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A participatory study of indoor environment quality in homes of children and youth in Kanehsatake First Nation

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Indoor air quality is an important determinant for the health of children and youth, but the conditions within Indigenous communities are understudied. We collaborated with Kanehsatake First Nation in Quebec, Canada, to address this gap using a community-based participatory research approach. Levels of key indoor air indicators, including particulate matter ($PM_{2.5}$), CO_2, and relative humidity, were measured in 31 randomly selected households between June 2021 and January 2022. Questionnaires were administered remotely to collect information on housing conditions. Excessive humidity was common, with 52% of households having a relative humidity above 55%. The mean $PM_{2.5}$ concentration was 21.0 (standard deviation 38.5) µg/m^3, with higher mean levels observed in smoking compared to non-smoking households (36.1 µg/m^3 and 10.1 µg/m^3, respectively). The mean CO_2 level in participating households was 881 ppm (standard deviation 256), with 30% ($n = 9$) of homes exceeding 1000 ppm. Flooding rates were high, with 55% of households reporting at least one past flood. One-third of houses were inadequately ventilated relative to occupancy, and over one-quarter reported needing major repairs. The results indicate the value and importance of characterizing the indoor environment in First Nations households and the viability of data collection through community-based participatory research in environmental health research.

Keywords Indoor air quality, Housing condition, First Nation, Remote data collection, Community engagement

In 2019, the Canadian Parliament passed the National Housing Strategy Act, which recognizes housing as a human right and commits the Federal government to further the progressive realization of the right to adequate housing[1]. However, many Indigenous people in Canada live in inadequate housing, particularly among those living in remote or northern communities[2]. Housing is an important social determinant; housing quality, affordability, location, appropriateness, and accessibility or in combination, can influence Indigenous peoples' health and well-being[3]. The indoor environment is also a critical determinant of physical and psychological health, especially in children and youth. Exposure to poor housing conditions and indoor air pollutants has been shown to increase the risk of developing adverse mental and respiratory health outcomes in younger populations[3–6].

Disparities in socioeconomic status (SES), housing adequacy, and access to interventions for improving indoor air quality (IAQ) are common moderators of the relationship between the indoor environment and health[7]. Moreover, poor indoor environments tend to impact vulnerable communities the most due to differential access to health preventive resources and a higher incidence of underlying health conditions[8]. In Canada, studies have shown that members of the general population spend approximately 89% of their time indoors[9]. Maintaining adequate housing conditions and IAQ is thus a critical public health consideration.

Canadian children and youth living in inadequate housing environments have been shown to exhibit higher exposure to air contaminants, decreased school performance, a higher risk of injury[10]and a higher

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risk of developing asthma[11]. Exposure to indoor air pollutants is a key concern when considering the indoor environment. Indeed, poor ventilation, overcrowding, moisture damage, and inadequate temperature regulation systems are associated with increased exposure to indoor air pollutants such as particulate matter (PM), volatile organic compounds (VOCs), and radon gas[12,13]. Exposure to these pollutants has been associated with various adverse respiratory outcomes, including pneumonia, asthma exacerbation, and acute respiratory tract infections[14,15].

Several studies have shown that PM and certain VOC levels in First Nations (FN) households are several times higher than those measured in the general population[16–18]. Furthermore, respiratory health is an ongoing concern in FN populations, with FN communities reporting elevated rates of chronic and acute respiratory disorders such as asthma and chronic obstructive pulmonary disease[19–24]. The trends in adverse respiratory health in Indigenous communities may be attributable to several underlying factors, including inadequate and unsuitable housing conditions. In 2021, a census report showed that 19.7%, or 206,845 people) of FN households needed major repairs, and the situation was even worse (37.4%) for FN people living on reserve[25], and similar findings have been reported in other studies[26,27]. In Canada, the correct terminology for these communities is “reserve,” unlike the United States, where the correct term is “reservation.”

Inadequate housing is known to exacerbate children’s negative physical and mental health outcomes[4], and respiratory health issues have been documented as housing-related health outcomes in FN children[5,6]. Even though poor housing conditions among First Nations have been reported, there is very limited information on the relationship between housing conditions and the indoor air quality parameters that are known risk factors for the health of children and youth.

The First Nations principles of ownership, control, access, and possession – more commonly known as OCAP® – assert that First Nations have control over data collection processes, and that they own and control how this information can be used. There are limited case studies for how research on housing conditions and health can be conducted in partnership between the community and researchers. This study aimed to characterize the indoor environment experienced by children and youth in the Kanehsatake First Nation, focusing on several important indoor air pollutants and household conditions. This research served as a pilot for a larger study entitled Food, Environment, Health, and Nutrition of First Nation Children and Youth (FEHNCY).

FEHNCY is a cross-nation study to characterize FN children and youth’s nutrition, environments, and health. It is a multi-year collaborative project between the Assembly of First Nations (AFN), FN community members, Indigenous Services Canada (ISC), Health Canada, and university research partners. Moreover, while community-based participatory research (CBPR) has been well-characterized and adapted for environmental health research, few studies have sought to apply CBPR methods in an entirely remote fashion. However, the COVID-19 pandemic presented major barriers to conducting in-person CBPR. As such, this is the first study to explore methods for adapting CBPR to remote contexts in environmental research.

Results

Participant recruitment began in June 2021 and ended in January 2022. Of the 510 homes in the community, 82.9% ($n = 427$) were not eligible for participation. Primary reasons for non-eligibility were the absence of a child between 3 and 19 years of age in the household and children not identifying as FN . Of the 83 remaining eligible homes, 57 were contacted, and 31 agreed to participate in the study.

IAQ data

Air Quality Monitors (AQ Eggs) were deployed in all 31 households between June 2021 and January 2022 for a mean exposure period of 6.26 days (minimum = 5, maximum = 11). VOC tubes were deployed in 14 households between June 2021 and January 2022 for a mean exposure period of 5.75 days (minimum = 5, maximum = 6). Radon detectors were deployed between June 2021 and June 2022 in all 31 households for a mean exposure period of 206 days (minimum = 108, maximum = 299).

