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Research Article

Phthalate Concentration Estimation and Exposure Assessment and Health Risk Assessment in Indoor Organic Film

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Organic films act as passive air samplers and can be employed to assess the concentration of semivolatile organic compounds (SVOCs), such as phthalates, in the gas phase over a defined period using the kinetic adsorption model. Consequently, indoor organic films have been identified as effective media for evaluating human exposure to SVOCs. This study proposed an organic film-based method for assessing SVOC exposure in the indoor environment. Exposure assessments of various phthalate pathways were conducted on children and adults. Organic films were collected for analysis from 110 residential dwellings in metropolitan areas over a two-month period. The exposure assessments were categorized into inhalation, oral, and dermal exposure pathways. Diethyl phthalate was highest in inhalation exposure, dibutyl phthalate represented the highest dermal exposure, and bis(2-ethylhexyl) phthalate was identified as the highest contributor to oral exposure. For children, the primary exposure pathways included dermal absorption of DBP, DEP, diisobutyl phthalate (DiBP), butylbenzyl phthalate (BBP), and di-n-hexyl phthalate (DNHP); dust ingestion of DEHP and di-n-octyl phthalate (DNOP); and inhalation of dimethyl phthalate (DMP). The ECR and HQ for inhalation, dermal, and ingestion did not exceed the threshold in children and adults at all pollutants, suggesting no potential health impact. In contrast, the primary routes of exposure for adults were dermal absorption of DBP, DMP, DEP, DiBP, BBP, and DNHP, along with dust ingestion of DEHP and DNOP. The findings of this study provide valuable baseline data for future research in health risk and SVOC exposure assessments utilizing indoor organic films.

1. Introduction

The use and production of consumer products containing chemical substances such as semivolatile organic compounds (SVOCs) has continued to increase since the mid-20th century [1]. SVOCs encompass a wide range of chemical compounds, including phthalates, bisphenols, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polybromodiphenyl ethers (PBDEs). According to the World Health Organization [2], SVOCs have boiling points at standard atmospheric pressure (101.3 kPa) falling within the range of 240–260°C and 380–400°C. They are often detected in the furniture and home appliances used by residents as well as the finishing materials on floors and walls for flame-retardant properties and plasticity. SVOCs are released from various common chemical products and materials used in indoor environments, and they form organic films on impermeable surfaces, such as windows, through processes like absorption, adsorption, or condensation. Organic films are known to reduce hazardous chemical substances in the air but also act as sources of human exposure to these substances. Certain SVOCs have

been linked to neurotoxicity and reproductive damage in humans [3].

Phthalates, well-known endocrine-disrupting chemicals among SVOCs, serve as plasticizers to add softness and flexibility to various plastic products, ranging from construction materials to cables, floor materials, toys, and tableware [4]. Human exposure to phthalates has been associated with xenobiotic metabolism and mutations in the reproductive system, such as DNA damage in sperm [5, 6]. Phthalates can volatilize from their source materials into the air, and the release coefficient increases with temperature. Once airborne, phthalates can redistribute into gas or particle phases or undergo wet or dry deposition processes like oxidation and photolysis in the atmosphere [7, 8]. Human exposure to phthalates can occur through various routes, including contact with different products in daily activities, inhalation from the air, and, for children, potentially through phthalate use in plastic products like food containers, cosmetic containers, and toys, which could enter the mouth or be ingested [9–11].

Numerous studies have investigated human exposure to indoor phthalates, predominantly focusing on the health impacts associated with phthalate exposure from house dust [10–14]. However, since house dust can be easily removed through cleaning, these studies typically consider exposure via dust ingestion, and few have assessed the health impacts of each different phthalate exposure pathway individually. However, after release from sources, SVOCs in indoor environments can exist in both the gas phase and be adsorbed onto indoor airborne particles [4]. Phthalate exposure pathways can include inhalation of airborne or particulate substances, dust ingestion, and skin contact, highlighting the need for an exposure assessment and health risk assessment that accounts for all the various pathways.

Furthermore, organic films that adsorb onto indoor surfaces can be used to study pollutant accumulation and behavior. Indoor organic films function as passive air samplers and have shown promise for monitoring and estimating human SVOC exposure in the gas phase using the kinetic adsorption model over a defined period [9]. SVOCs with an octanol-to-air distribution coefficient $(\log K_{oa}) < 14$ approximate the values expected by the equilibrium partitioning model, and compounds with low $\log K_{oa}$ values have been shown to reach equilibrium between the air and organic films rapidly [9]. Since organic films act as natural passive air samplers, they can accumulate phthalates from indoor air through surface adsorption, allowing for the estimation of long-term phthalate pollution levels using impermeable and homogeneous organic films [15]. However, despite several studies investigating phthalate exposure using indoor organic films globally [4, 9, 16, 17], none have been conducted in South Korea. In addition, human exposure studies conducted through indoor organic films are focused on exposure assessment, and only studies that evaluated the health effects of ingestion exposure to phthalates have been conducted [17]. Phthalates that can occur indoors can be exposed to the human body through various exposure pathways such as inhalation, dermal, and ingestion [4]. However, there are no studies that have evaluated the health effects of phthalates by considering all three exposure pathways through which the human body can be exposed.

Therefore, this study proposes a method for assessing SVOC exposure and health risk in an indoor environment using organic films collected from residential buildings. Inhalation, dermal, and oral exposures were assessed. Distribution coefficients were used to determine the phthalate concentration among SVOCs in gas, particle, and dust phases. As a result, this study provides baseline data for a method using indoor organic films to assess SVOC exposure and health risk assessment.

2. Methods

2.1. Test Materials. This study measured and analyzed the concentration of eight phthalates: bis(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DiBP), butylbenzyl phthalate (BBP), di-n-octyl phthalate (DNOP), and di-n-hexyl phthalate (DNHP). These SVOCs are detectable in indoor organic films based on studies conducted in South Korea and overseas [9, 14]. The aim was to perform an exposure assessment of SVOCs in organic films through multiple exposure pathways. All standard phthalate samples were purchased from AccuStandard, Inc. (New Haven, CT, USA).

