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Health risk assessment of occupational exposure to hazardous volatile organic compounds in swine gestation, farrowing and nursery barns

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Livestock producers are exposed to a high number of airborne pollutants during their daily duties of cleaning, feeding and maintenance activities. Hazardous air pollutants (HAPs) are a major group of pollutants that may cause cancer or other serious health effects including neurological, respiratory, reproductive and developmental disorders. In this study, health risks of occupational exposure to eight hazardous VOCs (phenol, *p*-cresol, *o*/*m*-cresol, benzene, toluene, ethylbenzene, *o*-xylene, and *m*/*p*-xylene) that are most likely to be emitted from swine buildings were assessed using Monte Carlo simulation. The purpose of the study was to calculate emission rates and to quantify cancer and hazard risks of the target VOCs. Cancer and hazard risks were calculated for workers A, B, and C, who spent six hours in the gestation, farrowing and nursery barns, respectively, and one hour in the office space every day. Concentrations of the target VOCs did not exceed their recommended exposure limits (RELs). But, concentrations of *p*-cresol and benzene exceeded their preliminary remediation goals (PRGs). The highest emission rates in $\mu g\ s^{-1}$ were measured from the gestation rooms while the highest emission rates in μg per s per head were measured from the farrowing rooms. Cancer risks of ethylbenzene, benzene and *p*-cresol were higher than EPA's benchmark of one per million. Hazard risks of benzene, toluene, *p*-cresol, and *o*/*m*-cresol were higher than the maximum acceptable risk threshold (10^{-4}). Worker B (farrowing) had the highest cumulative cancer (16.6 in one million) and hazard (11 342 in one million) risks. It was followed by workers A (gestation) and C (nursery). Sensitivity analysis showed that inhalation unit risk (IUR) had the highest impact on cancer risk assessment while recommended exposure limit (REL) had the highest impact on hazard risk assessment.

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Environmental impact

This study presents health risks of occupational exposure to hazardous volatile organic compounds (VOCs) in swine gestation, farrowing, and nursery barns and worker's office space. The results indicate that farrowing room workers have the highest cancer and hazard risks. Cancer risks of ethylbenzene, benzene, and *p*-cresol can exceed the benchmark cancer risk threshold and hazard risks of benzene, toluene, *p*-cresol, and *o*/*m*-cresol can exceed the maximum acceptable hazard risk threshold. The results of this study can be used to develop risk assessment and prevention programs for livestock producers.

Introduction

Hazardous air pollutants (HAPs) are a major group of pollutants that are harmful to the ecology, environment, and human health. The Clean Air Act (CAA) Amendments require the United States Environmental Protection Agency (U.S. EPA) to control 187 HAP emissions that may cause cancer or other serious health effects including neurological, respiratory, reproductive and developmental disorders.[1] EPA's most recent data indicate that 95% of the U.S. citizens face an increased likelihood of developing cancer or other chronic health problems as a result of breathing HAPs.[2] Consequently, assessing health risks associated with exposure to HAPs has become an increasingly important topic. Health risks of occupational exposure to dust and endotoxins have been widely studied[3–5] but the effects of HAPs have not been thoroughly explored.

Cancer risks are assessed using inhalation unit risk (IUR) estimates of carcinogenic compounds. For cancer-causing compounds, EPA assumes there are no exposures that have "zero risk", which means even a very low exposure to a cancer-causing volatile organic compound (VOC) can increase the risk of cancer. For non-carcinogenic compounds, EPA assumes that at low doses the body's protective mechanisms repair any damage caused by the pollutant but these VOCs can still be harmful at low doses as the dose–response relationship depends on various factors including chemical structure of the VOC, individual sensitivity, and type of the health effect. A

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reference concentration (RfC) or recommended exposure limit (REL) is used to calculate chronic non-cancer effects.

Variability in VOC concentrations and IUR and REL values may result in high uncertainty in risk assessment. Measurement uncertainties include sampling size limitations (daily and seasonal variations), poor sampling and incomplete extraction of the analytes. Most of the time scientists estimate IUR and REL values based on animal studies. Converting these estimates to those expected in people can cause uncertainties. Also, low dose exposure parameters are derived from observable dose responses assuming there is a linear relationship between dose and response even though it may not be the case all the time. For hazard risk, parameters are derived assuming a threshold exits below which no adverse effects will occur in general population although such a threshold is not observable and can only be estimated.[6,7] To manage these uncertainties, Monte Carlo simulation has been commonly used as a risk assessment tool.[7–9] By using Monte Carlo simulation, it is possible to develop a probability distribution of the risk rather than calculating one single risk value.

Environmental Protection Agency has standards to control HAP emissions from various sources including vehicles, landfills, chemical companies, power plants and petroleum refineries. Until today, only a few researchers measured HAP emissions from livestock facilities but livestock facilities can be another significant source of HAP emissions. Benzene, toluene, ethylbenzene, xylenes (BTEX), phenol, and cresols all have a benzene ring in their chemical structures and are shown to be produced by degradation of aromatic amino acids (*e.g.*, tryptophan and tyrosine).[10–12] In livestock facilities, amino acid degradation takes place in animals' digestive systems and manure storage and handling systems. Other sources of hazardous VOCs can be vehicles, disinfectants, and rubber materials used inside or near the livestock buildings.[13] Phenol and *para*-cresol are well known odorous compounds that have been shown to be emitted from swine and dairy buildings.[14–16] Xylenes that are found in three isomeric forms (*ortho*, *para*, and *meta*), benzene, and toluene have been also shown to be emitted from swine and dairy buildings.[9,14,17] There are no data about ethylbenzene emissions from swine buildings but it has been reported to be emitted from cattle farms.[18,19]

Among all VOCs, special attention should be paid to a few specific VOCs. Rosenfeld *et al.*[20] reported that odor detection thresholds of most of the VOCs are much lower than their human health thresholds and the presence of these VOCs in the environment can be sensed before their concentrations reach a dangerous level. But, there are a few VOCs that cannot be sensed by human before their concentrations reach a dangerous level since their odor detection thresholds are higher than their human health threshold. Benzene is one of these dangerous VOCs (Table 1).[21–27] *o*/*m*-Cresol, toluene, ethylbenzene, *o*-xylene and *m*/*p*-xylene can be also listed as dangerous VOCs. Odor detection thresholds of these VOCs are

