with a guard column AQ C18 (Phenomenex, $4 \times 2\,mm^2$) for separation. For preinjection, Kintex EVO C18 (Phenomenex, $30 \times 2.1\,mm^2$, 5 μm) was used, and injection volume was set to 7.5 μL (or 2 μL for highly concentrated samples). Mobile Phases A and B were aqueous (1 L Milli-Q water, 1-mL formic acid, 1-ml 5M ammonium formate) and organic phase (1 L methanol, 1-mL formic acid, 1-mL 5M ammonium formate), respectively. Mobile phase flow rate was set at 0.5 mL/min, and oven temperature was set at 40°C. All data were processed using Analyst 1.7.3 (SCIEX) and MultiQuant 3.0.3, respectively.

2.4 | Quality Assurance and Quality Control

No contamination was identified in the following blank samples: field blank and travel blank. Nonextracted solution standard samples (NESSs) returned accurate results (1 ppm ± 15%). For every 10 samples, a calibration point and solvent blank were also analysed to validate the LC-MS instrument performance. Data are shown in Table 1.

3 | Results and Discussion

3.1 | Airborne Methamphetamine Levels in Contaminated Properties

Figure 1 shows that airborne methamphetamine was detected in all residential rooms contaminated with methamphetamine activity. Six samples exceeded 15 $\mu g/m^3$. Of these, five were from rooms with a confirmed methamphetamine production history in the property, and one sample likely reflected early third-hand smoke exposure, having been collected after recent illegal squatting. Since a governmental report of Western Australia noted that in smokehouses without ongoing smoking activity are likely to have low airborne methamphetamine levels ($< 1\,\mu g/m^3$) [26], the majority of the air measurements below 1.0 $\mu g/m^3$ in the present study are most likely attributable to contamination from smoking alone. The sensitive analytical method used in this study allowed for the detection of low levels of methamphetamine in the air, which has been mostly neglected in previous studies. The presence of airborne methamphetamine means that exposure through inhalation could contribute to the total exposure as discussed in more detail below.

Methamphetamine volatilisation from contaminated surface is supposed to sustain the airborne concentrations. Li and Morrison [27] have described in detail the laboratory experiments on absorption and desorption of methamphetamine on gypsum drywall, providing evidence about the equilibrium of methamphetamine between the air and contaminated household materials, which could be influenced by temperature and relative humidity. Poppendick et al. [28] also studied the desorption characteristic of a methamphetamine surrogate, n-isopropyl benzylamine, to illustrate that methamphetamine can re-emit from contaminated building materials.

TABLE 1 | Validation for quantification of methamphetamine in air samples, wipes and carpets.

	Linearity[a]	Recovery (*mean* ± *SD* [%])[b,d]						Matrix effect (*mean* ± *SD* [%])[c,d]						Accuracy (%)[e] ± precision (%)[f]			LOD[g]	LOQ[h]
	(R^2)	pH2 MQ:MEOH		pH2 MQ		MQ:MEOH		pH2 MQ:MEOH		pH2 MQ		MQ:MEOH		pH2 MQ:MEOH	pH2 MQ	MQ:MEOH	(ng/L)	(ng/L)
		Ab	Rel	Ab	Rel	Ab	Rel	Ab	Rel	Ab	Rel	Ab	Rel					
XAD-2	0.994	78 ± 5	113 ± 1	32 ± 15	123 ± 40	31 ± 11	86 ± 38	39 ± 9	26 ± 6	38 ± 7	25 ± 4	37 ± 2	16 ± 4	100 ± 1	111 ± 36	88 ± 39	20	50
Wipe		117 ± 18	85 ± 6	103 ± 13	88 ± 5	70 ± 3	83 ± 7	53 ± 5	19 ± 12	49 ± 5	24 ± 9	44 ± 5	23 ± 5	98 ± 7	92 ± 5	93 ± 8		
Carpet		94 ± 11	78 ± 18	93 ± 7	89 ± 1	76 ± 4	96 ± 1	58 ± 4	− 19 ± 11	57 ± 7	− 23 ± 14	43 ± 4	− 20 ± 16	112 ± 26	133 ± 2	139 ± 2		