2.2. Measurements and Data Analysis. From September to November 2020, phthalate concentrations were measured in 110 residential houses in metropolitan regions (Seoul-si, Gyeonggi-do, and Incheon-si). The characteristics of the residences are summarized in Table 1. Organic films generated on impervious surfaces in various spaces, such as kitchen hoods, kitchen glass windows, living room glass windows, and bathroom mirrors, were collected using ethyl alcohol-soaked wipes to measure phthalate concentrations (TX-3211 AlphaWipe, Texwipe, Kernersville, USA) (Figure 1). Enough sample extract was applied to ensure adequate absorption by the alcohol wipes. After sample collection, the alcohol wipes were placed in brown vials to prevent changes due to ultraviolet light exposure, and the vials were stored at low temperature (≤6°C). The Soxhlet extraction was performed for 240 min by placing the alcohol wipe in the vial with 100 mL of pretreated DCM (20% in hexane *v*/*v*) in the Soxhlet extraction cup. The extracted phthalates were measured in 5 mL volumetric flasks.

Gas chromatography/mass spectrometry (GC/MS, Agilent 8890, USA) was used to assess the phthalates in the organic films in accordance with US Environmental Protection Agency (EPA) Method 8270E (SW-846) [18] and the Safety Test Criteria for Household Chemical Products [19] as indicated by the National Institute of Environmental Research; analysis conditions are shown in Table 2. A DB-5 column was used in the analysis (length 60 m × diameter 0.32 mm × film thickness 0.25 μm, Agilent. The injector was maintained at 280°C, and the column temperature was maintained at 70°C for 1 minute, then raised to 120°C at a rate of 25°C per minute, then raised to 4°C per minute, and maintained at 150°C for 2 minutes. Thereafter, the

Table 1: Summary of building characteristics of 110 studied residences.

Variables	Description	Results (n, %)
Building type	Apartment	69 (62.7%)
	Multi complex house	31 (28.2%)
	Studio apartment	4 (3.6%)
	House	6 (5.5%)
Building age	<2 years	10 (9.1%)
	2-9 years	21 (19.1%)
	10-19 years	31 (28.2%)
	≥20 years	46 (41.8%)
	No response	2 (1.8%)
Building floor level	1-3	37 (33.6%)
	4-7	34 (30.9%)
	8-15	23 (20.9%)
	≥16	14 (12.7%)
	No response	2 (1.8%)
Number of family	1	16 (14.5%)
	2-3	60 (54.5%)
	4	26 (23.6%)
	≥5	6 (5.5%)
	No response	2 (1.8%)
Frequency of indoor air ventilation	≤1 hours per day	38 (34.5%)
	1-6 hours per day	42 (38.2%)
	7-12 hours per day	2 (1.8%)
	Everyday	25 (22.7%)
	No response	2 (1.8%)
Frequency of cleaning	1-2 times per week	67 (60.9%)
	3-5 times per week	21 (19.1%)
	Everyday	20 (18.2%)
	No response	2 (1.8%)

temperature was raised to 300°C at a rate of 4°C per minute and maintained for 8 minutes. Mass spectrometry was performed at 70 eV in electron ionization mode. The phthalate detection range was 50-500 m/z in selected ion monitoring (SIM) mode, and the quantitation ion levels for DEHP, DBP, DMP, DEP, DiBP, BBP, DNOP, and DNHP were 279, 223, 163, 149, 223, 206, 279, and 251 m/z, respectively.

2.3. Quality Assurance and Control. The Soxhlet extraction method was used to perform the recovery test on the phthalates. Each alcohol wipe was placed in the Soxhlet extraction cup with 100 mL of the extraction solution (20% dichloromethane in hexane, v/v) for 240 min of extraction. The recovery was estimated as a percentage by dividing the measured concentration by the spiked theoretical concentration in a 5 mL volumetric flask. The method detection limit (MDL) for phthalates was calculated by multiplying the standard deviation by 3.14. The recovery for the target phthalates was measured in triplicate using each respective reference solution, and the mean recovery for each phthalate was as follows: DEHP, 96.85%; DBP, 101.87%; DMP, 103.20%; DEP, 109.15%; DiBP, 91.78%; BBP, 81.31%; DNOP, 89.83%; and DNHP, 88.03%. The MDLs for each phthalate were as follows: DEHP, 110.15 ng/m^2; DBP, 32.01 ng/m^2; DMP, 23.99 ng/m^2; DEP, 85.40 ng/m^2; DiBP, 99.23 ng/m^2; BBP, 54.89 ng/m^2; DNOP, 117.05 ng/m^2; and DNHP, 68.99 ng/m^2.

2.4. Exposure Assessment. To perform an exposure evaluation of SVOCs in organic films, the observed concentrations of SVOCs in organic films and distribution coefficients were utilized to estimate the gas, particle, and dust phase concentrations. The exposure evaluation of SVOCs per exposure pathway (i.e., inhalation, dust ingestion, and skin absorption) was performed using the calculated concentrations. The respective equations for the concentrations of SVOCs in the gas, particle, and dust phases are as follows [9, 19]:

$$\begin{aligned} C_g &= \frac{C_F}{K_{oa} \times f_{om} \times F_t}, \\ C_p &= C_g \times K_p \times \mathrm{TSP}, \\ C_d &= C_g \frac{f_{om\_d} \times K_{oa}}{\rho_d}, \end{aligned} \tag{1}$$

where C_g is the concentration of SVOCs in the gas phase (μg/m^3), C_F is the concentration of SVOCs in organic films (μg/m^2), f_{om} is the ratio of organic compounds (assumed to be 0.4) [20], K_{oa} is the octanol-air distribution coefficient, F_t is the organic film thickness (m) (assumed to be 1 m) [21], C_p is the concentration of SVOCs in the particle phase (μg/m^3), K_p is the gas-particle distribution coefficient (m^3/g), TSP is the mean particle concentration in indoor air (μg/m^3) (assumed to be 20 μg/m^3) [19], C_d is the concentration of SVOCs in the dust phase (μg/g), f_{om_d} is the volume ratio of organic compounds related to dust (assumed to be 0.2) [9], and ρ_d is the density of dust (g/m^3) (assumed to be 2×10^6 g/m^3) [9]. The distribution coefficients used in this study are shown in Table 3.