Table 1 Inhalation unit risks (IUR), recommended exposure limits (REL), preliminary remediation goals (PRG), and odor detection thresholds of the target VOCs

Compound name	IUR $(\mu g\ m^{-3})^{-1}$	REL[d] $(\mu g\ m^{-3})$	PRG[e] $(\mu g\ m^{-3})$	ODT $(\mu g\ m^{-3})$
Phenol	—	19 250	1100	1023[f]
p-Cresol	5×10^{-7}[a]	10 160	18	10.9[f]
o/*m*-Cresol	5×10^{-7}[a]	10 160	180	2873[g]
Benzene	5×10^{-6}[b]	319	0.25	4500[g]
Toluene	—	377 000	400	8025[g]
Ethylbenzene	2.5×10^{-6}[c]	434 000	1100	8700[g]
o-Xylene	—	434 000	110	348[g]
m/*p*-Xylene	—	434 000	110	348[g]

[a] EPA Cumulative Exposure Project (CEP).[21] [b] EPA Integrated Risk Information System (IRIS).[22] [c] OEHHA.[23] [d] REL: NIOSH Pocket Guide to Chemical Hazards.[24] [e] PRG: EPA Region 9 PRG Table.[25] [f] Parker *et al.*[26] [g] ODT: Miller.[27]

Table 2 Commercial and scientific names, CAS registry numbers, cancer classifications and other chronic health effects of the target VOCs (EPA[28] and IARC[29])

Commercial name	Scientific name	CAS #	Cancer classification[a]	Other chronic health effects
Phenol	Phenol	108-95-2	Group D	Enlarged liver, central nervous system effects, growth retardation
o-Cresol	2-Methyl phenol	95-48-7	Group C	Effects on the blood, liver, and kidney
m-Cresol	3-Methyl phenol	108-39-4	Group C	
p-Cresol	4-Methyl phenol	106-44-5	Group C	
Benzene	Benzene	71-43-2	Group A	Disorders in the blood, increased incidence of leukemia
Toluene	Methylbenzene	108-88-3	Group D	Impaired speech, hearing, and vision, attention deficits, growth retardation
Ethylbenzene	Ethylbenzene	100-41-4	Group 2B	Retardation of skeletal development and effects on the blood
o-Xylene	1,2-Dimethyl benzene	95-47-6	Group D	Impaired short-term memory, severe chest pain, labored breathing
m-Xylene	1,3-Dimethyl benzene	108-38-3	Group D	
p-Xylene	1,4-Dimethyl benzene	106-42-3	Group D	

[a] EPA's cancer classification: group A – carcinogenic to humans, group B – likely to be carcinogenic to humans, group C – suggestive evidence of carcinogenic potential, group D – inadequate information to assess carcinogenic potential, group E – not likely to be carcinogenic to humans. IARC's (International Agency for Research on Cancer) cancer classification: group 1 – known human carcinogen, group 2A – probable human carcinogen, group 2B – possible human carcinogen, group 3 – inadequate information, group 4 – probably not carcinogenic to humans.

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lower than their human health thresholds but higher than their preliminary remediation goals (Table 2).[28,29]

So far, research on livestock emissions has mainly focused on the VOCs that cause odor problems. Little or no attention has been paid to the VOCs that may not cause odor problems but still cause serious health problems. In this study, cancer and hazard risks of eight hazardous VOCs that are most likely to be emitted from swine buildings were calculated. The purpose of the study was to assess health risk of occupational exposure to the target hazardous VOCs in swine production buildings. Workers were exposed to these VOCs during their daily duties of cleaning, feeding and maintenance activities. Cancer risks of occupational exposure to benzene, ethylbenzene, *p*-cresol, and *o*/*m*-cresol and hazard risks of occupational exposure to benzene, toluene, ethylbenzene, *o*-xylene, *m*/*p*-xylene, phenol and cresols were calculated. Monte Carlo simulation was used to develop a probability distribution of the risk. In addition, emission rates of the target VOCs were calculated in order to provide complete and comparable data. The list of the target VOCs and their potential health effects are shown in Table 2.

Materials and methods

Sample collection and analysis

Hazardous VOC sampling was conducted at a commercial farrow-to-feeder swine production facility with gestation, farrowing and nursery rooms. This facility was located in western Minnesota and held about 900 sows which produce about 18 000 market pigs per year. It was visited three times over a span of 6 months and VOC samples were collected from representative rooms of gestation, farrowing, and nursery barns. Samples were also collected from a representative ambient location (ambient air entering the rooms) and workers' office space. The mean ambient temperatures during the first (7/28/11), second (9/21/11), and third (11/14/11) visits were 23, 12, and 3.3 °C, respectively. There were about 300 sows in the gestation, 450 pigs in the nursery, and 16 sows and litters in the farrowing rooms. The floor areas of the rooms were 738 m^2 (gestation), 178 m^2 (nursery), and 145 m^2 (farrowing). Workers worked seven hours a day and spent six hours in one of the production rooms (gestation, farrowing or nursery) and one hour in the office space.

In this study, a total of eight VOCs (phenol, *p*-cresol, *o*/*m*-cresol, benzene, toluene, ethylbenzene, *o*-xylene, and *m*/*p*-xylene) were sampled and analyzed. During each visit two sets of samples were collected. In addition, blank samples were collected and analyzed to check possible cross-contamination during sampling and storage.

Sampling and analysis of the VOCs were carried out according to NIOSH manuals of analytical methods (manual #1501 for BTEX[30] and #2546 for cresols and phenol[31]). Samples were collected by passing air through sorbent tubes using personal air pumps (SKC 210-1002MH, Eighty Four, PA). Pumps were placed on a concrete wall (about 1 m above ground) under the exhaust fan. Two types of sorbent tubes from SKC were used to collect samples (Anasorb coconut shell charcoal for BTEX and XAD-7 for cresols and phenol). Glass sealed ends of the tubes were broken just before sampling with a SKC sorbent tube end breaker. The pump flow rate was set at 45 mL min^{-1} for BTEX and 100 mL min^{-1} for cresols and phenol. Flow rates were adjusted using adjustable low flow sorbent tube holders (SKC) and checked before sampling using a digital flow meter (Alltech Digital Flow Check-HR™, Deerfield, IL) with representative sorbent tubes in lines. Samples were collected for three hours at each sampling location. Airflow rates and sampling time were chosen considering recommended airflow rates and breakthrough volumes in NIOSH manuals. Overall sample collection at the facility was started at noon and finished the following day at noon with a break during night time hours (10 PM to 7 AM).