$PM_{2.5}$, CO_2, relative humidity, and temperature

The summary of the levels of these four parameters detected by the AQ Eggs is described in Table 1. The mean $PM_{2.5}$ concentration across households was 21.0 µg/m^3 (± 38.5 µg/m^3). Mean $PM_{2.5}$ levels were more than three

	$PM_{2.5}$ in smoking households, $n = 13$ (µg/m^3)	$PM_{2.5}$ in non-smoking households, $n = 18$ (µg/m^3)	CO_2 (ppm)	Relative humidity (%)	Temperature (°C)
Mean ± SD	36.1 ± 54.0	10.1 ± 16.1	884 ± 256	52.4 ± 9.44	22.3 ± 1.90
Median (1st-3rd quartile)	17.4 (10.3–36.7)	6.1 (3.1– 8.7)	800 (681–1074)	55.2 (47.6–58.1)	22.5 (20.9–23.6)
Health Canada recommendations for indoor air	Keep level as low as possible	Keep level as low as possible	< 1,000 24-hour mean	< 55	
WHO recommendations for ambient Air	5 (annual mean) 15 (24-hour mean)	5 (annual mean) 15 (24-hour mean)			
Exceedance percentage % (n)	53.8 (7) for WHO 24-hr guidelines	11 (2) for WHO 24-hr guidelines	29.0 (9)	51.6 (16)	

Table 1. Summary of IAQ measurements from AQ Eggs ($n = 31$). Guidelines for indoor air levels provided by national and international policymakers are provided, along with the exceedance levels observed in the study community.

times higher in smoking households as compared to non-smoking households (36.1 μg/m^3 and 10.1 μg/m^3, respectively). The World Health Organization (WHO) recommends an exposure limit between 5 μg/m^3 and 15 μg/m^{3}for annual and 24-hour exposure[28], while Health Canada recommends keeping the level as low as possible[29]. $PM_{2.5}$ levels in the community exceeded the WHO's 24-hour limit in 53.8% ($n=7$) and 11% ($n=2$) of smoking and non-smoking homes, respectively. The 3 houses with the highest levels contained smokers, and two also reported using wood stoves as a secondary source of energy.

Carbon dioxide (CO_2) values across households averaged 884 ppm (± SD 256 ppm). Nearly one-third of participating households had mean CO_2values above the Health Canada recommended 24-hour average of 1000 ppm[30].

Mean relative humidity (RH) values were 52.4% (± 9.44%). Over half of the participating households (51.6%, $n=16$) exceeded Health Canada's definition of high relative humidity (55%)[31]. Of the nine households with CO_2 exceedances, RH exceedances were observed in four. Regression analysis using transformed variables showed weak positive associations between temperature and CO_2 ($R^2=0.30$). The mean temperature was 22.3 °C (± 1.90 °C).

Housing questionnaire results

The 31 households with completed IAQ measurements also completed the housing questionnaires. Key results are summarized in Table 2. Of these 31 households, 25.9% ($n=8$) were reported needing major repairs. While most households had a working kitchen fan (65%, $n=20$), only two households reported being equipped with working heat recovery ventilators (HRVs). There was at least one smoking guardian in 42% of homes ($n=13$), and in 13% ($n=4$) homes, there were two guardians who smoked.

Flooding, leaks and condensation

Over one-quarter (26%) of participants reported that their lot was not well drained. One in five (19%) reported standing water tended to be present within 4 feet (or 1.2 m) of the house. More than two-thirds (68%) of homes were located within 1/3 of a mile (500 m) of a river or lake. Over half (55%) of houses had flooded; of those, two-thirds (65%) had flooded twice or more. Most flooding was due to heavy rains/melting snow or ice/overflowing lakes or rivers, and/or sump pump malfunction. The basement was most often flooded, followed by the bathroom.

Nearly half of the houses (45%) had problems with plumbing, rain, or snow leaks. Condensation on windows in the wintertime (affecting most rooms in the house) was a problem reported by almost half (45%) of the respondents. One in 5 homes (19%) had cracked or broken windows. In houses with crawlspaces, 43% reported condensation on the crawlspace walls.

Mould

Two out of every 5 homes (39%) reported current mould problems – most often in the bathroom (mainly the bathtub/shower and around windows) and the bedroom (mainly around windows). One quarter of participants (25%) reported current mould problems in child's bedrooms.

VOCs

Concentrations of select observed VOCs are described in Table 3. Among the measured VOCs, decamethylcyclopentasiloxane (D5) was found to be the most abundant, with a detection frequency of 100% and geometric mean (GM) concentration of 23.54 μg/m^3. This was followed by toluene, octamethylcyclotetrasiloxane, (D4) and m-/p-xylene, at 14.66, 12.76, and 10.83 μg/m^3, respectively. O-xylene was detected at a 92.86% frequency, with a mean value of 3.78 μg/m^3. The other two remaining BTEX compounds (benzene and ethylbenzene) were detected at frequencies of 100%, as were hexane, camphene, heptane, and 1,3-butadiene-2-methyl. The sum of the GM values for the ten compounds detected at 100% (77.9 μg/m^3) accounted for 41.8% of the total GM value for the VOCs detected at over 50% frequency, and 40.8% of the total GM for all detected VOCs. Other common VOCs were found at notable detection frequencies. Alpha-pinene was detected at a frequency of 92.86%, with a GM concentration of 10.09 μg/m^3. Similarly, styrene was detected at a frequency of 78.57%, with a GM concentration of 1.26 μg/m^3. Naphthalene was present at a detection frequency of 72.4%, with a GM concentration of 0.55 μg/m^3. Nicotine was detected in 21.43% of homes at GM concentration of 0.81 μg/m^3.

Strong positive relationships were observed in all BTEX compounds when analyzed against one another for co-occurrence ($R^2 => 0.9$ for all BTEX). Examination of VOC levels in the present study in the context of nationally representative data is limited due to the small sample size ($n=14$). However, some patterns were observed when considering the GM for each compound. All BTEX compounds were observed at higher GM concentrations in this First Nation compared to average Canadian homes (Fig. 1). Toluene levels in the present study were 1.8 times higher than those found by the Canada Health Measures Survey (CHMS)[32] when comparing GMs. Similarly, benzene levels in the present study were almost twice as high (2.93 μg/m^3) compared to those found in CHMS data (1.94 μg/m^3). Additionally, ethylbenzene and m- and p-xylene levels were observed at 2.66 μg/m^3 and 10.83 μg/m^3 in this First Nation, while their respective levels in CHMS data are 1.23 μg/m^3 and 4.23 μg/m^3. In the CHMS, limonene was the most abundant VOC found across households, with a GM of 23.9 μg/m^3 and a DF of 99.9%. While limonene was detected in only 92.2% of homes in this study, its GM concentration was at a higher level of 32.6 μg/m^3. On the other hand, some compounds in this community were detected at lower levels than the nationally representative GMs. VOCs in this category include several aldehydes, including hexanal (5.24 μg/m^3 and 8.07 μg/m^3 in this First Nation and Canadian homes, respectively), benzaldehyde (1.93 μg/m^3 and 2.48 μg/m^3), nonanal (3.07 μg/m^3 and 6.80 μg/m^3), and octanal (1.69 μg/m^3 and 2.69 μg/m^3). Of the Health Canada-regulated VOCs, none of the compounds measured in any households exceeded the recommended indoor guidelines.