The SVOC exposure assessment in organic films was conducted for each exposure pathway, including inhalation exposure of concentrations in gas and particle phases, dermal exposure through organic films and gas phase concentrations, and oral exposure through dust phase concentrations. The average daily exposure to SVOCs for each exposure pathway was calculated according to the following equations:

$$\begin{aligned} A_{inh} &= \frac{(C_g + C_p) \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{ET}}{\mathrm{BW} \times \mathrm{AT}}, \\ A_{dermal} &= \frac{C_g \times \mathrm{SA} \times K_{p\_g} \times f_{SA} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{ET}}{\mathrm{BW} \times \mathrm{AT}}, \\ A_{dust} &= \frac{C_d \times f_2 \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{ET}}{\mathrm{BW} \times \mathrm{AT}}, \end{aligned} \tag{2}$$

where A_{inh} is the level of inhalation exposure (mg/kg/day), IR is the inhalation rate (m^3/day), EF is the exposure frequency

(a) Living room (b) Kitchen

(c) Bathroom

Figure 1: Organic film collection area.

Table 2: Analysis condition of GC/MS in this study.

Pollutants	Extract solution	Analysis condition		Reference
Phthalate	DCM 20% (in hexane, v/v)	Inlet temperature	280°C	EPA 8270E [18]
		Inflow	1 μL (splitless)	
		Detection temperature	280°C	
		Column	DB-5 (60 m length × 0.32 mm I.D.× film 0.25 μm)	
		Column oven	70°C (1 min) → 25°C/min → 120°C → 4°C/min → 150°C (2 min) → 4°C/min → 300°C (8 min)	
		Inlet temperature	250°C	NIER [19]
		Inlet mode	Splitless	
		Column oven	5°C (5 min) → 15°C/min → 300°C (13 min)	

(day/yr), ED is the exposure duration (yr), ET is the exposure time (h/day), BW is the body weight (kg), AT is the average exposure time (day), A_{dermal} is the level of dermal exposure (mg/kg/day), SA is the surface area (m^2), K_{p_g} is the transdermal permeability coefficient (m/h), f_{SA} is the rate of skin to air contact (0.25) [22], A_{dust} is the level of oral exposure (mg/kg/day), and f_2 is the rate of dust ingestion (g/day).

For the exposure factors such as body weight, inhalation rate, and exposure time, data from the Korean Exposure Factors Handbook for Children [23] and the Korean Exposure Factors Handbook [24], published by the National Institute of Environmental Research, were utilized. As data for South Korea was unavailable, the dust ingestion values and exposure factor rate from USA EPA [25] were used. The exposure factors employed in this study are shown in Table 4.

2.5. Health Risk Assessment. In this study, we conducted health risk assessment on inhalation, dermal, and ingestion exposure to 6 types of phthalates for which toxicity data—DEHP, DBP, DMP, DEP, DiBP, and BBP—were included. We conducted separate health risk assessments

Table 3: Phthalate parameter values.

Phthalates	Molecular weight	log K_{oa}	K_p (m^3/g)	K_d (m^3/day)	K_{p-g} (m/h)
DEHP	390.57	12.56	1.45E+06	3.63E+05	5.8
DBP	278.4	8.631	1.74E+02	4.27E+01	4.8
DMP	194.19	6.694	1.96E+00	4.90E-01	2.9
DEP	222.24	7.023	6.34E+00	1.58E+00	3.4
DiBP	278.35	8.412	1.03E+02	2.57E+01	4.6
BBP	312.37	9.018	4.19E+02	1.05E+02	5.9
DNOP	390.57	12.08	4.81E+05	1.20E+05	5.7
DNHP	334.45	9.800	2.52E+03	6.31E+02	5.6

K_{oa}: octanol-air partition coefficient; K_p: partition coefficient between the gas phase and particle phase; K_d: partition coefficient between the dust and gas phase; K_{p-g}: transdermal permeability coefficient from air through skin; DEHP: bis(2-ethylhexyl) phthalate; DBP: dibutyl phthalate; DMP: dimethyl phthalate; DEP: diethyl phthalate; DiBP: diisobutyl phthalate; BBP: butylbenzyl phthalate; DNOP: di-n-octyl phthalate; DNHP: di-n-hexyl phthalate.

for carcinogens and noncarcinogens. Table 5 shows the toxicity data for exposure pathways of the substances.

Risk was determined using excess cancer risk (ECR) for carcinogens and hazard quotient (HQ) for noncarcinogens. ECR is the product of the cancer slope factor (CSF) and lifetime average daily dose (LADD); meanwhile, HQ is the quotient of the average daily dose (ADD) divided by the reference dose (RfD). Risks were assessed using ECR for carcinogens. With a reference level set at 1.00×10^{-6} (excess cancer risk per one million individuals), as specified by the US EPA, we situated ECR values exceeding this threshold indicative of a potential health risk. For noncarcinogens, a threshold of 1 was used, where HQ values exceeding 1 were deemed to indicate potential risk.

$$\begin{aligned} \text{ECR} &= \text{CSF} \times \text{LADD}, \\ \text{HQ} &= \frac{\text{ADD}}{\text{RfD}}. \end{aligned} \tag{3}$$