[a]Linearity R^2 = coefficient of determination of calibration curve.
[b]Recovery = (calculated concentration from spiking before pretreatment/calculated concentration from spiking after pretreatment) ∗ 100%.
[c]Matrix effect = (calculation concentration from spiking after pretreatment/calculated concentration from NESS) ∗ 100%
[d]'Absolute value' is based on the methamphetamine chromatographic peak area; 'relative value' is based on the calculated concentration corrected by methamphetamine D-9.
[e]Accuracy = calculated concentrations / spiked concentrations ∗ 100%.
[f]Precision was defined by the RSD of replicate spiked samples prepared at the same spike level.
[g]Limit of detection = minimal analyte concentration that can be reliably distinguished from background noise.
[h]Limit of quantification = minimal analyte concentration that can be quantified with acceptable accuracy and precision.

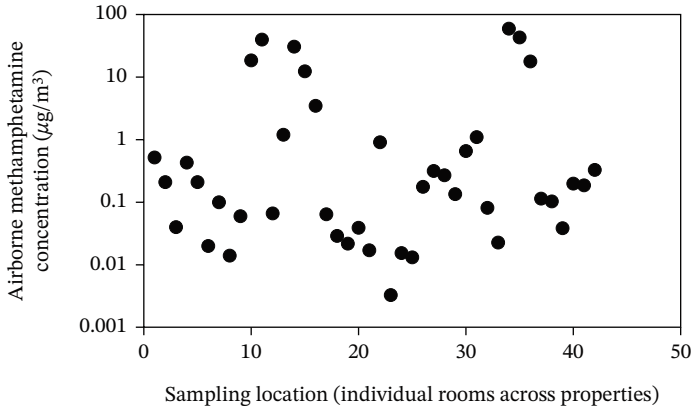

FIGURE 1 | Airborne methamphetamine levels across individual rooms in contaminated properties. Each point represents a single air sample from one room, from multiple properties included in this study.

It was hypothesised that airborne methamphetamine in the sampled properties was likely in equilibrium with methamphetamine present in contaminated surfaces and materials, as suggested by Wright et al. [24] and Yeh et al. [29]. This is likely to be a dynamic equilibrium due to air turnover in any building.

We observed that the airborne methamphetamine persisted in many properties for months although it is acknowledged that the persistence depends on the original contamination levels, as well as other factors such as ventilation, temperature, humidity and surface types. This is consistent with contamination observed in some properties years after the contaminating event, noting that, as has been found by other researchers, the bulk of room contamination is on surfaces and the likely main means of removal is slow release into adjacent air and subsequent dispersal and dilution into the environment [21, 30].

3.2 | Homogeneity of Airborne Methamphetamine in Contaminated Properties

Previous studies have shown considerable variation in levels of methamphetamine measured by wipes in different rooms of contaminated households [22, 31]. Russell et al. [31] reported greater variation, with the highest mean concentration of methamphetamine recorded in a garage, where manufacturing likely occurred. This suggests that properties with a history of manufacture exhibited wide spatial differences in contamination. Meanwhile, Gao et al. [22] reported similar mean surface concentrations in the bedrooms and kitchens, suggesting less variation and lower levels of contamination in homes used only for smoking, which appeared to be the main contamination source in their study. This pattern likely reflects the fact that, while smoking may occur in multiple rooms (producing more uniform residues), manufacturing tends to be confined to specific areas which contain utilities suitable for this process. However, it is worth noting that other rooms in a manufactured property would likely have been contaminated by those who smoke recreationally [22]. Hence, air concentrations of methamphetamine measured in different rooms of the same properties were compared to assess the homogeneity of the air mass in each property. A high level of homogeneity may help overcome the challenge of bias in sampling due to large variation in methamphetamine levels across different surfaces or rooms [22, 31]. This is because the mixing and distribution of air has the potential to integrate methamphetamine desorbing from all contaminated surfaces.