Exposure variable	Number of houses (%)
Type of home	
Single detached house	29 (94%)
Other	2 (6%)
Type of layout	
Bungalow	19 (66%)
Two-story or split level	10 (35%)
Year home was built	
1980 or before	14 (45%)
1981–1990	6 (19%)
1991–2000	4 (13%)
2011–2020	7 (23%)
Type of cladding on exterior wall of homes	
Vinyl	12 (39%)
Wood or wood plus other	7 (23%)
Composite	5 (16%)
Other (aluminum, stone, stucco, brick)	11 (36%)
Home in proximity to source of dust or fumes	13 (42%)
Current mould problems	19 (61%)
Primary heating type	
Electric baseboards	19 (61%)
Forced-air furnace	7 (23%)
Other (woodstove, hot water radiators, fireplace, space heaters)	5 (16%)
Secondary heating type	
No secondary heating source	12 (38.7)
Electric baseboards	5 (16.1)
Wood stove	5 (16.1)
Other (space heaters, gas stove, fireplace, forced air furnace, heat pump)	9 (29%)
Cooking fuel used electricity	29 (94%)
Presence of working kitchen fan	20 (65%)
Presence of working dehumidifier	13 (42%)
Guardian smokes	
Mother	5 (16%)
Father	4 (13%)
Both	4 (13%)
Presence of pets in household	27 (87%)
Presence of attached garage	7 (23%)
Household products used in the past month	
Candles	19 (61%)
Latex paint	4 (13%)
Oil-based wood stains	4 (13%)
Other (propane or propane-powered devices, oil-based paints, gasoline or gasoline-powered devices, paint remover, solvents)	7 (23%)
Number of rooms (average, range)	6, 2–12
Number of bedrooms (average, range)	3, 1–5
Number of bathrooms (average, range)	1.5, 1–4
Number of people per house (average, range)	4, 2–8
Number of people per room (average, range)	0.7, 0.2–1.5

Table 2. Housing questionnaire results from participating households ($n=31$).

Radon

Radon detectors were deployed in the 31 participating households for a period of 3 to 10 months (min = 108 days, max = 299 days) between June 2021 and June 2022. However, only 24 (78%) detectors were retrieved at the end of the deployment period due to loss and displacement. One detector was deployed for less than the required minimum of 3 months and was thus excluded from the final community analyses for a final sample size of $n=23$ radon detectors analyzed. The arithmetic mean radon level in these households was 79 Bq/m^3 (minimum = 15 Bq/m^3, maximum = 352 Bq/m^3). Two households exceeded the Health Canada recommended limit of 200 Bq/m^3[33]. No households had values above 600 Bq/m^3.

	DF	Arithmetic mean	Geometric mean	SD	Median	Lower 95% CI	Upper 95% CI	25th Ptl	50th Ptl	75th Ptl	90th Ptl
VOC name	%	μg/m³	μg/m³	μg/m³	μg/m³	μg/m³	μg/m³	μg/m³	μg/m³	μg/m³	μg/m³
Benzene	100.00	4.93	2.93	7.1	2.7	0.73	8.95	2.07	2.66	5.33	17.95
Camphene	100.00	2.96	1.92	3.5	1.6	0.81	4.92	1.18	1.64	3.39	9.75
Decamethyl cyclopentasiloxane	100.00	130.55	23.54	265.3	32.7	-31.20	278.29	4.83	32.66	93.05	690.04
Octamethyl Cyclotetrasiloxane	100.00	46.34	12.76	91.9	10.1	-14.97	83.55	4.18	10.09	31.44	248.40
Ethylbenzene	100.00	5.16	2.66	8.5	2.6	0.11	9.97	1.41	2.63	5.34	20.60
m-Xylene & p-Xylene	100.00	21.60	10.83	34.9	11.1	-0.12	40.12	5.00	11.10	21.61	90.42
Toluene	100.00	32.38	14.66	65.5	12.1	-6.27	69.51	6.48	12.12	25.24	149.67
Alpha-pinene	92.86	21.73	10.09	22.9	9.1	5.96	32.72	4.00	9.11	38.20	64.74
d-Limonene	92.86	64.12	32.60	74.8	39.7	18.27	105.45	23.83	39.72	67.76	229.79
Heptanal	92.86	2.28	1.62	2.2	2.0	0.88	3.51	0.93	1.98	2.61	6.18
Hexanal	92.86	9.18	5.24	8.8	6.1	3.21	13.67	3.08	6.13	13.70	25.65
Nonanal	92.86	5.20	3.07	6.6	3.6	1.41	9.05	1.64	3.62	6.12	17.23
o-Xylene	92.86	6.94	3.78	10.7	3.2	0.01	12.30	1.94	3.24	7.10	27.95
Octanal	92.86	2.40	1.69	2.2	1.8	0.97	3.60	0.87	1.81	3.04	6.46
Benzaldehyde	78.57	4.51	1.93	5.4	3.7	1.25	7.48	0.59	3.71	5.95	14.79
Styrene	78.57	1.26	1.26	0.9	1.2	0.61	1.71	0.52	1.21	2.01	2.72
Naphthalene	71.43	0.78	0.55	0.7	0.6	0.32	1.14	0.23	0.55	1.13	2.07

Table 3. Characteristics of VOC levels in households selected for VOC monitoring ($n = 14$). Compounds shown below had detection frequency (DF) > 50%. SD = standard deviation, CI = confidence interval, Ptl = percentile.