3. Results

3.1. Phthalate Concentration Distribution in Organic Films. Table 6 and Figure 2 summarize the concentrations and detection frequency rates of phthalates in organic films. For the 110 investigated homes, the detection frequency rates of phthalates in organic films were as follows: DEHP, 100.0%; DBP, 100.0%; DMP, 17.3%; DEP, 46.4%; DiBP, 95.5%; BBP, 99.1%; DNOP, 70.9%; and DNHP, 9.1%. The highest and lowest mean concentration of phthalates in organic films was exhibited by DEHP ($124.99 \pm 192.89\,\mu g/m^2$) and DMP ($0.11 \pm 0.08\,\mu g/m^2$), respectively. Additionally, the concentration was $23.75 \pm 46.83\,\mu g/m^2$ for DBP, $0.52 \pm 0.65\,\mu g/m^2$ for DEP, $9.90 \pm 21.94\,\mu g/m^2$ for DiBP, $1.49 \pm 2.29\,\mu g/m^2$ for BBP, $6.76 \pm 28.33\,\mu g/m^2$ for DNOP, and $1.10 \pm 0.72\,\mu g/m^2$ for DNHP. The phthalate concentrations in organic films, in decreasing order, were DEHP > DBP > DiBP > DNOP > BBP > DNHP > DEP > DMP.

3.2. Estimated Phthalate Concentrations in Gas, Particle, and Dust Phases. Table 7 shows the estimated concentrations of the eight target phthalates in the gas, particle, and dust phases derived from organic films, as calculated using the concentrations in organic films and the distribution coefficients.

In the gas phase, the highest and lowest median concentration were DEP ($4.50 \times 10^{-2}\,\mu g/m^3$) and DNOP ($8.15 \times 10^{-7}\,\mu g/m^3$). In the particle phase, the highest and lowest median concentrations were DEHP ($1.23 \times 10^{-3}\,\mu g/m^3$) and DMP ($1.38 \times 10^{-6}\,\mu g/m^3$). In the dust phase, the highest and lowest median concentrations were DEHP ($15.4\,\mu g/m^3$) and DMP ($1.73 \times 10^{-2}\,\mu g/m^3$).

3.3. Exposure Assessment of Phthalates. Table 8 shows the average daily exposure by each exposure pathway for the phthalates in the gas, particle, and dust phases arising from organic films.

The normality test determined that the measured phthalate values in organic films were skewed; thus, the median was used to estimate the levels of inhalation, dermal, and oral exposures in the assessment. For the phthalates in organic films, the average daily inhalation exposure indicated that the level of exposure was the highest for DEP at 4.14×10^{-5} mg/kg/day and the lowest for DNOP at 7.97×10^{-9} mg/kg/day in children and the highest for DEP at 6.73×10^{-6} mg/kg/day and the lowest for DNOP at 1.30×10^{-9} mg/kg/day in adults. The average daily dermal exposure was the highest for DBP at 5.36×10^{-5} mg/kg/day and the lowest for DNOP at 1.28×10^{-9} mg/kg/day in children and the highest for DBP at 2.07×10^{-5} mg/kg/day and the lowest for DNOP at 4.96×10^{-10} mg/kg/day in adults. The average daily oral exposure was the highest for DEHP at 3.90×10^{-5} mg/kg/day and the lowest for DMP at 4.37×10^{-8} mg/kg/day in children and the highest for DEHP at 3.15×10^{-6} mg/kg/day and the lowest for DMP at 3.53×10^{-9} mg/kg/day in adults.

Figure 3 compares the contribution of each substance in the three exposure pathways. For children, the main exposure pathway was dermal absorption for DBP, DEP, DiBP, BBP, and DNHP at 39.6–57.7% contribution, dust ingestion for DEHP and DNOP at 96.4–96.9% contribution, and inhalation for DMP at 53.5% contribution. The primary exposure pathway for adults was dermal absorption for DBP, DMP, DEP, DiBP, BBP, and DNHP which contributed 67.4-78.5%, and dust ingestion for DEHP and DNOP, which contributed 91.8-93.6%.

3.4. Health Risk Assessment of Phthalates. Table 9 shows the health risk by each exposure pathway for the phthalates in the gas, particle, and dust phases arising from organic films.

For DEHP, which is the substance of carcinogenic health risk assessment in this study, ECR was calculated, and only the toxicity reference value for ingestion exposure exists, so only the health risk for ingestion exposure was evaluated. The ECR for ingestion exposure of DEHP was found to be 3.92×10^{-8} for children and 1.27×10^{-6} for adults, which did not exceed the standard of 1.00×10^{-6}.

For DEHP, DBP, DMP, DEP, DiBP, and BBP, which are the substances of noncarcinogenic health risk assessment in

Table 4: The exposure factor values used in this study.

Category	Age groups	Value	Reference
Inhalation rate (m^3/day)	Children	12.73	Korean Exposure Factors Handbook for Children [23]
	Adults	14.62	Korean Exposure Factors Handbook [24]
Body weight (kg)	Children	10.42	Korean Exposure Factors Handbook for Children [23]
	Adults	64.5	Korean Exposure Factors Handbook [24]
Dust ingestion (g/day)	Children	0.035	Korean Exposure Factors Handbook for Children [23]
	Adults	0.02	Update for Chapter 5 of the Exposure Factors Handbook [25]
Surface area (m^2)	Children	0.636	Korean Exposure Factors Handbook for Children [24]
	Adults	1.735	Korean Exposure Factors Handbook [24]
Exposure frequency (day/yr)	Children	365	This study
	Adults		
Exposure duration (day/yr)	Children	6	Risk Assessment Guidance for Superfund [32]
	Adults	24	
Exposure time (h/day)	Children	18.1	Korean Exposure Factors Handbook for Children [23]
	Adults	15.86	Korean Exposure Factors Handbook [24]
Average time (day)	Children	2,190	This study
	Adults	8,760	

Table 5: Toxicity of substances.

