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Assessing dermal exposure to organochlorine pesticides in different populations of a prototypical agricultural city in South China

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Persistent organic pollutants have been widely detected in the environment and pose a substantial threat to human health. However, few studies have directly investigated exposure to organochlorine pesticides (OCPs) through skin contact. Therefore, we aimed to evaluate dermal exposure to OCPs in different populations in a typical agricultural city in South China. Skin wipe samples were collected from the faces, hands, forearms, and shanks of 120 volunteers (50% male and 50% female) across various age groups. All ten target OCPs were detected in the samples, with concentrations ranging from non-detectable (ND) to 7200 ng/m^2. The concentration of OCPs displayed a consistent pattern of face > hand > forearm > shank regardless of age or sex. Daily average doses of dermal ingestion (DAD_{derm}) and hand-to-mouth contact ingestion (DAD_{oral}) ranged from ND to 68 ng/kg/d and from ND to 7.8 ng/kg/d, respectively. Hexachlorocyclohexane (HCH) was the primary contributor, accounting for 68% of the DAD_{derm} and 91% of the DAD_{oral}. No significant age- or sex-based differences were observed in DAD_{derm}, but DAD_{oral} showed significant variation, being markedly higher in preschoolers than in other age groups and higher in females than in males. Carcinogenic risks associated with OCPs dermal exposure ranged from ND to 2.4×10^{-5}, with older adults facing the highest risk and females having significantly higher risk than males.

Keywords Organochlorine pesticide, Skin wipe sample, Dermal exposure, Carcinogenic risk

Organochlorine pesticides (OCPs), particularly dichlorodiphenyltrichloroethane (DDT) and hexachlorocyclohexane (HCH), have been used extensively in many regions. Despite phased bans since the 1970s, their persistence and propensity for long-distance dispersal have led to substantial residual levels worldwide. Traces of DDT and HCH have been detected in soil, water, air, food, and the human body, presenting severe threats to both the environment and public health, including carcinogenic risks[1,2].

Under aerobic conditions, DDT degrades to DDE, whereas anaerobic conditions produce DDD, which can further dechlorinate to form DDMU. Notably, DDE and DDD exhibit stability that is equal to or greater than that of their precursor DDT[3]. In the early 1960s, global DDT consumption reached approximately 400 000 tons annually, with 70–80% allocated to agriculture[4]. Currently, 4000–5000 tons of DDT is still used annually worldwide, primarily to control the spread of malaria and kala-azar, with a recent uptick in production noted in India, North Korea, and China[5]. Meanwhile, HCH, a powerful organochlorine insecticide with eight isomers, predominantly features α-HCH, β-HCH, γ-HCH, and δ-HCH, with γ-HCH being the most potent insecticidal variant and the main component in HCH formulations[6,7]. In 2009, α-HCH, β-HCH, and γ-HCH were designated as persistent organic pollutants[8]. Estimates place the global production and stockpiling of HCH at between 4.8 and 7.2 million tons[9]. Historically, China was a major HCH and DDT producer and consumer, with production exceeding 4 million tons of HCH and 0.46 million tons of DDT from 1950 to 1983, representing 33% and 20%

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of the world's total output, respectively[6,10,11]. Following the switch to lindane in 1991, China's HCH production and usage declined considerably[12,13].

Current research on human exposure to OCPs has primarily focused on dietary intake and dust interactions. However, direct investigations of dermal OCPs exposure remain limited, often substituting environmental dust measures and modeling for actual exposure assessments[14,15]. The persistence and mobility of OCPs indicate that their residual presence in the environment may pose serious health risks to humans. Furthermore, studies have shown that ship antifouling paints, which are still widely used, are one of the main sources of DDT in outdoor environments[16,17]. In southern China, where the climate is notably humid, DDT is often incorporated into preservative coatings applied to wooden furniture and interior walls[15,18], resulting in indoor DDT contamination. Located in southern China, Maoming is a key agricultural hub in Guangdong Province and has a notable history of OCPs application. As a coastal city, Maoming is particularly vulnerable to the compounded effects of these factors, thereby increasing the risk of OCPs exposure for its inhabitants.

Skin contact is a critical route of exposure, yet direct assessments of OCPs on human skin via surface wipe sampling are particularly scarce. Therefore, in this study, we aimed to meticulously evaluate OCPs dermal exposure and related health risks within diverse demographic cohorts in Maoming. To this end, we collected skin wipe samples from different age groups, including preschoolers, thresholders, middle-aged adults, and older adults, while considering variables such as age, sex, body location, body weight, occupation, and lifestyle factors. This study is pioneering in its detailed analysis of OCPs exposure through skin contact among various population groups, providing vital data for enhancing understanding in this area.