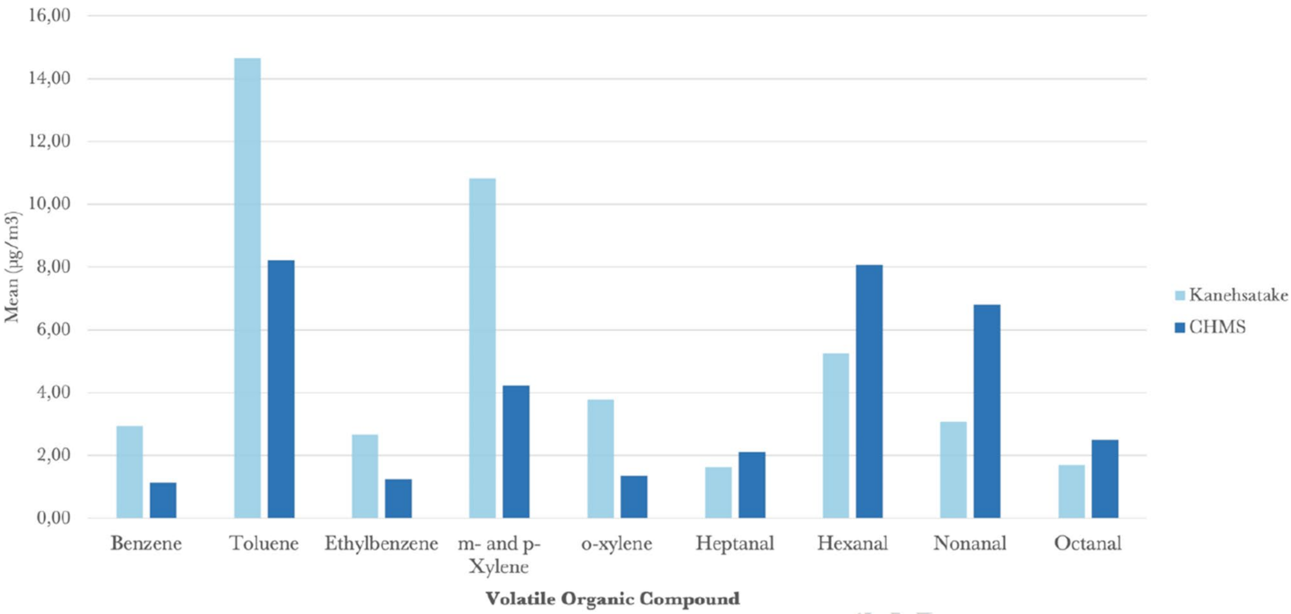
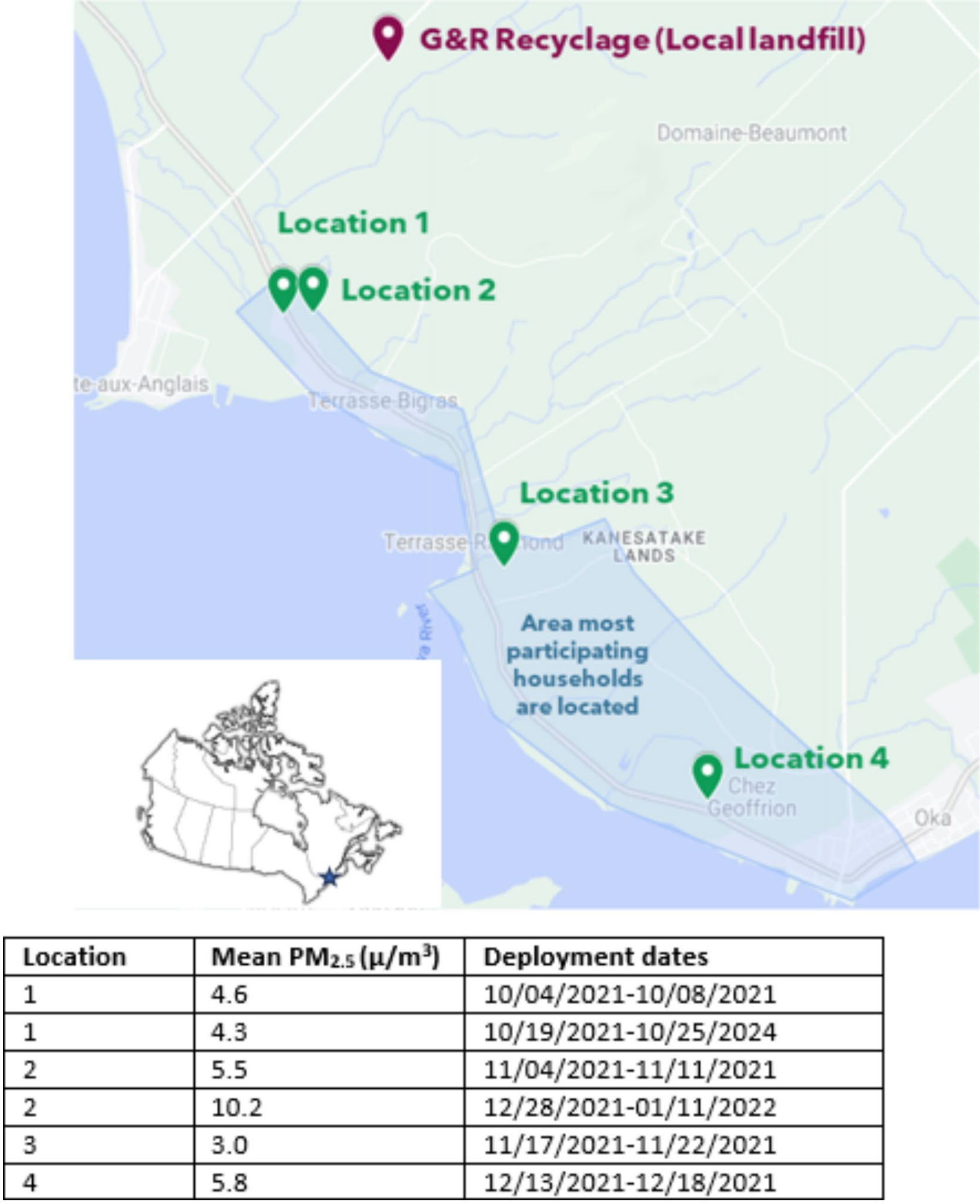


Fig. 1. Comparison of BTEX (benzene, toluene, ethylbenzene and xylene isomers) and aldehydes (hexanal, heptanal, octanal and nonanal) levels in present study (Kanehsatake) to those found in the general Canadian population (CHMS). Geomeric means are compared due to the large discrepancy in sample size.

Ambient air quality

The outdoor AQ Egg was deployed in four locations in the community between October 2021 and January 2022 to monitor ambient air. An AQ Egg unit was deployed twice in two locations (Fig. 2). The mean ambient $PM_{2.5}$ levels observed over this period were nearly all below 10 μg/m³.

A comparison of the mean values of $PM_{2.5}$, RH, and temperature indoors and outdoors for the 12 houses that had a deployment of indoor AQ Egg units matching the exposure periods for the outdoor units is provided in Table 4. While paired indoor/outdoor values were not available, using mean values for ambient levels in the community provided some semi-quantitative comparisons of the two environments. In general, $PM_{2.5}$ values



Location	Mean PM$_{2.5}$ (μ/m^3)	Deployment dates
1	4.6	10/04/2021-10/08/2021
1	4.3	10/19/2021-10/25/2024
2	5.5	11/04/2021-11/11/2021
2	10.2	12/28/2021-01/11/2022
3	3.0	11/17/2021-11/22/2021
4	5.8	12/13/2021-12/18/2021

Fig. 2. Map showing the community's location in Canada and the locations of outdoor AQ Egg units deployed in the community. Mean PM$_{2.5}$ levels in ambient air during the deployment time(s) are provided in the table.

were lower outdoors, resulting in an indoor/outdoor (I/O) ratio greater than 1 in most cases. The mean values outdoors were over 10 only during two periods in 2 households (December 2021 and January 2022; mean PM$_{2.5}$ 12.38 and 15.05 μg/m^3, respectively), possibly due to fireworks during Christmas and New Year celebrations.