Figure 2 indicates that when there was no active ventilation, airborne methamphetamine concentrations remained similar regardless of whether sampling occurred in the same or a different room within the property. Under such conditions, air sampling may have an advantage over surface wipe sampling in this area, as airborne methamphetamine concentrations are expected to be relatively homogeneous throughout rooms with minimal air exchange.

This study observed slight variations in airborne methamphetamine between rooms. This variation may result from differences in the location of methamphetamine-related activities but also from the mobilisation of methamphetamine between rooms due to foot traffic [22]. However, as this study included only four paired samples from the same room ($n = 4$) and six from different rooms, future studies should increase the number of rooms and properties sampled.

It is worth noting that some sampling methodologies try to address the potential great variation in surface contamination by focussing on likely high yielding contaminated surfaces for detection purposes. In any case, the current results, alongside future research, may support the use of air sampling as a tool for contamination detection.

3.3 | Correlation Between Air Sampling and Other Sampling Methods

When used in conjunction with other sampling methods, air sampling can assist in better understanding the true extent of methamphetamine contamination. In this study, airborne methamphetamine values had a positive correlation with methamphetamine values from different methods of sampling, most notably with wipe ($R^2 = 0.76$) and bulk sampling ($R^2 = 0.94$). In settings where third-hand smoke of methamphetamine exposure occurs, airborne methamphetamine is likely sourced from desorption of surface residues. As a result, higher airborne methamphetamine levels are expected as their concentrations

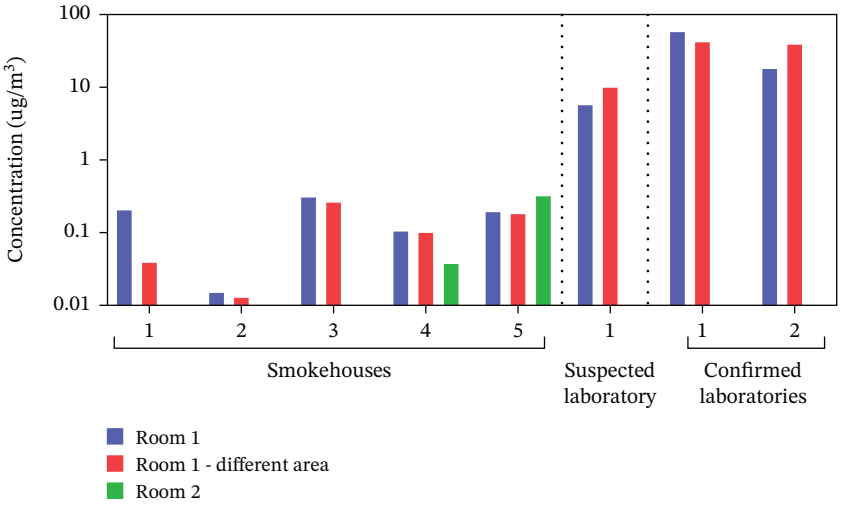

FIGURE 2 | Homogeneity of airborne methamphetamine in different locations in the same or a different room within a contaminated property.

increase on both the surface (wipe sampling) and within the plasterboard (bulk sampling). As anticipated, the concentration of methamphetamine in samples from bulk and wipe sampling also had a positive correlation.

A recent study investigated airborne methamphetamine concentrations in car cabins, a setting with a much smaller air volume to surface area ratio than in houses, and found that airborne methamphetamine concentrations (0.54–1.3 $\mu g/m^3$) were higher than those observed in this study, despite having similar surface concentrations (0.15–1.5 $\mu g/100\,cm^2$) [32]. This observation suggests that the relationship between airborne methamphetamine values and wipe results is largely affected by the volume of surrounding air to surface ratio. However, in this study, the air volume of each room was not measured. It is recommended for future studies that the air volume is recorded to assist interpretation.