After sampling completed, tubes were capped immediately and carried to the laboratory in a cooler and stored at 4 °C until analysis. VOCs were extracted by liquid extraction as described in the manuals. The front and back sorbent tube sections of the tubes were placed in separate vials (4 mL glass vials with PTFE septa, Supelco, Bellefonte, PA). One mL carbon disulfide was used to desorb BTEX. After carbon disulfide was added, caps of the vials were crimped immediately. Vials were left for 30 minutes with occasional agitation at room temperature. Two mL methanol was added to the vials for cresols and phenol. After vials were capped, they were ultrasonicated (Branson 3510R, Danbury, CT) for 30 minutes. One μL samples were injected into the injection port of a gas chromatograph (GC) equipped with an auto sampler and a flame ionization detector (5890 series II, Hewlett Packard, Agilent Technologies, Santa Clara, CA). The GC column was DB-Wax (0.25 mm I.D., 30 m length and 0.25 μm film thickness, J & W Scientific, Agilent Technologies). For BTEX, the column was held at an initial temperature (40 °C) for 10 minutes and then the temperature was increased up to 230 °C at a rate of 10 °C min^{-1}. For cresols and phenol, the column temperature was increased from 160 to 225 °C at a rate of 3 °C min^{-1}. Column retention times of the VOCs were compared with those of standards. All standards were of analytical grade and purchased from Sigma Aldrich (St Louis, MO). Calibration solutions were prepared daily. To prepare calibration curves 5 μL calibration solutions were injected directly onto the front section of the sorbent tubes. Then, sorbent tube ends were capped and allowed to stand overnight. After that, analytes were desorbed and analyzed as described above. Three sorbent tubes were prepared for each concentration level.

Calculation of emission rates

Airflow exchange or ventilation rates for each room was recovered from the room's ventilation controllers used at the facility which has counter wheels for the variable speed fans that ran continuously. Geothermal heat exchangers were used to heat and cool down the rooms. The maximum ventilation airflow rates of the rooms were reported to be considerably less compared to those of similar conventional facilities due to the sizeable amount of cooling provided by geothermal heat exchangers.[32]

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Airflow rates were recorded at the beginning and at the end of each three-hour sampling period. These two measurements were averaged. VOC concentrations were standardized by subtracting ambient air concentrations from room concentrations. Emission rates (μg s^{-1}) were calculated by multiplying standardized room concentrations (μg m^{-3}) by averaged airflow rates (m^3 s^{-1}). Emission rates in μg s^{-1} m^{-2} and μg s^{-1} $head^{-1}$ were calculated by dividing emission rates by room area and the number of animals, respectively.

Calculating cancer and hazard risks

A first evaluation of the risk was carried out by comparing VOC concentrations to NIOSH's recommended exposure limits (RELs). After the first evaluation, a more specific risk assessment was done by calculating cumulative health risks. Since all target VOCs were volatile, inhalation was considered as the main exposure route to VOCs and inhalation exposure concentrations of the VOCs were calculated. Cancer and hazard risks were calculated for workers A, B, and C who spent six hours in the gestation, farrowing and nursery barns, respectively, and one hour in the office space every day.

Calculating cancer risk of carcinogenic VOCs. Inhalation exposure concentrations and cancer risks of the carcinogenic VOCs were calculated using the following equations:[33,34]

$$EC = \{(C_{room} \times ET_{room} + C_{office} \times ET_{office}) \times EF \times ED\}/AT \quad (1)$$

$$\text{Cancer risk} = EC \times IUR \quad (2)$$

where EC is the exposure concentration (μg m^{-3}), C_{room} is the VOC concentration of the swine room (μg m^{-3}), C_{office} is the VOC concentration of the office space (μg m^{-3}), EF is the exposure frequency (330 days per year), ED is the exposure duration (25 years), ET is the daily exposure time (ET_{room}: 6 h/24 h and ET_{office}: 1 h/24 h), and AT is the averaging time (365 days per year × 70 years). IUR is the inhalation unit risk (Table 1).

After calculating individual cancer risks, cumulative cancer risk was calculated by summing individual cancer risks.

According to EPA's classification, ethylbenzene is a group D carcinogen, which means there is no adequate information to assess its carcinogenic potential. But, the International Agency for Research on Cancer classifies ethylbenzene as a group 2B carcinogen (possible human carcinogen) based on the National Toxicology Program's (NTP) studies.[29] Therefore, ethylbenzene was accepted as a carcinogenic VOC. Other researchers also accepted ethylbenzene as a carcinogenic VOC.[34]

Calculating hazard risks of carcinogenic and non-carcinogenic VOCs. Inhalation exposure concentrations of the carcinogenic and non-carcinogenic VOCs were calculated using eqn (1) but the averaging time (AT) was calculated as 365 days per year × 25 years. Then, hazard risk was calculated by dividing exposure concentrations by recommended exposure limits (REL).[33,34] REL values of the target VOCs are shown in Table 1.

$$\text{Hazard risk} = EC\ (\mu g\ m^{-3})/REL\ (\mu g\ m^{-3}) \quad (3)$$

After calculating individual hazard risks, cumulative hazard risk was calculated by summing individual hazard risks.

Uncertainty and sensitivity analysis

Monte Carlo simulation and sensitivity analysis were conducted using Risk Solver Platform from Frontline Systems (Frontline Systems, Inc., Incline Village, NV). For cancer assessments the inputs were C_{room}, C_{office} and IUR (eqn (2)), and for hazard risk assessments the inputs were C_{room}, C_{office} and 1/REL (eqn (3)). Triangle distribution was used for IUR and 1/REL inputs. IUR and REL values were used as the maximum and most likely values and zero was assigned as the minimum risk value.[7]

For VOC concentrations (C_{room} and C_{office}) lognormal distribution was used as VOC concentrations have been reported to have a lognormal distribution in a number of studies.[7,35,36] Tests were run at 5000 iterations to ensure stability of the simulations. Sensitivity analysis was conducted to find how uncertainty in cancer and hazard risks can be apportioned to uncertainties in measurements and IUR and REL parameters.