Housing conditions and IAQ

The forward stepwise regression model indicated that the presence of one or more smoking guardians in the household was a significant predictor of higher indoor PM$_{2.5}$ concentrations (Table 5, $\beta = 1.27$, SE = 0.367, $p = 0.002$). CO$_2$ showed a strong positive relationship with styrene ($R^2 = 0.79$) and a weak positive correction with benzene ($R^2 = 0.48$), and weaker ones ($R^2 = \leq 0.3$) with xylenes and ethylbenzene.

Levels of BTEX, styrene, and naphthalene were highest in a household that had two smoking guardians present. Levels of benzene, ethylbenzene, and m, p-xylene in this house were at least four times higher than those found in the household with the second highest readings for these VOCs.

A Spearman correlation test indicated that number of persons per room, as an indication of overcrowding, did correlate significantly with PM$_{2.5}$ ($p = 0.449$), CO$_2$ ($p = 0.839$) or relative humidity ($p = 0.920$).

	Average $PM_{2.5}$ (μg/m^3)			Average RH (%)			Average temperature (°C)		
Household_ID	Indoor	Outdoor	I/O ratio	Indoor	Outdoor	I/O ratio	Indoor	Outdoor	Difference
1	17.4	2.96	5.87	52.5	68.3	0.77	20.4	4.3	16
2	10.0	4.45	2.24	58.6	74.5	0.79	20.3	12.6	8
3	67.4	3.60	18.71	43.7	44.3	0.99	23.5	-14.4	38
4	6.1	2.96	2.07	51.2	68.3	0.75	21.3	6.4	15
5	3.6	3.77	0.96	53.5	72.2	0.74	19.1	9.2	10
6	17.8	12.38	1.44	36.7	64.3	0.57	24.4	-4.7	29
7	2.9	6.65	0.44	46.9	61.0	0.77	20.2	7.9	12
8	5.0	6.27	0.80	42.2	60.9	0.69	20.0	2.3	18
9	9.6	4.93	1.95	54.6	68.9	0.79	24.1	16.2	8
10	6.5	3.77	1.72	48.3	72.2	0.67	21.9	9.2	13
11	6.3	15.05	0.42	32.7	68.3	0.48	22.7	-0.5	23
12	12.8	5.48	2.34	23.6	50.8	0.47	25.8	-10.9	37

Table 4. Comparison of $PM_{2.5}$, relative humidity (RH) and temperature indoors and outdoor for the overlapped exposure time.

Variable	Predictor	Beta	Std. error	Sig.
$PM_{2.5}$	Presence of one or more smoking guardians or adults in household	1.27	0.37	0.002*
	Presence of pets	1.00	0.53	0.073
	Use of chemicals in the home in the past 2 weeks	0.80	0.40	0.055

Table 5. Relationship between smoking and $PM_{2.5}$ levels and reported household predictor variables.

Discussion

Household characteristics

To our knowledge, this is the first study to measure the indoor environment in FN communities using remote, community-based data collection methods. The findings of this study indicate that a number of IAQ attributes are worse in this community than national average and recommended values. This demonstrates the value of measuring these characteristics in this community and other FN communities, both to identify health risks and to support strategic mitigation efforts.

The main household conditions reported by occupants in this study were flooding, the presence of moulds, excessive dampness, and elevated relative humidity values. This community is in close proximity to a major river, and flooding was extremely frequent in the participating households (Fig. 2). The community's proximity to a large body of water, compounded with the lack of a working sump pump in most houses and a history of significant flooding events in the region[34], may have been related to the high frequency of leaks, flooding, and subsequent dampness inside houses. Flooding risk in Indigenous communities in Canada is generally higher than in other communities in Canada due to their geography and socioeconomic disparities, such as poor housing conditions and lack of resources for educational and preventive resources[35,36]. The high incidence of flooding and dampness indicates a need for resources and action towards future prevention in this community.

The household questionnaire findings are consistent with previous First Nation surveys highlighting relatively poor household conditions in FN. In this study, over one-quarter of houses were reported to need major repairs; this is higher than the proportion reported for First Nation houses in the 2016 and 2021 Census[25,37]. These factors may have also contributed to the high relative humidity observed across the households. The lack of heat recovery ventilators (HRVs) in most homes is also concerning, given the evidence linking HRVs as impactful interventions for reducing poor IAQ and indoor air-related respiratory illness[38].

Several studies have examined the effectiveness of ventilation or filtration interventions on the concentrations of indoor air contaminants, both in FN and in urban centres. A study conducted in a Montreal daycare showed that the presence of a mechanical ventilation system was significantly correlated with lower formaldehyde levels, supporting evidence that indoor ventilation systems may also be critical interventions in minimizing VOC exposure to children[39]. Weichenthal et al[40]. showed a reduction in $PM_{2.5}$levels of 37.1% in a randomized, double-blind crossover study of air purifiers in a Manitoba First Nation. These results corresponded with a positive respiratory health outcome, specifically a mean 217 mL increase in Forced Expiratory Volume in 1 s in household occupants. While the present study was not an interventional study, all results were communicated back to households along with suggestions for improving air quality. These measures included accessible interventions such as installing an HRV and recommendations that smoking only take place outdoors. However, it has been suggested that material interventions be compounded with discussion around behavioural changes, such as location and frequency of smoking[41]. This integrated and holistic approach to improving air quality is important to consider when communicating results back to home occupants. It highlights the value of community-led strategies for improving air quality in ways that are both culturally meaningful and sustainable for community members.

IAQ

Particulate matter values in smoking households were higher than those found in smoking households in the general Canadian population, though these latter measurements were taken using a different air quality sensor. $PM_{2.5}$ can penetrate the lower airways and cross the alveolar barrier, and $PM_{2.5}$is associated with several respiratory illnesses. Children are particularly vulnerable to these effects as their pulmonary systems do not completely develop until late adolescence[42]. Indoor air CO_2levels, as an indication of ventilation, failed to meet recommended standards[29] in approximately one-third of households and indoor relative humidity was significantly associated with reduced ventilation (increased CO_2level), emphasizing the importance of ventilation in controlling humidity. While indoor relative humidity's direct health effects are unclear, higher humidity can be conducive to the growth of pathogenic biological contaminants[43]. As such, determining accessible ways to reduce humidity indoors, as well as sharing knowledge within and between communities about the effects of high humidity, should be a priority.