While methamphetamine deposits on carpet also had a positive correlation with airborne methamphetamine (Figure 3), reliable correlations are difficult to ascertain due to the limited sample size. Similarly, it is not possible to establish any correlation between the mass of methamphetamine deposited on carpet and methamphetamine from wipe samples (Figure 3).

One atypical result was observed in which methamphetamine was not detected in the air sample, while the corresponding wipe sample had a surface concentration of 2.23 $\mu g/100\,cm^2$. Other wipe samples with lower methamphetamine concentrations had detectable corresponding methamphetamine concentrations in the air. Such atypical results were also reported in one previous study where no airborne methamphetamine was detected, but surface wipes found methamphetamine in heating, ventilating and air-conditioning systems in a former clandestine laboratory [25, 33].

3.4 | Relationship Between Exposure Route and Methamphetamine Risk

As indicated in Section 3.3, there is a good positive linear correlation between air levels of methamphetamine and its concentration on surfaces. This relationship can be used to calculate the contribution of both types of contamination to human exposure and risk.

Until recently, inhalation was not considered a possible exposure route of third-hand exposure to methamphetamine. Compared to surface contamination, the significance of inhalation has been subject to very limited investigation.

In a house believed to have been used for methamphetamine manufacture, Wright et al. [24] calculated that inhalation may account for 20% of total contamination dose in infants and 59% for adults. Consequently, the suitability of the HIL based purely on exposure to surface contamination was questioned.

The current study provides much more data in relation to methamphetamine contamination in air and on surfaces, mostly in smokehouse scenarios, and the relationship between them. This data along with information included in Parker and Howell [26] suggests that, for a given level of surface contamination, the corresponding levels of methamphetamine in air may be much lower than found in the single instance by Wright et al. [24], at least in the case of methamphetamine contamination from smoking the drug.

However, it is worth noting that the data in this study for each location consisted of a single surface and single air measurement. In contrast, Wright et al. [24] based their contamination levels on averages across several areas within a single house, although the method of averaging was not provided.

Since the contamination processes and corresponding levels are different for smoking and making methamphetamine and the focus of this research is smokehouses, it is useful to separate these sources out in respect to the air versus surface contamination relationship.

In Figure 4, this relationship is presented in respect to houses that were not known nor considered to be the result of manufacture, based on either knowledge of the property or the presence of low-level contamination consistent with being a smokehouse.