Pollutants	Exposure pathway	Carcinogenic Oral slope factor or inhalation unit risk ($(mg/m^3)^{-1}$, $(mg/kg/day)^{-1}$)	Noncarcinogenic RfD(C) or DNEL (mg/m^3, mg/kg/day)	Reference
DEHP	Inhalation	—	1.3E-01	ECHA
	Dermal	—	7.2E-01	ECHA
	Oral	1.4*E*-02	2.0E-02	US EPA
DBP	Inhalation	—	2.0E-02	ECHA
	Dermal	—	7.0E-02	ECHA
	Oral	—	1.0E-01	US EPA
DMP	Inhalation	—	—	—
	Dermal	—	—	—
	Oral	—	9.4E+00	ECHA
DEP	Inhalation	—	2.6E+00	ECHA
	Dermal	—	7.5E+00	ECHA
	Oral	—	8.0E-01	US EPA
DiBP	Inhalation	—	7.2E-01	ECHA
	Dermal	—	—	—
	Oral	—	2.1E-01	ECHA
BBP	Inhalation	—	2.0E-01	US EPA
	Dermal	—	4.5E+00	ECHA
	Oral	—	5.0E-01	ECHA

this study, HQ was calculated, and health risks for inhalation, dermal, and ingestion exposure were evaluated, respectively. HQ of inhalation exposure was the highest health risk for DBP and the lowest for BBP. HQ of dermal exposure was the highest health risk for DBP and the lowest for DEHP. HQ of ingestion exposure was the highest health risk for DEHP and the lowest for DMP. However, all phthalates did not exceed the threshold of 1 for both children and adults in all exposure pathways, so there was no possibility of health effects.

4. Discussion

For phthalates in organic films, Li et al. [17] reported that the concentration of DBP was the highest at $87.8 \pm 34.8\,\mu g/m^2$, followed by DEHP at $55.6 \pm 36.6\,\mu g/m^2$ and DiBP at

Table 6: Phthalate concentrations and detection frequency rates in indoor organic films.

Pollutants	N	DF (%)	Concentration distribution ($\mu g/m^2$)				
			Mean	S.D.	Median	Min	Max
DEHP	110	100	124.99	192.89	61.56	3.28	1239.20
DBP	110	100	23.75	46.83	6.90	0.06	251.15
DMP	110	17.3	0.11	0.08	0.07	0.02	0.31
DEP	110	46.4	0.52	0.65	0.29	0.09	3.07
DiBP	110	95.5	9.90	21.94	2.15	0.11	158.85
BBP	110	99.1	1.49	2.29	0.58	0.06	15.09
DNOP	110	70.9	6.76	28.33	0.39	0.12	216.26
DNHP	110	9.10	1.10	0.72	1.27	0.13	2.34

DF: detection frequency; S.D.: standard deviation.

$33.2 \pm 18.3\,\mu g/m^2$. Huo et al. [4] reported that the median concentration in the winter was the highest for DEHP at $7.6\,\mu g/m^2$, followed by DBP at $1.5\,\mu g/m^2$ and DiBP at $0.46\,\mu g/m^2$, and in the summer, the median concentration was the highest for DEHP at $3.6\,\mu g/m^2$, followed by DBP at $1.3\,\mu g/m^2$ and DiBP at $0.27\,\mu g/m^2$. Wang et al. [9], who carried out a study on university residents in China, reported that the mean concentration of phthalates in organic films was the highest for DEHP at $423\,\mu g/m^2$, followed by DBP at $205\,\mu g/m^2$. Thus, earlier research on phthalates in indoor organic films found higher concentrations of DEHP, DBP, and DiBP, which is consistent with our findings. The implication is that, for phthalates in indoor organic films, DEHP, DBP, and DiBP exhibit higher concentrations than other phthalates.

High concentrations of DBP, DMP, DEP, DiBP, BBP, and DNHP were found in this study, while the particle phase had significant concentrations of DEHP and DNOP. The findings were consistent with those of Huang et al. [13], who observed high concentrations of DMP, DEP, and DiBP in the gas phase, and Wang et al. [9], who reported high concentrations of DMP and DEP in the gas phase, as well as DNOP and DEHP in the particle phase. The significant variation in concentrations between the gas and particle phases across different phthalates is presumed to be due to the variation in distribution coefficients between the gas and particle phases for each substance [20]. Previous studies have shown that the vapor pressure decreases as the molecular weight of phthalates increases, and phthalates with low vapor pressures are highly likely to bind to the surface of substances in the particle phase; thus, phthalates with high vapor pressures are abundant in the gas phase [26, 27]. Accordingly, low molecular weight phthalates such as DEP and DMP are believed to be predominantly distributed in the gas phase, whereas high molecular weight phthalates such as DEHP and DNOP tend to be distributed in the airborne particle phase.

Analyzing mean phthalate concentrations by building type showed that concentrations of DEHP, DBP, DEP, and DiBP were the highest in houses at $214.09 \pm 234.66\,\mu g/m^2$, $46.70 \pm 85.35\,\mu g/m^2$, $0.74 \pm 1.03\,\mu g/m^2$, and $14.80 \pm 29.29\,\mu g/m^2$, respectively. This is likely because houses tend to be older than building types. Nevertheless, further studies should be conducted as the number of households investigated for building type was a small sample size. Among the 110 households, 69 were apartments, 31 were multiplex houses, 4 were studios, and 6 were houses.

Abdi et al. [28], who conducted a study in Iran, reported that the average daily inhalation, dermal, and oral exposure was the highest for DEHP at 1.08×10^{-7}, 6.22×10^{-7}, and 1.31×10^{-3} mg/kg/day, respectively, in children, and 4.17×10^{-8}, 1.01×10^{-6}, and 1.82×10^{-4} mg/kg/day, respectively, in adults. In comparison to the results of our study, the levels of inhalation and dermal exposure were lower, whereas the oral exposure was higher. According to a study on university residents in China [9], where the concentrations of phthalates in organic films were estimated to calculate the average daily exposure in gas, particle, and dust phases, the level of inhalation exposure was the highest for DEP at 1.06×10^{-3} mg/kg/day, the level of dermal exposure was the highest for DEP at 2.24×10^{-3} mg/kg/day, and the level of oral exposure was the highest for DEHP at 5.21×10^{-5} mg/kg/day. These levels were all higher than those estimated in our study.