Materials and methods

Sampling

Sampling was conducted in Maoming, China from December 8 to December 21, 2020 and involved 120 participants (60 males and 60 females) spanning the following age groups: preschoolers (5–6 years), thresholders (17–23 years), middle-aged adults (30–50 years), and older adults (70–100 years). Preschoolers were enrolled from a local kindergarten, thresholders and middle-aged participants were represented by students and staff from Guangdong University of Petrochemical Technology, and older adults were recruited from a Maoming nursing home. The sampling process involved the use of medical sterile gauze pads (Beijing Boer You Biotech Co., Ltd., 7.5 cm × 7.5 cm, made from degreased cotton). Prior to use, the gauze was purified through a 72 h Soxhlet extraction with dichloromethane, vacuum-dried, and stored at sub-zero temperatures. For skin wipe sampling, the gauze was simply moistened with isopropanol. Then, hold the gauze with tweezers and use both sides of the gauze to wipe the skin 3 times each. The participants provided skin wipe samples from their faces, hands, forearms (between the elbow and wrist of the arm), and shanks (between the knee and ankle of the leg). They were advised to refrain from washing these areas for at least two hours prior to sampling. Additionally, participants filled out a questionnaire detailing their age, sex, pre-sampling activities, and skincare product use on the sampled sites.

Informed consent was obtained from all participants and their guardians, and the research protocol was approved by the Research Ethics Committee of the Guangdong University of Petrochemical Technology. All human skin experiments in this study were performed in accordance with relevant named guidelines and regulations.

Sample analyses

The analytes for our OCPs investigation included six DDT derivatives (*o*, *p*'-DDT, *p*, *p*'-DDT, *o*, *p*'-DDE, *p*, *p*'-DDE, *o*, *p*'-DDD, and *p*, *p*'-DDD) and four HCH isomers (α-HCH, β-HCH, γ-HCH, and δ-HCH). We added 100 ng of internal standards (PCB24, PCB82, and PCB198) to the collected skin wipe samples before immersing them in a 20 mL mixture of n-hexane and acetone (3:1, v/v) for ultrasonic extraction over 20 min; this process was repeated three times. The resulting extracts were concentrated to approximately 1 mL via rotary evaporation. Silica solid-phase extraction cartridges (Poly-Sery SPE, 1 g, 6 mL; ANPEL Laboratory Technologies, Shanghai, China) were prepared through preconditioning with 10 mL of hexane. The extracts were loaded onto these cartridges and eluted with a 12 mL mixture of hexane and dichloromethane (1:1, v/v). The eluates were then concentrated to 1 mL and dried under a gentle nitrogen flow. The concentrated samples were re-dissolved in 100 μL of iso-octane and transferred to injection vials, with an addition of 100 ng of recovery standards (PCB30, PCB65, and PCB204) prior to analysis.

The OCPs concentrations were measured using a gas chromatograph coupled with a mass spectrometer (Agilent 6890GC-5975B Series MS) in electron ionization mode. The system featured a DB-5 MS capillary column (60 m × 0.25 mm × 0.25 μm; Agilent) and a 1 μL injection volume (splitless mode). The injection and ion source temperatures were set at 290 °C and 260 °C, respectively. The gas chromatograph temperature program began at 120 °C, ramped up to 180 °C at 6 °C/min, increased to 240 °C at 1 °C/min, held for 1 min, increased to 290 °C at 6 °C/min with a 15 min hold, increased to 310 °C at 5 °C/min, and maintained this final temperature for 5 min. For identification, we used the scan mode to determine the primary and secondary ion masses for pure OCPs standards and the selected ion monitoring mode for OCPs qualification.

Quality assurance and quality control

Existing literature has studied the removal efficiency of organic flame retardants from the skin surface using gauze wipes, and the results show that wiping three times achieves a removal rate of over 95% for organic flame retardants[19]. In this study, during skin wipe sampling, both sides of the gauze were used to wipe the skin 3 times each (a total of 6 times), fully meeting the requirements for quality control and assurance of the experiment.