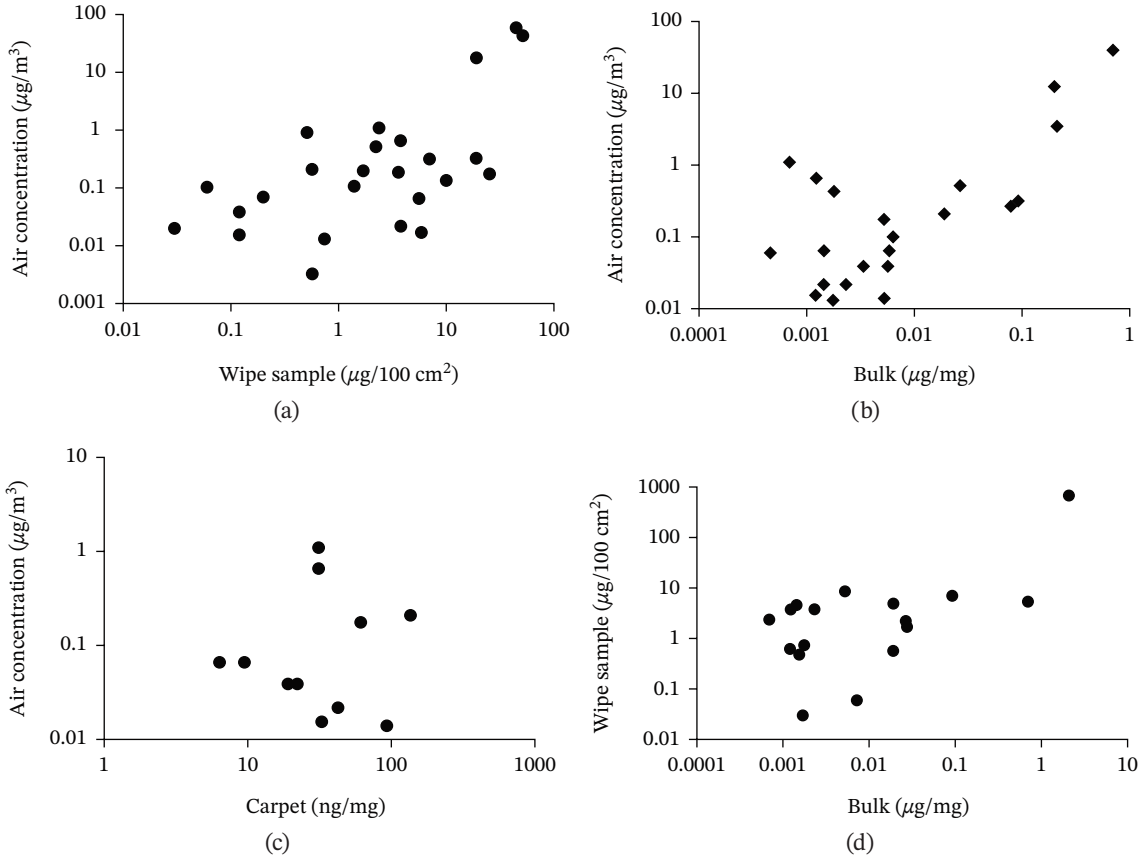

FIGURE 3 | Positive correlation between airborne methamphetamine concentrations and wipe sampling (a, $R^2 = 0.76$), bulk sampling (b, $R^2 = 0.94$), carpet sampling (c) and correlation between bulk and wipe sampling (d).

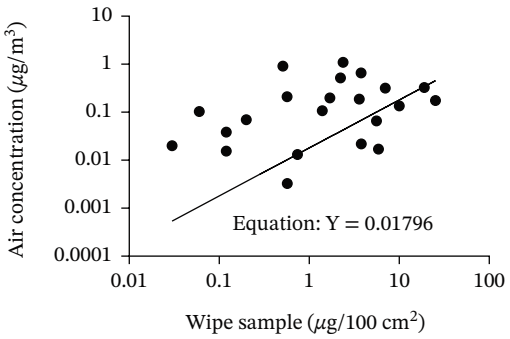

FIGURE 4 | Relationship between air and surface methamphetamine contamination for smokehouses. The low regression value highlights the weak association between air and surface contamination for smokehouses ($R^2 = 0.13$).

Although the R^2 is not high, the slope of the relationship (0.018) and the bulk of the contamination paired points indicate low levels of air contamination against those of surface contamination, at least compared with the findings of Wright et al. [24]. For these researchers, the relationship between air and surface contamination for the one property assessed, a laboratory, was 0.37 (4.7 $\mu g/m^3$ divided by 12.6 $\mu g/100\,cm^2$).

If calculated based on the procedure and assumptions adopted by Wright et al. [24] and using the current data from Figure 4, the risk posed by inhalation would likely represent far lower proportions of total exposure for both children and adults compared with surface exposure. This is in contrast to the comparatively higher proportions reported by Wright et al. [24].

However, when considering the air versus surface contamination levels for suspected or known laboratories, the inhalation route seems to become a much more substantial source of exposure and risk, as shown in Figure 5. Using the approach of Wright et al. [24], the relative contribution of inhalation would likely be higher for both children and adults in these settings.