Few studies to date have sought to characterize the relationships between IAQ, housing conditions, and health risks in FN communities. However, this study's IAQ measurements are consistent with the current state of knowledge comparing IAQ levels in First Nation households with recommended levels and nationally representative averages. The $PM_{2.5}$results of this study mainly parallel similar studies concerning air quality in FN, Inuit, and Métis communities. In a study by Kovesi et al[16]., the mean indoor $PM_{2.5}$ level across four Ontario FN was 17.1 μg/m^3, but a higher proportion of households, 53%, exceeded the recommended limit for indoor CO_2(> 1000 ppm). However, in contrast to the study by Kovesi et al[16]., where wood stove use was likely an important driver of indoor $PM_{2.5}$, wood stove use was uncommon in the present community. The median $PM_{2.5}$ level (7.9 μg/m^3) was slightly higher than that in woodstove-heated homes in Nova Scotia and BC (4.2 and 5.8 μg/m^3, respectively). Similarly, Weichenthal et al[40]. found indoor $PM_{2.5}$ levels in a sample of households in a Manitoba First Nation to be several times higher than those found in residential homes in Canada and North America. Ambient $PM_{2.5}$ was nearly always lower than indoor concentrations, indicating minimal ambient contribution to indoor levels.

In this study, one-third of households (29%, *n* = 9) exceeded the WHO-recommended 24-hr guidelines for exposure to ambient $PM_{2.5}$. It must be noted that the presence of smoking occupants is identified as a strong predictor for indoor PM values both in FN and the general population. Indeed, mean $PM_{2.5}$ levels in this community were more than three times higher in smoking households than in non-smoking households (36.1 μg/m^3 and 10.1 μg/m^3, respectively), and the stepwise regression model selected smoking as a significant predictor of indoor PM levels. Health Canada has reported similar patterns in smoking prevalence and indoor PM in studies conducted across various Canadian cities, with the mean national $PM_{2.5}$ level reported as < 35 μg/m^3 in smoking homes and < 15 μg/m^{3}in non-smoking homes[29]. The mean $PM_{2.5}$ in smoking households in this study were slightly higher than those found in Canadian cities.

Upon analysis of continuous monitoring data from the AQ Eggs, the PM levels in several households appeared to follow a cyclic daily pattern in concentration fluctuations, with peak daily concentrations occurring in the mornings and evenings for many households and low concentrations consistent throughout the daytime. These patterns suggested that the observed indoor PM values could be attributed to daily occupancy and behaviour patterns, such as cooking, with household occupancy higher in the mornings and evenings Tahmasebi et al[44]. recently observed that indoor PM fluctuations correspond with evening cooking activities and evening rush hours in urban London, UK households. Similarly, in a prediction model recently developed by Samek et al[45]., daily fluctuations in outdoor $PM_{2.5}$and occupant activities were established as important contributors to the changes in the PM environment. Previous studies involving Indigenous populations have supported the association between woodstove use and indoor PM[16,17]. While the questionnaire administered in this study did not record the time of day at which various activities took place in the household, future studies in this area may benefit from collecting this information to provide more accurate details regarding the sources of indoor PM. We did not find a significant relationship between crowding and $PM_{2.5}$, but this may reflect the small sample size (*n* = 31) and reduced statistical power.

Indoor VOCs

Concentrations of several VOCs were higher than values in the CHMS[32], although they were not above the guideline recommendations. Source profiles of the VOCs detected at high frequencies in this study suggest that occupant and household activity were important sources of VOCs in this sample. Tobacco-related VOCs, including BTEX (benzene, toluene, ethylbenzene, xylenes) and styrene, were all detected at a frequency of 100% and 78.6%, respectively. Other common sources of BTEX include vehicle exhaust, indoor gasoline or fuel storage, and the regular use of household products such as paints and candles. D5 and D4 are anthropogenic VOCs commonly used in personal care products such as antiperspirants, sunblock, and candles. The dominance of these VOCs in sample households suggests that household activities and occupant behaviour were important determinants of VOCs in these households. The detection frequency results of this study are consistent with the results of Singleton et al[17]., who studied VOC levels in the homes of Alaska Native children and found BTEX compounds to be present in all participating households at relatively high levels. Most household occupants (66%) in the current study reported having used chemicals indoors within the 3 weeks before the VOC tubes were deployed for sample collection. Several factors may have contributed to shaping the VOC profiles across households. Given these elevated concentration trends observed in several key VOCs, it was surprising to find lower aldehyde levels in this community compared to the general Canadian population measured in CHMS[31]. Common household aldehyde sources include renovation materials such as lacquers, varnishes, and finishes[46];

lower aldehyde levels may thus be related to a lower rate of renovation activities in households in this First Nation than in the general population. The data collection methodology for the VOCs in the present study was adapted directly from the CHMS to ensure comparability. Therefore, although the difference in sample size between the CHMS and the current study is significant, the use of a standardized methodology nevertheless supports their comparability.

The contribution of human activities to airborne VOC concentrations was suggested by several positive correlations between CO_2 and certain VOCs Due to the small sample size (14 homes) with collected VOCs, statistical analyses between VOC levels and household predictors were limited and should be interpreted with caution.

Remote CBPR data collection

This study was conducted during the COVID-19 pandemic, at a time when public health measures limited in-person engagement. As such, adapting the methods to a remote setting was important to meeting the community's needs. As the first study to apply a remote method for community-based participatory data collection with First Nation collaborators, this work provides a useful model for future environmental health studies. Community researchers played a critical role in the remote data collection process, as well as in raising questions and feedback from participants over the course of data collection through direct, real-time communication. Additionally, participant retention rates were extremely high using this remote framework, with 100% of enrolled households completing both the housing questionnaire and multi-day monitoring by the AQ Egg and VOC samplers. A notable challenge to this adaptation was the inability to conduct in-person engagement activities; community engagement activities and community researcher training were conducted online. In future studies of this nature, expanding the scope of the remote community engagement activities to reach parents, children, and youth may further strengthen participation outcomes.

Overall, this data collection model provided an important foundation for future studies applying remote, community-based research frameworks. Particularly in the context of air quality research, where monitors are becoming increasingly user-friendly, community-based collaboration becomes a new option for addressing air quality, respiratory, and related housing concerns in ways that recognize differences in individual and community experience.

Limitations

There were several limitations to this study. Since there are no standard methodology, instrumentation, and reporting methods for IAQ parameters, a number of differing methodologies have been used by different studies in the literature to collect AQ data. This is particularly true of $PM_{2.5}$, which can be measured using the standard gravimetric method or various non-standardized photometric methods. In this study, we used a portable device to facilitate data collection by local research assistants. While the data were useful in showing the major AQ issues, the absolute values may not be accurate as the sampling device has not yet been validated by the standard gravimetric method or correlated with research-grade monitors in the field. This results in limiting the opportunity for cross-study comparisons.