Additional statistical analysis. Additional statistical analyses were conducted using JPM software version 9.0.2 from SAS (SAS Institute Inc., Cary, NC). Concentrations and emission rates of the VOCs were compared using Analysis of Variance (ANOVA) with sampling location as the main effect ($p < 0.05$).

Results and discussion

Concentrations and emission rates of the target VOCs

Calibration curves are presented in Fig. 1. Averages of three measurements are shown for each data point. The concentration range of the curves was between 0.1 and 20 ppbv. High linear correlations were found between peak area counts and VOC concentrations. Coefficients of determination (R^2) of the curves ranged from 0.87 to 0.99. The lowest concentrations shown on the calibration curves were 0.39 μg m^{-3} (phenol), 0.44 μg m^{-3} (*p*-cresol and *o*/*m* cresol), 0.32 μg m^{-3} (benzene), 0.38 μg m^{-3} (toluene), and 0.43 μg m^{-3} (ethylbenzene, *o*-xylene, and *m*/*p*-xylene).

Measured concentrations of the VOCs are shown in Table 3. Farrowing room concentrations were significantly higher than the concentrations of the nursery and gestation rooms. Except for *p*-cresol, there was no significant difference between the concentrations of the gestation and nursery rooms. Office space concentrations were close to ambient concentrations, mostly there was no significant difference between office space and ambient concentrations (Table 3). BTEX concentrations of swine nursery, farrowing, and gestation barns were reported in the literature but Beck *et al.*[18] studied respiratory health effects of dairy farming and measured toluene (2.5 μg m^{-3}), ethylbenzene (0.4 μg m^{-3}), *m*/*p*-xylene (2.2 μg m^{-3}), and *o*-xylene (1.0 μg m^{-3}) concentrations of cattle barns. Concentrations reported by Beck *et al.*[18] were lower than the ones measured in this study. Concentrations reported by Filipy *et al.*[19] for dairy barns (0.93 μg m^{-3} for benzene, 0.12 μg m^{-3} for ethylbenzene, and 0.06 μg m^{-3} for *m*,*p*-xylene) were also lower than the ones reported in Table 3.

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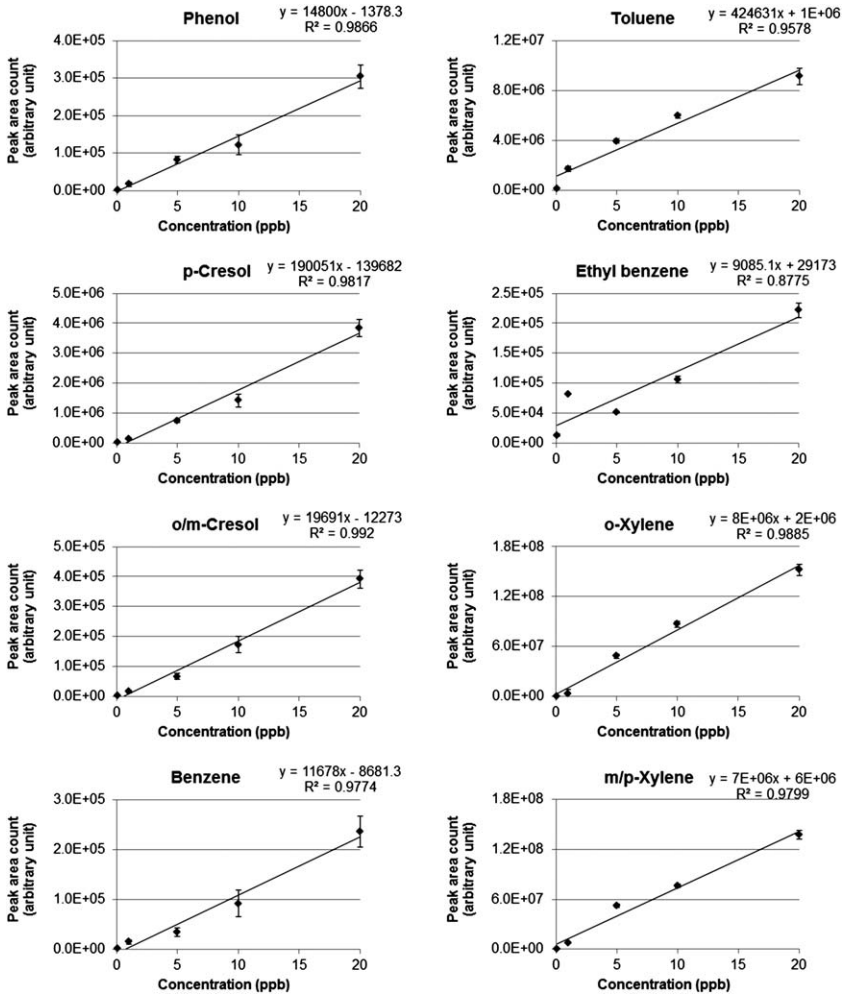

Fig. 1 Calibration curves of the target VOCs.

Table 3 Concentrations (μg m^{-3}) of the target VOCs[a,b]

Compound name	Gestation room	Farrowing room	Nursery room	Office space	Ambient
Phenol	15.2 ± 4.9^{AB}	21.6 ± 8.0^{A}	11.5 ± 4.1^{BC}	3.6 ± 0.3^{C}	<0.39
	8.3–21.8	12.1–32.5	6.2–17.2	3.2–3.9	—
p-Cresol	57.6 ± 5.4^{B}	85.0 ± 8.3^{A}	42.6 ± 3.9^{C}	9.7 ± 0.6^{D}	8.5 ± 0.3^{D}
	50.4–65.4	75.8–96.8	37.5–48.5	9.5–10.8	8.2–8.9
o/*m*-Cresol	23.0 ± 6.0^{B}	35.3 ± 9.5^{A}	17.9 ± 5.3^{B}	3.4 ± 0.1^{C}	<0.44
	15.5–31.5	22.8–48.9	11.6–25.5	3.2–3.5	—
Benzene	10.3 ± 2.2^{B}	16.0 ± 3.1^{A}	7.9 ± 1.5^{B}	3.2 ± 0.1^{C}	<0.32
	7.2–13.5	11.5–19.5	5.8–9.2	3.1–3.4	—
Toluene	61.9 ± 10.2^{B}	93.2 ± 15.6^{A}	46.4 ± 8.5^{B}	10.7 ± 0.8^{C}	9.93 ± 0.64^{C}
	52.3–76.0	76.9–114.2	36.5–58.9	10.5–12.2	9.2–10.9
Ethylbenzene	45.0 ± 9.2^{B}	65.7 ± 11.2^{A}	33.8 ± 6.7^{B}	3.3 ± 0.3^{C}	4.37 ± 0.18^{C}
	34.7–59.8	50.5–79.8	25.3–41.9	3.1–3.9	4.1–4.5
o-Xylene	44.1 ± 8.2^{B}	64.8 ± 11.8^{A}	33.3 ± 6.4^{B}	3.0 ± 0.1^{C}	<0.43
	32.4–53.5	49.5–79.5	23.8–39.8	2.9–3.2	—
m/*p*-Xylene	59.5 ± 11.3^{B}	88.2 ± 15.2^{A}	45.8 ± 9.0^{B}	4.6 ± 0.4^{C}	3.6 ± 0.3^{C}
	48.3–75.5	72.1–108.2	36.1–58.8	4.1–4.9	3.2–3.9