The risk assessment results showed that the health risks of all substances across all exposure pathways were higher for children than for adults. This is believed to be the result of children spending more time indoor than adults and the exposure and health risks being high because children have a lighter average weight. In addition, it is known that younger age groups live closer to the ground and are mainly active on the floor, so it is judged necessary to manage children's exposure through various exposure pathways.

Phthalates are known to be present in various materials and consumer products, where they are used for varying purposes, including not only as plasticizers to add flexibility to plastic products but also as additives in a wide range of everyday products such as cosmetics, dyes, adhesives, air fresheners, toys, and medical supplies. Thus, the differences in the levels of exposure to indoor phthalates between this study and previous studies could be attributed to differences in the patterns of use of everyday chemical products in each country and the influence of indoor human activities and living conditions, such as variations in ornaments, temperature, humidity, and ventilations, on phthalate concentrations. However, it should be noted that this study only measured the concentration of phthalates in organic films in actual residential homes from September to November 2020, in metropolitan regions (Seoul-si, Gyeonggi-do, and Incheon-si; i.e., large cities), which limits extrapolation to other residential environments such as those in agricultural, fishing, and industrial communities. Furthermore, because the respective data were mean values published in the Korean Exposure Factors Handbook for Children [23] in the case of children and in the Korean Exposure Factors Handbook [24] in the case of adults, there is a possibility of over- or underestimation of the body weight, inhalation rate, exposure time, and average lifespan in the estimation of the levels of inhalation, dermal, and oral exposures using organic films.

Most Koreans perform cleaning and ventilation almost every day, and in the case of house dust, which was used

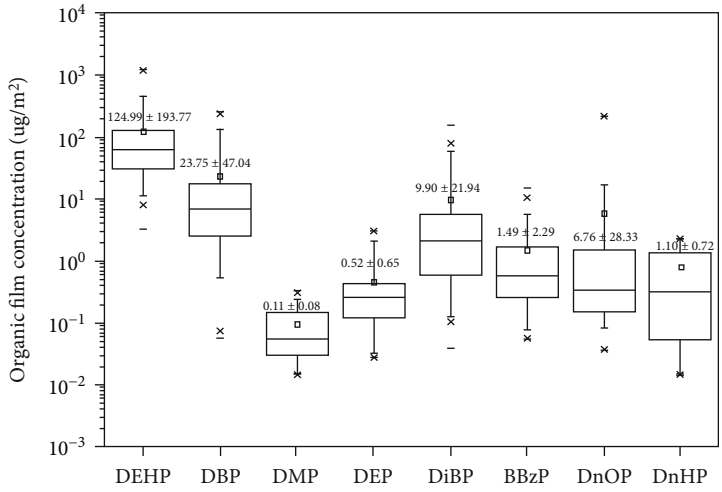

Figure 2: Phthalate concentration distribution in indoor organic films.

Table 7: Estimated phthalate concentrations in gas, particle, and dust phases.

		DEHP	DBP	DMP	DEP	DiBP	BBP	DNOP	DNHP
C_g (μg/m^3)	Mean	8.61E-05	1.39E-01	5.56E-02	8.23E-02	9.63E-02	3.56E-03	1.41E-05	4.37E-04
	Median	4.24E-05	4.04E-02	3.52E-02	4.50E-02	2.10E-02	1.39E-03	8.15E-07	5.03E-04
	Min	2.26E-06	3.40E-04	1.23E-02	1.44E-02	1.03E-03	1.34E-04	2.52E-07	4.95E-05
	Max	8.53E-04	1.47E+00	1.60E-01	4.84E-01	1.54E+00	3.60E-02	4.50E-04	9.29E-04
C_p (μg/m^3)	Mean	2.50E-03	4.75E-04	2.18E-06	1.04E-05	1.98E-04	2.98E-05	1.35E-04	2.21E-05
	Median	1.23E-03	1.38E-04	1.38E-06	5.70E-06	4.31E-05	1.17E-05	7.84E-06	2.54E-05
	Min	6.56E-05	1.16E-06	4.80E-07	1.82E-06	2.12E-06	1.12E-06	2.42E-06	2.50E-06
	Max	2.48E-02	5.02E-03	6.28E-06	6.13E-05	3.18E-03	3.02E-04	4.33E-03	4.69E-05
C_d (μg/g)	Mean	3.12E+01	5.94E+00	2.72E-02	1.30E-01	2.47E+00	3.73E-01	1.69E+00	2.76E-01
	Median	1.54E+01	1.72E+00	1.73E-02	7.13E-02	5.39E-01	1.46E-01	9.80E-02	3.18E-01
	Min	8.20E-01	1.45E-02	6.00E-03	2.28E-02	2.65E-02	1.40E-02	3.03E-02	3.13E-02
	Max	3.10E+02	6.28E+01	7.85E-02	7.67E-01	3.97E+01	3.77E+00	5.41E+01	5.86E-01

C_g: concentration in gas phase; C_p: concentration in particle phase; C_d: concentration in dust phase.

in existing exposure assessments, it is judged that it will be difficult to apply it to indoor SVOC exposure assessment due to the fact that most of it is removed through cleaning and ventilation and redispersion problems. However, since indoor organic films are evaluated for surfaces that are less regularly cleaned than house dust, it is believed to be more useful in reflecting the long-term exposure characteristics of SVOCs.