Therefore, the risks associated with exposure through inhalation in smokehouses would not appear to significantly contribute to the total risk in contrast to manufacturing situations. In drawing such general conclusions, it is important to note that only single sampling locations were employed to generate the data in the present study.

It is difficult to know why the role of inhalation is different in magnitude between smokehouses and laboratories. It may be that much higher levels of surface contamination in the latter cause the methamphetamine to exist on the surface possibly as the more volatile base (rather than hydrochloride salt) as well as being absorbed, which may make it more prone to volatilisation.

In a study by Yeh et al. [29], the contribution of inhalation in this regard was found to be about 28% for adults based on the partitioning of methamphetamine between air and surfaces. Although calculations were not done for children, the greater

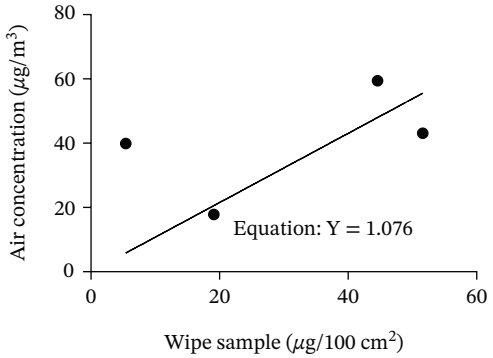

FIGURE 5 | Relationship between air and surface methamphetamine contamination for suspected laboratories. The linear regression ($R^2 = 0.80$) only visualises the general trend and should not be interpreted as a statistical relationship, due to the limited number of data points.

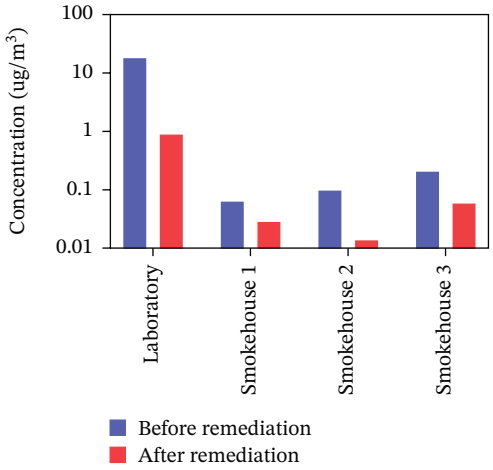

FIGURE 6 | Concentrations of airborne methamphetamine taken before and after remediation in the same rooms for contaminated properties.

likelihood of dermal and hand-to-mouth exposure suggests that inhalation plays a substantially smaller role in this group.

Based on the current study, even though the HIL was only derived for a surface exposure scenario, it still should be protective because at such low levels of contamination any contribution of methamphetamine inhalation should be marginal.

3.5 | Airborne Methamphetamine Concentrations Before and After Remediation

In this study, four houses were examined to compare airborne methamphetamine concentrations before and after a single round of remediation. Typical remediation of smokehouses involves cleaning wall surfaces (excluding ceilings) with an alkaline-based product, to reduce surface methamphetamine concentrations. According to the 'Guide for Testing and Remediation of Methylamphetamine and Illicit Drug Residues in Residential Properties' [30], ceilings and associated fixtures (i.e. fans and lights) are cleaned if ceilings are discoloured, the associated walls have high surface concentrations above $5\,\mu g/100\,cm^2$ or if manufacturing activity is suspected.

As expected, remediation reduced airborne methamphetamine levels, but were still detected, despite surface concentrations being remediated to below the $0.5\,\mu g/100\,cm^2$ guideline (except for one property remediated to $0.51\,\mu g/100\,cm^2$). In the smokehouse properties, one possible explanation is that airborne methamphetamine may originate from unremediated ceilings, as ceiling cleaning is not typically undertaken for smokehouses based on the above guide unless specific visual or contamination criteria are met. Gao et al. [22] similarly reported that ceilings are not adequately remediated, as they had the highest mean surface concentrations after remediation.