Field blank analysis, which included wipes and silica cartridges, confirmed the absence of the target compounds. Spiked recovery was assessed by introducing 100 ng of a 12-polychlorinated biphenyl (PCB) standard mix to pre-moistened gauze wipes (three replicates) and to the solvent (three replicates), followed by processing using the same protocol as that applied to the samples. The PCB recovery rates ranged from 73 to 94% for the blank spikes and from 66 to 80% for the matrix spikes. The mean recoveries across all samples were 80 ± 9.3% for PCB24, 88 ± 11% for PCB82, and 85 ± 11% for PCB198. The limit of detection for OCPs was 0.28–8.7 ng/wipe.

Data analysis

Calculating OCPs concentrations through dermal exposure

We posited that OCPs concentrations on skin areas covered by clothing were comparable to those found on the shank. To estimate the daily average dose of dermal absorption (DAD_{derm}, ng/kg/d), we employed the penetration coefficient model[20], using the following equation:

$$\text{DADderm} = \frac{\left(\frac{C_{face}\times A_{head}+C_{hand}\times A_{hand}+C_{arm}\times A_{arm}+C_{shank}\times A_{torso}}{l_m}\right)\times k_{p-l}\times ED}{Bodyweight}$$

where C_{face}, C_{hand}, C_{arm}, and C_{shank} represent the area-based concentrations (ng/m^2) of OCPs on the face, hand, arm, and shank, respectively, and A_{head}, A_{hand}, A_{arm}, and A_{torso} denote the skin surface areas (m^2) of the head and neck, hands, arms, and other clothing-covered regions, respectively. Skin surface areas were calculated using formulas tailored to the Chinese population, as suggested by Yu et al. (2003)[21]. Additionally, Lm refers to the thickness of the skin lipid layer, which is assumed to be 1.3 µm for adults and 0.88 µm for children, based on Nazzaro-Porro et al. (1979)[22]. The permeability coefficient (K_{p-l}) represents the rate at which chemicals can penetrate from skin lipids into the dermal capillaries (measured in µm/h), and it is computed according to the methodology developed by Weschler and Nazaroff (2012)[23]. Finally, ED signifies the exposure duration, which was set to 24 h/d.

The daily average dose of hand-to-mouth contact exposure (DAD_{oral}, ng/kg/d) was calculated using the following equation proposed by Stapleton et al. (2008)[24]:

$$DAD_{oral} = \frac{C_{hand}\times A_{hand}\times TE\times SAC\times EF}{Bodyweight}$$

where C_{hand} and A_{hand} refer to the concentration of OCPs on hand skin and surface area of the hand, respectively; TE represents the transfer efficiency, which is assumed to be 70% and indicates the fraction of chemical mass transferred per contact; SAC is the percentage of the hand area in contact with each exposure and is set at 10%; EF denotes the daily frequency of contact (per day), with that of adults set at 24 times and that of children set at 216 times, according to the findings of Stapleton et al. (2008).

Non-cancerous risk assessment

The non-carcinogenic risk was assessed by using the hazard index (HI) to evaluate the health risks associated with dermal exposure and hand-to-mouth contact with OCPs, according to the following formulas[25]:

$$\text{HIderm} = \frac{\text{DADderm}}{\text{RfDderm}}$$

$$\text{HIoral} = \frac{\text{DADoral}}{\text{RfDoral}}$$

where RfD_{derm} and RfD_{oral} are the reference doses for dermal exposure to and hand-to-mouth contact with OCPs, respectively. Owing to the absence of RfD values for certain OCPs target compounds, only p, p'-DDT and γ-HCH were included in the carcinogenic risk assessment, with RfD values set at 500 and 300 ng/kg/d, respectively[26].

Cancer risk assessment

The cancer risk attributable to dermal exposure (CSR) and hand-to-mouth contact exposure (COR) to OCPs was calculated using the following Eq. [27]:

$CSR = DAD_{derm} \times CSF_{derm}$.

$COR = DAD_{oral} \times CSF_{oral}$.

where CSF_{derm} and CSF_{oral} denote the carcinogenic slope factors for dermal and hand-to-mouth exposure to OCPs, respectively, with both values considered equal[28]. Due to unavailable CSF values for certain OCPs, the carcinogenic risk assessment was limited to *p*, *p*'-DDT, *p*, *p*'-DDE, *p*, *p*'-DDD, *α*-HCH, and *β*-HCH. Their respective CSF values are 3.4×10^{-7}, 2.4×10^{-7}, 3.4×10^{-7}, 6.3×10^{-6}, and 1.8×10^{-6} $(ng/kg/d)^{-1}$ [26].