[a] Mean ± standard deviations are shown in the first and min–max values are shown in the second rows. [b] Capital letters (A, B, C, and D) show results used to compare means. Within each row, means that are connected with the same letter are not significantly different ($p < 0.05$).

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Table 4 Emission rates (ER) of the target VOCs[a,b]

	Comp. name							
	Phenol	*p*-Cresol	*o*/*m*-Cresol	Benzene	Toluene	Ethylbenzene	*o*-Xylene	*m*/*p*-Xylene
ER (μg s^{-1})								
Gestation	70.4 ± 16.5^{A}	231 ± 18.8^{A}	107 ± 20.9^{A}	48.4 ± 9.2^{A}	242 ± 17.6^{A}	189 ± 25.2^{A}	206 ± 29^{A}	260 ± 20.0^{A}
	42.7–86.3	209–259	79.8–133	37.1–59.7	219–263	157–219	167–251	230–284
Farrowing	14.1 ± 4.4^{B}	50.7 ± 3.5^{B}	22.6 ± 4.5^{B}	10.3 ± 1.8^{B}	53.3 ± 5.0^{B}	39.4 ± 4.7^{B}	41.6 ± 5.6^{B}	54.3 ± 4.8^{B}
	8.3–18.5	46.2–55.0	15.7–27.9	7.9–12.3	46.4–59.7	32.0–44.2	34.2–48.4	47.2–59.5
Nursery	5.5 ± 2.4^{B}	16.5±4^{C}	8.7 ± 3.3^{B}	3.8 ± 0.8^{B}	17.8±6^{C}	14.1±4^{C}	16 ± 4.1^{B}	20.4±6^{C}
	3.2–9.3	11.2–21.7	5.7–13.8	3.0–4.9	12.3–26.7	10.8–20.2	12.1–21.5	14.7–29.7
ER (μg s^{-1} m^{-2})								
Gestation	0.10 ± 0.02^{A}	0.31 ± 0.03^{B}	0.14 ± 0.03^{A}	0.07 ± 0.01^{A}	0.33 ± 0.02^{A}	0.26 ± 0.03^{A}	0.28 ± 0.04^{A}	0.35 ± 0.03^{A}
	0.06–0.12	0.28–0.35	0.11–0.18	0.05–0.08	0.30–0.36	0.21–0.30	0.23–0.34	0.31–0.38
Farrowing	10 ± 0.03^{A}	35 ± 0.15^{A}	0.16 ± 0.03^{A}	0.07 ± 0.01^{A}	0.37 ± 0.03^{A}	0.27 ± 0.03^{A}	0.29 ± 0.04^{A}	0.38 ± 0.03^{A}
	0.06–0.13	0.32–0.38	0.11–0.19	0.06–0.09	0.32–0.41	0.22–0.31	0.24–0.34	0.33–0.41
Nursery	0.03 ± 0.01^{B}	0.09 ± 0.02^{C}	0.05 ± 0.02^{B}	0.02 ± 0.00^{B}	0.10 ± 0.03^{B}	0.08 ± 0.02^{B}	0.09 ± 0.02^{B}	0.11 ± 0.04^{B}
	0.02–0.05	0.06–0.12	0.03–0.08	0.02–0.03	0.07–0.15	0.06–0.11	0.07–0.12	0.09–0.17
ER (μg per s per head)								
Gestation	0.23 ± 0.05^{B}	0.77 ± 0.06^{B}	0.36 ± 0.07^{B}	0.16 ± 0.03^{B}	0.81 ± 0.06^{B}	0.63 ± 0.08^{B}	0.69 ± 0.10^{B}	0.87 ± 0.07^{B}
	0.14–0.29	0.70–0.86	0.27–0.44	0.12–0.20	0.73–0.88	0.52–0.73	0.56–0.84	0.77–0.95
Farrowing	0.73 ± 0.43^{A}	2.6 ± 1.31^{A}	1.41 ± 0.28^{A}	0.64 ± 0.11^{A}	3.33 ± 0.31^{A}	2.46 ± 0.30^{A}	2.60 ± 0.35^{A}	3.39 ± 0.30^{A}
	0.52–1.16	2.89–3.43	0.98–1.74	0.50–0.77	2.90–3.73	2.00–2.76	2.13–3.02	2.95–3.72
Nursery	0.01 ± 0.01^{B}	0.04 ± 0.0^{C}	0.02 ± 0.01^{C}	0.01 ± 0.00^{C}	0.04 ± 0.01^{C}	0.03 ± 0.01^{C}	0.04 ± 0.01^{C}	0.05 ± 0.01^{C}
	0.01–0.02	0.02–0.05	0.01–0.03	0.01–0.01	0.03–0.06	0.02–0.04	0.03–0.05	0.03–0.07

[a] Mean ± standard deviations are shown in the first and min–max values are shown in the second rows. [b] Capital letters (A, B and C) show results used to compare means. Within each column, means that are connected with the same letter are not significantly different ($p < 0.05$). Emissions rates in μg s^{-1}, μg s^{-1} m^{-2} and μg per s per head should be evaluated separately.