This study revealed that low-molecular-weight phthalates are predominantly distributed in the gas phase with low to no contribution to oral exposure through dust ingestion, while high-molecular-weight phthalates have a limited contribution to inhalation and dermal exposure. In the gas phase, SVOCs can migrate directly from the skin to the capillaries and into the bloodstream, making dermal adsorption more harmful to the human body [14, 29]. Previous research has also demonstrated that wearing a phthalate-containing garment can increase phase. Thus, low-molecular-weight phthalates are presumed to enter the body mainly through dermal absorption. However, most studies on dermal phthalate exposure assume that it is due to dermal absorption from personal care products or direct contact with phthalate-containing products, and only a few studies consider the possibility of dermal absorption of gas phase phthalates [1, 17, 26, 30, 31]. While exposure pathways for indoor SVOCs include inhalation of airborne or particulate substances, dust ingestion, and skin contact, previous indoor phthalate exposure assessments in South Korea mainly focused on house dust, with no assessments conducted on organic films. However, a phthalate exposure assessment using house dust measures only inhalation exposure and excludes other potential exposure pathways. Thus, to incorporate various phthalate exposure pathways in indoor environments, this study estimated phthalates in organic films to identify the concentrations in varying media. The present investigation is thus highly significant as the first national study to suggest a method of estimating phthalate concentrations via different exposure pathways based on the measured values of

Table 8: Exposure assessment-based phthalate concentration estimates.

Exposure pathway	Pollutants	Age groups	Average daily dose (mg/kg/day)			
			Mean	Median	Min	Max
Inhalation	DEHP	Children	2.38E-06	1.17E-06	6.25E-08	2.36E-05
		Adults	3.87E-07	1.91E-07	1.02E-08	3.84E-06
	DBP	Children	1.29E-04	3.74E-05	3.14E-07	1.36E-03
		Adults	2.09E-05	6.08E-06	5.11E-08	2.21E-04
	DMP	Children	5.12E-05	3.25E-05	1.13E-05	1.48E-04
		Adults	8.32E-06	5.28E-06	1.84E-06	2.40E-05
	DEP	Children	7.58E-05	4.14E-05	1.32E-05	4.46E-04
		Adults	1.23E-05	6.73E-06	2.15E-06	7.25E-05
	DiBP	Children	8.89E-05	1.93E-05	9.52E-07	1.43E-03
		Adults	1.45E-05	3.14E-06	1.55E-07	2.32E-04
	BBP	Children	3.31E-06	1.29E-06	1.24E-07	3.35E-05
		Adults	5.37E-07	2.10E-07	2.02E-08	5.44E-06
	DNOP	Children	1.38E-07	7.97E-09	2.46E-09	4.40E-06
		Adults	2.24E-08	1.30E-09	4.00E-10	7.15E-07
	DNHP	Children	4.23E-07	4.87E-07	4.79E-08	8.99E-07
		Adults	6.88E-08	7.92E-08	7.79E-09	1.46E-07
Dermal	DEHP	Children	1.38E-07	6.79E-08	3.62E-09	1.37E-06
		Adults	5.32E-08	2.62E-08	1.40E-09	5.28E-07
	DBP	Children	1.85E-04	5.36E-05	4.51E-07	1.95E-03
		Adults	7.13E-05	2.07E-05	1.74E-07	7.54E-04
	DMP	Children	4.45E-05	2.82E-05	9.81E-06	1.28E-04
		Adults	1.72E-05	1.09E-05	3.79E-06	4.96E-05
	DEP	Children	7.73E-05	4.22E-05	1.35E-05	4.54E-04
		Adults	2.98E-05	1.63E-05	5.21E-06	1.75E-04
	DiBP	Children	1.22E-04	2.66E-05	1.31E-06	1.96E-03
		Adults	4.72E-05	1.03E-05	5.06E-07	7.58E-04
	BBP	Children	5.80E-06	2.27E-06	2.18E-07	5.87E-05
		Adults	2.24E-06	8.76E-07	8.41E-08	2.27E-05
	DNOP	Children	2.21E-08	1.28E-09	3.96E-10	7.08E-07
		Adults	8.55E-09	4.96E-10	1.53E-10	2.73E-07
	DNHP	Children	6.76E-07	7.79E-07	7.66E-08	1.44E-06
		Adults	2.61E-07	3.01E-07	2.96E-08	5.55E-07
Oral	DEHP	Children	7.92E-05	3.90E-05	2.08E-06	7.85E-04
		Adults	6.40E-06	3.15E-06	1.68E-07	6.35E-05
	DBP	Children	1.50E-05	4.37E-06	3.67E-08	1.59E-04
		Adults	1.22E-06	3.53E-07	2.97E-09	1.29E-05
	DMP	Children	6.89E-08	4.37E-08	1.52E-08	1.99E-07
		Adults	5.58E-09	3.53E-09	1.23E-09	1.61E-08
	DEP	Children	3.30E-07	1.80E-07	5.76E-08	1.94E-06
		Adults	2.67E-08	1.46E-08	4.66E-09	1.57E-07
	DiBP	Children	6.27E-06	1.36E-06	6.71E-08	1.01E-04
		Adults	5.07E-07	1.10E-07	5.43E-09	8.14E-06
	BBP	Children	9.44E-07	3.69E-07	3.55E-08	9.55E-06
		Adults	7.63E-08	2.99E-08	2.87E-09	7.73E-07
	DNOP	Children	4.28E-06	2.48E-07	7.66E-08	1.37E-04
		Adults	3.46E-07	2.01E-08	6.20E-09	1.11E-05
	DNHP	Children	6.99E-07	8.05E-07	7.92E-08	1.48E-06
		Adults	5.65E-08	6.51E-08	6.40E-09	1.20E-07