In terms of participation, the household participation rate was only 37.3% of all eligible homes (those with children aged 3–19 years old) in the community. The recruitment period began only three months after the COVID-19 outbreak, and household occupants may have declined participation due to being focused on pandemic management. The small sample size limits the statistical power of the presented analyses, particularly when determining interrelationships between IAQ factors and between IAQ factors and health outcomes. This was particularly true of the VOC detectors, which were only deployed in 14 households. In the original recruitment model, up to 20 VOC monitors were meant to be deployed in a random selection of 100 recruited households in the community. However, due to the low participation rate and small sample size, VOC tubes were only deployed in 14 of the 31 participating households.

Conclusions

This community experienced a remarkable frequency of flooding events and proximate locations of standing water associated with household dampness. In general, exceedance percentages were elevated for several air contaminants in homes in Kanehsatake compared to recommended values set by national and international governing bodies, including $PM_{2.5}$ and relative humidity. Most houses lacked controlled mechanical ventilation.

This was the first study to conduct an indoor air evaluation of FN households strictly using entirely remote data collection methods. This study was a critical step toward improving data sovereignty and building community capacity in Indigenous communities by equipping community members with the tools and training required to collect all data independently. Additionally, by piloting a protocol for physically distanced, remote IAQ data collection, this study was an important methodological tool for future IAQ studies conducted under travel restrictions, both within and outside of the FEHNCY project. Lessons learned from this work will be considered going forward with the FEHNCY project. This pilot work highlighted key IAQ areas to analyze for consolidation in future FEHNCY studies (e.g. aldehyde level disparities, elevated relative humidity). Significantly, this study contributed to filling critical knowledge gaps on indoor air quality in FN and will help to guide communities and policymakers in developing programming and public health interventions.

Methods

AAA

All participants provided their informed consent to participate in the study. This project was designed to ensure the highest standard of community-based participatory research ethics and integration of community interests, desires, and protocols. The University of Ottawa Research Ethics Board, which operates in accordance with the Tri-Council Policy Statement[47] and other applicable laws and regulations, has examined and approved the ethics application for this study. Certificate number H-09-19-4741. Ethics approvals were also obtained from all research institutions involved in this study: the Research Ethics Board of Health Canada, the Children's Hospital of Eastern Ontario, University of Laval, McGill University, and l'Université de Montreal. The study was approved by the Assembly of First Nations in Resolution 04/2019 at the Annual General Assembly in Fredericton, New Brunswick.

Study design and community selection

This was a cross-sectional, community-based participatory research (CBPR) study conducted in collaboration with the Kanehsatake First Nation in Canada. Kanehsatake partnered with the FEHNCY project in June 2020 as the project's pilot community. Kanehsatake has a population of approximately 1,700 living on reserve. The community was situated within an AFN region as of December 31st, 2018. As this study was conducted during the COVID-19 pandemic, Kanehsatake was also identified based on the community's capacity for conducting CBPR under public health guidelines.

Co-governance of research and principles of OCAP®

All activities related to this study, including its conceptualization, design, and revision, were conducted in close collaboration with FN stakeholders, including community leaders and representatives from the AFN. All procedures followed the FN Principles of Ownership, Control, Access, and Possession (OCAP®), which centralizes community members as autonomous agents and owners of all knowledge and data collected within their community. An Indigenous Health Promotion lens, which prioritizes collaboration and intergenerational capacity-building around research activities, was adopted to promote community mobilization, education, and capacity-building in the context of air quality and health. A community advisory circle comprised of volunteer members of the participating community also met regularly throughout the study period, and their feedback was implemented in the study processes.

Community researchers

All data were collected by trained community members, and community feedback was prioritized in the methodological approach. Two community researchers (CRs) were hired in the spring and summer of 2020, and a training program was designed to assist them with learning about the study procedures. Responsibilities of the CRs included assisting with the recruitment of participants, air quality monitor deployment, questionnaire administration, and some data management. They also communicated directly with the FEHNCY coordinating team throughout the duration of the study, providing regular updates and feedback on the study's progress.

Participant recruitment & community engagement

A list of households in Kanehsatake was drafted by integrating data from administrative sources. All lists were generated in collaboration with community leaders, members of the AFN housing unit, and FEHNCY team members. The target recruitment sample was 100 households. Household inclusion criteria were the presence of at least one child between the ages of 3–19 in the household and the child's self-identification as having First Nation ancestry. Community engagement began in late 2020; activities included handing out information brochures, and plant grow kits at the local schools, airing radio announcements, and holding participatory activities such as a moose burger barbecue at the elementary school and local photo contests. CRs contacted eligible household occupants over the phone or using Zoom for healthcare to discuss the study, and consent for collecting air quality samples and household information was documented verbally. 31 houses were included in the study.

IAQ assessment

Indoor air quality (IAQ) indicators, including $PM_{2.5}$, CO_2, volatile organic compounds (VOCs) and radon, were assessed in each participating homes. The Air Quality Eggs (AQ Egg Model 2018, Wicked Device LLC, Ithaca NY; for specifications see https://www.aqmd.gov/aq-spec/product/air-quality-egg-2018-model) for monitoring $PM_{2.5}$, CO_2, relative humidity (RH) and temperature and VOC passive thermal desorption tubes (packed with Carbopack B resin, manufactured by PerkinElmer Inc., Shelton CT). to measured VOC's were deployed at the same time, for 5 days. The radon detection device (long-term Alpha Track Radon Tests kit (AT-100, Accustar Laboratories, Hanover MA)), was deployed between 90 and 180 days. The radon kit includes a CNRPP approved and listed under the device code # 8205 Class 24 AT REM AT-100 Alpha Track Detector. It filters out dust and radon progeny for precise measurements and uses electrochemical etching and computer-aided image analysis for superior track resolution. Each detector is barcoded and sealed in a radon-tight pouch to prevent labeling errors.

The AQ Egg and VOC tube were placed in either living room or children's bedroom, while the radon device was placed in the basement, if the family spent more than 4 h per day in the basement, or otherwise in a suitable location on the first floor. All devices were placed on a hard surface such as bookshelf, wall unit, dresser, or side table and from other objects that may obstruct free air movement. A minimal distance of 10 cm was required between radon detector and VOC tube and between devices and other objects on the same horizontal surface. Both the radon detector and VOC tube were at least 30 cm away from AQ Egg unit. In addition, the radon detector was placed at least 20 cm from an exterior wall.