This can be due to the differences between dairy and swine species. Chmielowiec-Korzeniowska[37] measured benzene (19 μg m^{-3}), ethylbenzene (25 μg m^{-3}), xylene (32 μg m^{-3}), and toluene (14 μg m^{-3}) concentrations of swine fattening houses. These concentrations were close to the ones reported in Table 3. Cai *et al.*[15] measured VOC concentrations of swine rooms and reported mean *p*-cresol and phenol concentrations of gestation rooms as 69.0 ± 55.8 and 7.0 ± 4.5 μg m^{-3},

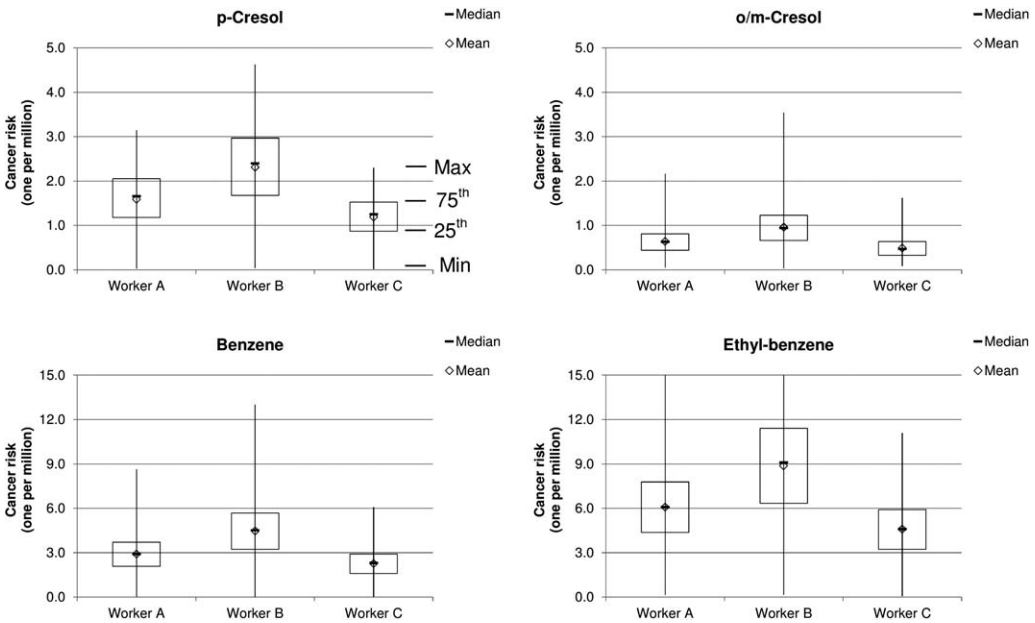

Fig. 2 Cancer risks of workers A (gestation), B (farrowing), and C (nursery). Box plots represent the 25th, 50th (median), and 75th percentiles.

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respectively. These values were also close to the ones reported in Table 3.

Emission rates (μg s^{-1}, μg s^{-1} m^{-2}, and μg s^{-1} $head^{-1}$) of the target VOCs are shown in Table 4. Airflow rates of the gestation, farrowing and nursery rooms ranged from 3.96 to 5.15 m^3 s^{-1}, 0.57 to 0.69 m^3 s^{-1}, and 0.39 to 0.54 m^3 s^{-1}, respectively.

The highest emission rates (for all VOCs) in μg s^{-1} were measured for the gestation room. For *p*-cresol, toluene, ethylbenzene, and *m*/*p*-xylene, the lowest emission rates were measured for the nursery room. For other compounds there was no significant difference between emission rates of the nursery and farrowing rooms. When emission rates in μg s^{-1} m^{-2} were compared, except for *p*-cresol there was no significant difference between emission rates of gestation and farrowing rooms but emission rates of the nursery room were significantly lower. When emission rates in μg s^{-1} $head^{-1}$ were considered, the highest emission rates were calculated for the farrowing room. It was followed by the gestation and nursery rooms. There are no studies in the literature that report BTEX emission rates of dairy or swine farms, but Cai *et al.*[15] measured phenol and *p*-cresol emission rates of swine finishing barns. Emission rates of phenol were 0.06 μg s^{-1} m^{-2} and 0.07 μg s^{-1} $head^{-1}$ and emission rates of *p*-cresol were 0.91 μg s^{-1} m^{-2} and 1.09 μg s^{-1} $head^{-1}$ during winter season. Although these values were reported for swine finishing rooms, they were close to the ones reported for the gestation rooms in Table 4.

Cancer and hazard risks of the target VOCs

Concentrations of the target VOCs did not exceed their recommended exposure limits (RELs). But, *p*-cresol and benzene concentrations of the rooms exceeded their preliminary remediation goals (PRGs) (Tables 2 and 3).

Monte Carlo simulation results are presented in Fig. 2 and 3. The median (50^{th} percentile), 25^{th} and 75^{th} percentiles, minimum and maximum values of the calculated risks are shown in these figures. Mean risk values are given in Table 5. Table 5 also shows cumulative cancer and hazard risks.

Cancer risk. Box plots of cancer risks are shown in Fig. 2. Among four carcinogenic VOCs studied, ethylbenzene had the highest median and mean cancer risk values. Mean risk values of ethylbenzene for workers A (gestation), B (farrowing), and C (nursery) were 6.07, 8.86, and 4.59 per million, respectively (Fig. 2, Table 5). These risk values exceeded EPA's benchmark of one per million (10^{-6}). Risk values of benzene and *p*-cresol also exceeded EPA's benchmark. Mean risk values of benzene were 2.91 (worker A), 4.47 (worker B), and 2.26 (worker C) and mean risk values of *p*-cresol were 1.59 (worker A), 2.31 (worker B), and 1.19 (worker C) per million (Fig. 2, Table 5). Nadal *et al.*[34] studied cancer risks of occupational exposure in a municipal waste organic fraction treatment plant and reported risk values ranging from 1.53 to 8.59 per million. These risk values were in the same range as the ones found in this study.

Worker B who spent six hours in the farrowing room and one hour in the office space per day had the highest cumulative cancer risk (16.6 per million). It was followed by worker A (11.21 per million), who spent six hours in the gestation barn and worker C (8.53 per million), who spent six hours in the nursery barn per day (Table 5).