However, this study's dataset suggests that the unremediated ceilings are unlikely to contribute substantially to the detected methamphetamine. In suspected laboratory properties, where all surfaces are required to be remediated (including ceilings) below $0.5\,\mu g/100\,cm^2$, airborne methamphetamine was still detected postremediation (Figure 6). If unremediated ceilings were the primary source, postremediation airborne concentrations would be expected to be higher in smokehouse than those of laboratories; however, Figure 6 shows the opposite trend. This pattern suggests the involvement of an additional mechanism, where residues from deeper layers of the plasterboard migrate towards the surface and subsequently desorb into the air. This may also mean that even after remediation that surfaces may recontaminate from such a migration effect, conceivably to above the HIL. However, this requires future investigations to retest porous material after remediation, as recommended by Gao et al. [22].

Despite detectable airborne methamphetamine in remediated smokehouses where surface concentrations are below $0.5\,\mu g/100\,cm^2$, estimated exposure levels are still likely to remain below the reference dose for both children and adults, due to the apparent very small contribution of air to overall exposure. For the clandestine laboratory, postremediation concentrations could potentially exceed the child reference dose when combined with surface contamination ($0.5\,\mu g/100\,cm^2$ plus airborne exposure); however, the HIL remains still likely protective for adults due to the inclusion of conservative child-related safety factors.

4 | Limitations With the Study Design

We acknowledge the lack of supporting information such as temperature and humidity, and also, air volumes of the sampling locations were not recorded. Furthermore, air measurements were collected at only one point in time for each location, which only provides a 'snapshot' rather than a longitudinal profile, and the limited number of measurements restricts the strength of any conclusions that can be drawn. Future research focusing on smokehouses should prioritise standardising environmental conditions by monitoring and regulating humidity and temperature during long-term studies of concentration loss. It is also recommended that future studies collect multiple data points per location, as only a single measurement was taken in this study.

We also acknowledge that some of the results may have been affected due to issues with the sampling tubes. It was discovered in July 2023 that the tubing may have stretched from repeated

insertion and removal of XAD-2 tubes. After this date, the ends of the XAD-2 tubes were sealed with adhesive seals (Parafilm), replaced with new tubing or both. Yet for each sampling event, the apparatus was tested and adjusted before sampling via an external calibration. Although results obtained prior to this date may have underestimated airborne methamphetamine concentrations, this is considered unlikely. This is because air first passed through the XAD-2 or external calibrator and then the tubing and finally the air sampler, minimising the chance of loss.

5 | Conclusions

This is the first study to examine airborne methamphetamine data from real smokehouse scenarios, and the results support the previous hypothesis that inhalation exposure should be considered as part of the risk assessment. In the case of low-level contamination, including after effective remediation, inhalation exposure may be insignificant. However, exposure by inhalation may be a major contributor to total exposure risk for highly contaminated properties. In any case, more research is necessary to better determine these relationships. This study also revealed that airborne methamphetamine concentrations were relatively homogeneous. With future research, air sampling may serve as a potential tool for high contamination detection such as for clandestine laboratories.

Although beyond the scope of the current study, further research is needed to establish sufficient scientific evidence to determine the level at which indoor methamphetamine residue contamination causes adverse health effects and therefore requires remediation. This is critical to guide methamphetamine contamination policy at the central and local government level and to prevent predatory methamphetamine clean-up industry practices.

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Disclosure

MTK had no role in the study design, analysis, interpretation, or the decision to publish this manuscript.

Conflicts of Interest

The authors declare the following potential conflicts of interest: Joong C. Nam previously collaborated with MTK (Methamphetamine Testing Company), which provided sampling locations used in this study. However, the author is no longer employed or affiliated with MTK. All other authors declare no conflicts of interest related to this work.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. Table S1: Detailed information on air sampling duration, measured airborne methamphetamine concentrations and sampling locations for all samples included in this study.