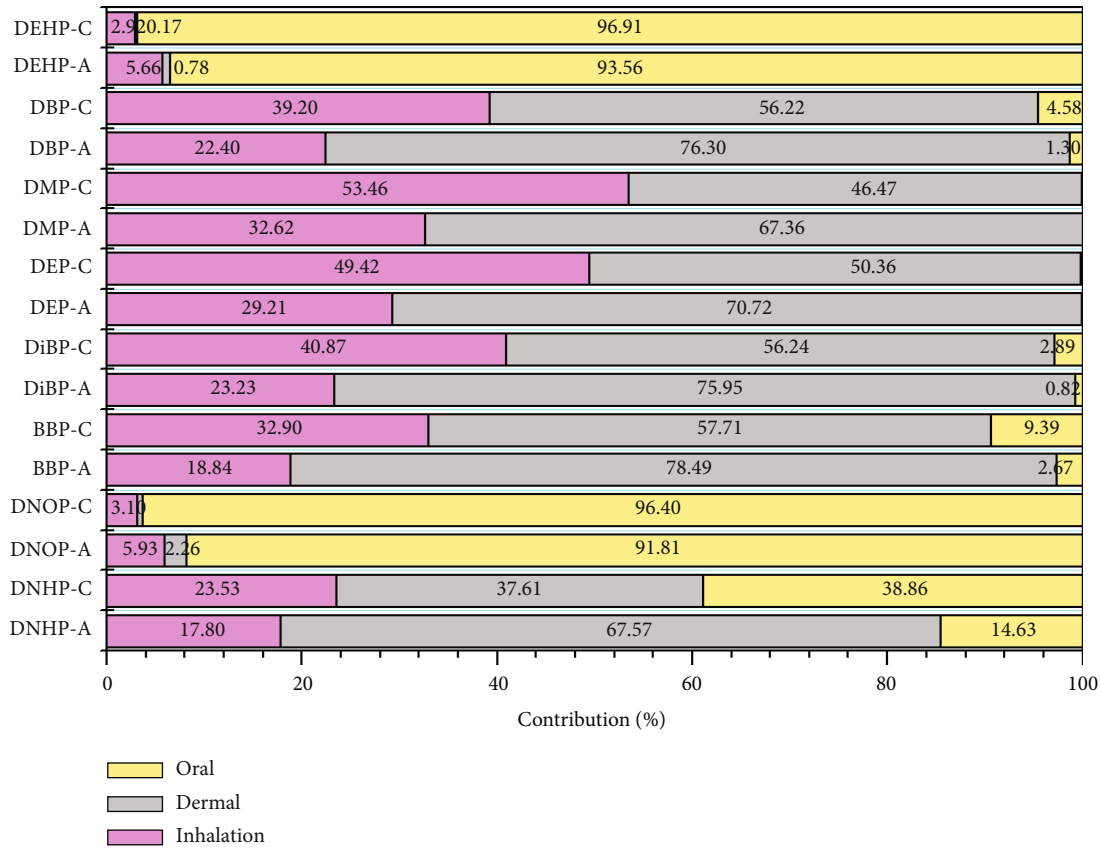

Figure 3: Contribution of each substance based on exposure pathway. -C: children's average daily dose; -A: adult's average daily dose.

Table 9: Health risk assessment-based phthalate concentration estimates.

		DEHP	DBP	DMP	DEP	DiBP	BBP
ECR_oral	Children	3.92E-08					
	Adult	1.27E-08					
HQ_inh	Children	3.16E-05	6.54E-03	—	5.58E-0	9.40E-05	2.26E-05
	Adult	5.14E-06	1.06E-03	—	9.07E-06	1.53E-05	3.68E-06
HQ_dermal	Children	9.43E-08	7.66E-04	—	5.63E-06	—	5.04E-07
	Adult	3.64E-08	2.96E-04	—	2.17E-06	—	1.95E-07
HQ_oral	Children	1.95E-03	4.37E-05	4.65E-09	2.26E-07	6.50E-06	7.38E-07
	Adult	1.58E-04	3.53E-06	3.76E-10	1.82E-08	5.25E-07	5.97E-08

phthalate concentrations in organic films. Therefore, these findings will provide baseline data for health risk and exposure assessment of SVOCs using indoor organic films.

5. Conclusion

This study gathered baseline data for exploring suitable assessment methods of health risk and exposure to phthalates using indoor organic films in accordance with South Korean statutes. The measured phthalate concentrations in organic films in real-world residential conditions were estimated with respect to gas, particle, and dust phases using distribution coefficients. Subsequently, exposure assessment and health risk assessment were conducted on inhalation, dermal, and oral pathways.

In organic films, the highest mean phthalate concentration was that of DEHP at $124.99 \pm 192.89\,\mu g/m^2$. Analyzing the median of estimated phthalate concentration revealed that the highest DEP concentration was $4.50 \times 10^{-2}\,\mu g/m^3$ in the gas phase, the highest DEHP at $1.23 \times 10^{-3}\,\mu g/m^3$ in the particle phase, and the highest DEHP at $15.4\,\mu g/m^3$ in the dust phase. The exposure assessment showed that in children, dermal absorption was the main exposure pathway for DBP, DEP, DiBP, BBP, and DNHP; dust ingestion for DEHP and DNOP; and inhalation for DMP. In adults, the main pathway for DBP, DMP, DEP, DiBP, BBP, and DNHP

exposure was dermal absorption, whereas that of DNOP was dust ingestion. The ECR and HQ for inhalation, dermal, and ingestion did not exceed the threshold in children and adults at all pollutants, suggesting no potential health impact.

This study indicated that low-molecular-weight phthalates are predominantly distributed in the gas phase and do not contribute to oral exposure via dust ingestion, whereas high-molecular-weight phthalates contribute little to dermal exposure and inhalation. Previous exposure assessments on indoor phthalates in South Korea have mostly tested house dust; however, more recent studies have proposed indoor organic films as a medium for assessing SVOC exposure and health risk assessment. This study assessed real-world inhalation, dermal, and oral phthalate exposure pathways in indoor organic films in a South Korean setting. The findings provide useful baseline data for future exposure assessments and health risk assessments, including SVOCs other than phthalates.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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