Hazard risk. Box plots of hazard risks are shown in Fig. 3. Among eight VOCs, benzene had the highest mean and median hazard risks. Mean hazard risk values of benzene were about 5 (worker A), 8 (worker B), and 4 (worker C) thousand per million. Benzene was followed by toluene, *p*-cresol and *o*/*m*-cresol. Hazard risks of these VOCs exceeded the maximum acceptable risk threshold (10^{-4}) (Nadal *et al.*, 2009). Hazard risks of ethylbenzene, *o*-xylene, and *m*/*p*-xylene were relatively small (less than 35 per million). This was expected since their REL values were higher than those of other VOCs.

Worker B (farrowing) had the highest hazard risk. Worker B's mean hazard risk ranged from 30 to 8000 per million. Worker B was followed by worker A (gestation) with a hazard risk between 16 and 5000 per million and worker C (nursery) with a hazard risk between 12 and 4000 per million. The cumulative hazard risk of worker B (farrowing) was about 11.3 thousand per

Table 5 Cancer and hazard risks of the target VOCs ($\times 10^{-6}$)[a]

	Carcinogenic risk			Non-carcinogenic risk		
Compound name	Worker A[b]	Worker B	Worker C	Worker A	Worker B	Worker C
Phenol	—	—	—	122.3	175.6	94.8
p-Cresol	1.59	2.31	1.19	877.7	1288	659.3
o/*m*-Cresol	0.64	0.96	0.49	351.1	526.0	273.8
Benzene	2.91	4.47	2.26	5075	7869	3995
Toluene	—	—	—	947.8	1406	716.9
Ethylbenzene	6.07	8.86	4.59	15.6	22.9	12.0
o-Xylene	—	—	—	15.6	22.9	11.7
m/*p*-Xylene	—	—	—	20.9	31.0	16.2
Total risk	11.21	16.6	8.53	7426	11 342	5780

[a] Mean risk values of the target VOCs are shown. Total risk is calculated by summing individual risks. [b] Workers A, B, and C work 7 hours a day. Worker A spends six hours in the gestation barn, worker B spends six hours in the farrowing barn, and worker C spends six hours in the nursery barn. All workers spend one hour a day in the office space.

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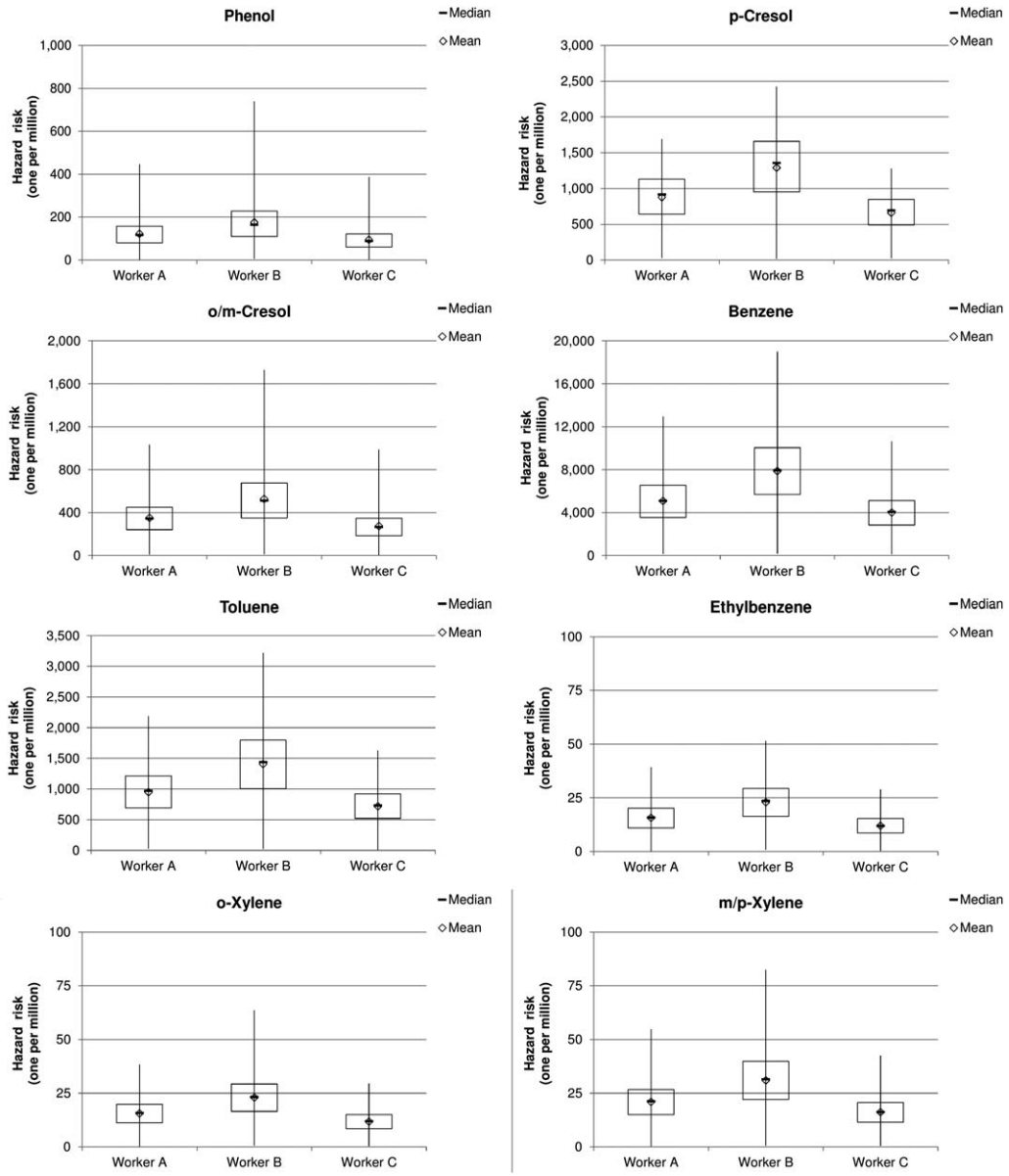

Fig. 3 Hazard risks of workers A (gestation), B (farrowing), and C (nursery). Box plots represent the 25th, 50th (median), and 75th percentiles.

million, which means 1.13% of the farrowing barn workers are likely to have serious chronic health problems. It should be noted that this value was calculated using mean risk values. If the minimum risk values had been used, the cumulative risk would have been 0.03 and if the maximum risk values had been used, the cumulative risk would have been 2.7%. It should be also noted that these cumulative risks were calculated for eight VOCs. The cumulative hazard risks can be two or three times higher when all hazardous VOCs are taken into account.