The AQ Egg consists of a sampling fan and dual Plantower PMS5003 laser sensor, which detects incoming particles using a reflective beam counter. Temperature and relative humidity were measured using the instrument's RHT03 MaxDetect sensing technology. The Eggs have a digital gas sensor (DGS) for measuring

CO_2 concentrations in parts per million (ppm). $CO_2$was measured as a proxy for home ventilation[23]. The devices were calibrated by the manufacturer without further manipulations. The AQ Egg's Plantower sensor is sensitive to relative humidity. The following correction factor developed by the University of Northern British Columbia and Environment and Climate Change Canada for this device was applied for both indoor and outdoor measurements to improve the representativeness of AQ results, and comparability between these results and measurements taken using standard research-grade monitors[48] (Eq. 1).

$$PM_{2.5} = EggPM_{2.5} \times 0.524 - 0.0862 \times RH + 5.75 \quad (1)$$

The passive sampling uptake rate of the VOC passive desorption tubes (UR, mL/min) was either experimentally determined or estimated based on the chemical's air diffusivity, as described in a previous study[49]. The analysis of VOC tubes followed the same procedure and conditions as described in Zhu et al., 2013. VOC tubes were sent to a commercial laboratory at the end of the data collection in the community and analyzed using thermal desorption TD, Model: ATD 650, PerkinElmer) coupled with gas chromatography/mass spectrometry (GC/MS, Model: 6890 GC and 5977 MS, Agilent). Mass (M, pg) on the tube was first determined by the instrument and then converted to indoor air concentration (μg/m^3) using Eq. 2.

$$Concentration\left(\mathrm{\mu g/m^3}\right) = M/\left(URxt\right) \quad (2)$$

where t is the exposure time (min).

In addition, an outdoor AQ Egg monitor was deployed with unit's bottom at a height of about 60 cm above the ground to collect information on ambient air quality of $PM_{2.5}$ and CO_2 levels as well as temperature and RH. The outdoor monitor was deployed in a series of central locations in the community (Fig. 2).

For the AQ Eggs, no duplicate or blank samples were deployed due to a limited number of available instruments. AQ Egg units were calibrated by the manufacturer and have intra-unit variability of 4–8%.

For VOC and radon samples, three field blanks and five field duplicates were included in each type of samples. The limit of detection (LOD) for VOC tubes was estimated by the commercial lab conducting the analysis. Blank corrections were applied by subtracting mean blank sample levels, and any corrected values less than the instrument's limit of detection were replaced with ½ limit of detection for further analysis.

Housing conditions

Information on housing conditions was collected with a housing questionnaire. The questionnaire was administered to one adult occupant of participating households by the CR. The housing questionnaire was developed in collaboration with the AFN, and was adapted from the Canada Mortgage and Housing Corporation (CHMC) Mould in Housing: Information for First Nation Housing Managers Tool[50]. The questionnaire is designed to collect key information about household characteristics, including age of the house and building material, as well as potential predictors of household air quality such as water damage, ventilation systems, and occupant behaviour. A short follow-up questionnaire asking about factors that may have affected air quality in the home during the monitor deployment period (such as burning food or candles) was also administered when the monitors were collected from the households. The questionnaires were collected using a tablet and stored using the KoBo Toolbox secure online database initially developed by the Harvard Humanitarian Initiative (https://hhi.harvard.edu/kobotoolbox). 'Major repairs' was defined as households in need of structural repairs to walls, ceilings, or floors, as well as households with defective electrical or plumbing functions.

Data management statistical analysis

AQ Egg data were downloaded for analysis at the University of Ottawa. Housing questionnaire data were transferred from the Kobo Toolbox to a secure personal network-attached storage server (MyCloud) for integration with air quality data. All data were compiled into Statistical Analysis Software (SAS version 9.4, Cary, NC) and transferred to R Studio for further analysis. AQ Egg data were summarized using descriptive statistics. Prior to further analysis, data were assessed for normality using Shapiro-Wilk tests, along with quantile-quantile plot normality visualizations. $PM_{2.5}$ values, along with relative humidity, failed the Shapiro-Wilk test for normality and skewness was visualized through Q-Q plots. $PM_{2.5}$ data were log-transformed prior to correlation analyses. Relative humidity data were highly right-skewed and were transformed using a square-root transformation for correlation analyses. Pearson correlation coefficients were used to assess relationships between continuous variables for AQ Egg measurements. Exceedance percentages were determined through comparison with national and international recommended values. Common household risk factors were determined a priori for integration into a model for multivariable analysis between household conditions and air quality. These risk factors included the presence of a smoking guardian, woodstove and fireplace use, the presence of a heat recovery ventilator (HRV), and the occurrence of floods and leaks. A forward stepwise regression model was built to determine the statistical influence of household predictors on air quality levels. A significance level of $p = 0.1$ was required for the entry and removal of predictors in the model at subsequent steps. A multivariable regression model was used to predict the outcome of indoor air levels with the presence or absence of several household predictors. Statistical relationships between dichotomous VOC measurements and housing conditions were limited to the descriptive phase due to sample size restraints.

COVID-19 adaptations

All study proceedings were adapted to minimize the risk of COVID-19 transmission for all staff, participants, and community members. While initially, the project methods involved extensive travel and in-person engagement with the community, the COVID-19 pandemic required unexpected adaptation of all methods to a remote setting, with no presence of external research collaborators visiting the community. AQ Egg monitor, VOC tube and radon monitor were deployed and collected by an adult of the participating household under the instruction of CRs. The original plan, which involved in-person house evaluations by housing specialists, was omitted. Instead, housing questionnaire data were collected by CRs either socially distanced outside of participants' homes (when allowed) or remotely via Zoom or over the phone. All CR training procedures and community engagement activities were likewise conducted online through video-sharing platforms, social media, and other communication technologies. Special sanitation protocols were approved for the handling of monitors before mailing to communities, at various stages of handling and deployment, and upon receiving monitors back at the University of Ottawa.

Data availability

Access to the datasets generated during and/or analyzed during the current study is controlled by the Kanehsatake First Nation, to which the data belong. These data may be available from the corresponding author and the community partner upon reasonable request.

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Author contributions

R.D.N.: Methodology, investigation, validation, formal analysis, resources, writing – original draft, writing – review and editing; J.Z.: Conceptualization, methodology, supervision, writing – review & editing; T.K.: Conceptualization, methodology, supervision, writing – review & editing; G.M.: Conceptualization, supervision; R.K.: Data Curation; M.N.F.: Data curation; A.I.: Data curation; I.L: Conceptualization, supervision; L.B.: Project administration, funding acquisition, H.M.C.: Conceptualization, funding acquisition, supervision, review & editing. All authors reviewed the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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