Sensitivity analysis. Sensitivity analysis results are shown in Fig. 4. Results of workers A (gestation), B (farrowing), and C (nursery) were similar to each other. IUR had the highest impact on cancer risk assessment (57–93%) while REL had the highest impact on hazard risk assessment (47–94%). This indicated that although the sample size was not big uncertainty in measurements did not exceed the uncertainty in IUR and REL values. Unlike the results of this study, Zhou *et al.*[7] reported that VOC concentrations were more influential than IURs on cancer risk assessment. This was explained as a result of uncertainty generated due to small sample size.

Office space concentrations had a very small impact (<1%) on the cancer and hazard risk calculations. This was expected since workers spent a small portion of their time in the office space and office space concentrations were much lower than those of swine rooms. *o*/*m*-Cresol had a higher impact (35%) on cancer risk estimate compared to benzene (21%), ethylbenzene (21%), and *p*-cresol (6%). For hazard risk assessment, phenol had the highest impact (45%), followed by *o*/*m*-cresol (35%), benzene and ethylbenzene (22%), *o*-xylene and *m*/*p*-xylene (21%), toluene (17%) and *p*-cresol (6%).

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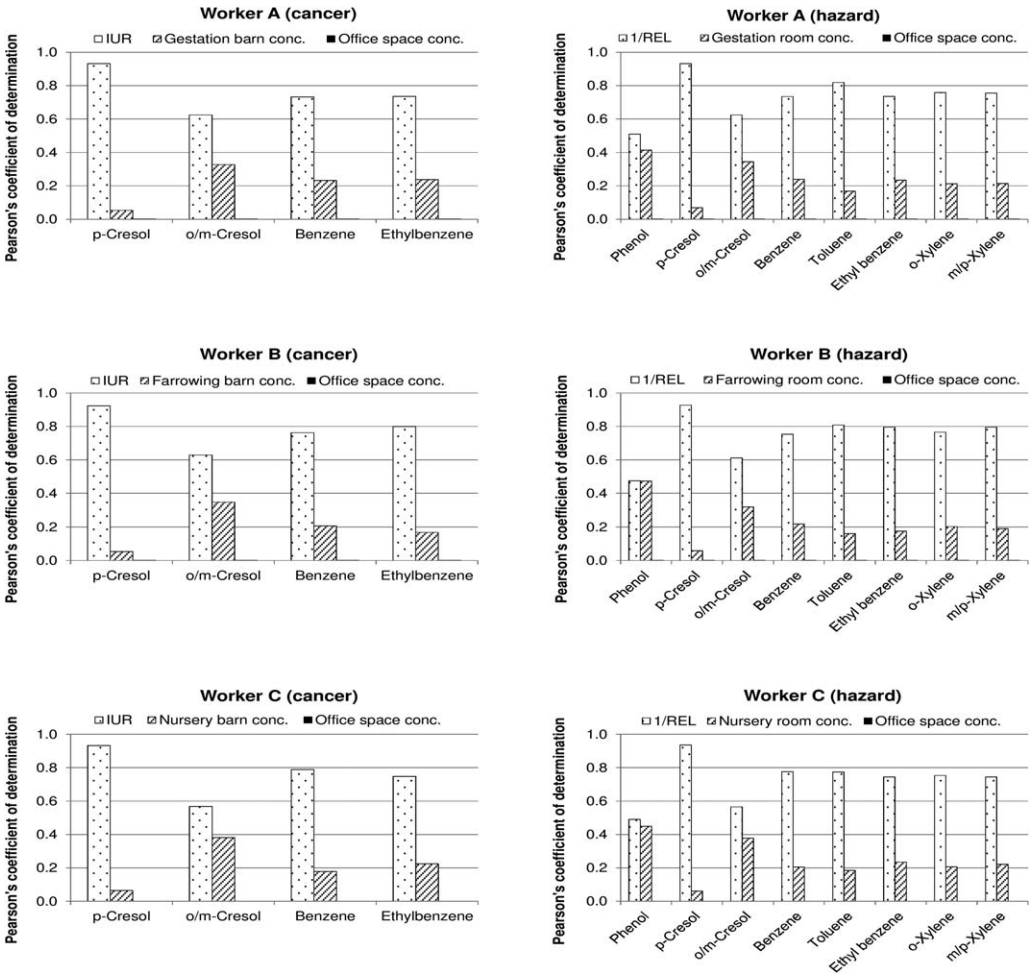

Fig. 4 Sensitivity analysis of cancer (left) and hazard risk (right) assessments (IUR: inhalation unit risk and REL: recommended exposure limit).

Conclusions

Concentrations of the target VOCs did not exceed their recommended exposure limits (RELs). But, *p*-cresol and benzene concentrations of the rooms exceeded their preliminary remediation goals (PRGs). Farrowing room concentrations were significantly higher than nursery and gestation room concentrations. Except for *p*-cresol, there was no significant difference between the concentrations of gestation and nursery rooms. The highest emission rates in μg s^{-1} were measured for the gestation rooms while the highest emission rates in μg s^{-1} $head^{-1}$ were measured for the farrowing rooms.

Cancer risks of ethylbenzene, benzene and *p*-cresol exceeded EPA's benchmark threshold (10^{-6}). Hazard risks of benzene, toluene, *p*-cresol, and *o*/*m*-cresol exceeded the maximum acceptable risk threshold (10^{-4}). Worker B who spent six hours in the farrowing room and one hour in the office space per day had the highest cumulative cancer and hazard risks. The cumulative hazard risk of worker B was 1.13%. It was followed by worker A (gestation room) and worker C (nursery room). To prevent exposure to high concentrations for a long period of time, workers can be rotated between tasks.

Inhalation unit risk had the highest impact on cancer risk assessment and REL had the highest impact on hazard risk assessment. This indicated that uncertainty in measurements did not exceed the uncertainty in IUR and REL values. Although uncertainty in measurements was not high, in future studies VOC samples can be collected for longer periods of time. Also, VOC samples can be collected from swine finishing rooms and other types of animal buildings.

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