Results and discussions

Detection frequency of OCPs at different skin sites

In all skin wipe samples, the ten target OCPs compounds were detected at varying levels (Fig. 1), with detection frequencies ranging from 1–32% and an average frequency of 15%. The detection frequencies across the four sampling sites were relatively consistent and ranged, from 12–18%. Notably, the HCH isomers showed a 23% higher average detection frequency than the DDT-related compounds and metabolites, which had an average frequency of 9.2%. Among the OCPs compounds, *α*-HCH and *p*, *p*'-DDE had the highest detection frequencies at 33% and 32%, respectively.

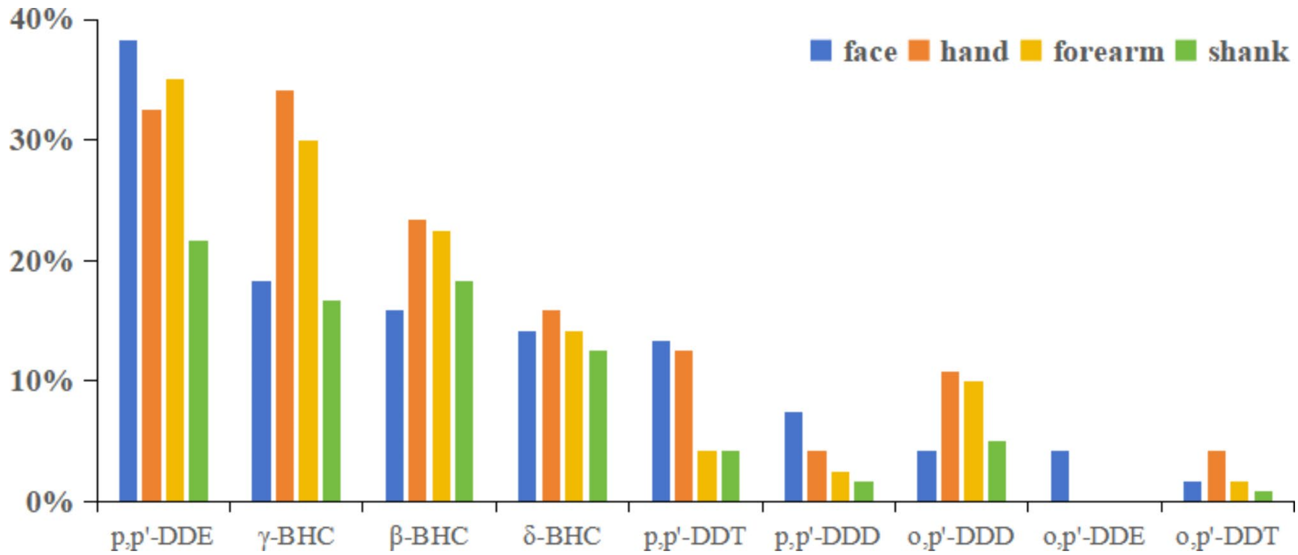

Fig. 1. Organochlorine pesticide (OCPs) detection frequency of wipe samples at different skin sites.

	Preschooler (5–6 years old)		Thresholder (17–23 years old)		Middle-aged (32–50 years old)		Elderly (70–100 years old)	
	Male	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
OCPs concentration in selected skin (ng/m^2)								
Face	2.5(ND-1300)	330(ND-2000)	300(ND-3800)	90(ND-800)	540(ND-3500)	610(ND-2500)	450(11-2320)	920(14-7200)
Hand	1.4(ND-59)	41(3.2–320)	32(ND-520)	13(ND-300)	73(ND-550)	120(ND-260)	16(1.9–140)	56(ND-3900)
Forearm	ND(ND-37)	5.6(ND-150)	16(ND-180)	12(ND-420)	36(ND-330)	57(ND-360)	7.0(1.1–24)	24(ND-1400)
Shank	ND(ND-9.2)	3.5(ND-76)	ND(ND-22)	15(ND-61)	5.3(ND-53)	8.2(ND-85)	1.7(ND-13)	4.8(0.55–480)
OCPs dermal exposure levels (ng/kg/d)								
Head and Neck	0.021(ND-10)	3.0(ND-16)	1.2(ND-18)	0.43(ND-38)	1.8(ND-13)	2.4(ND-9.3)	1.9(0.048-510)	3.9(0.060-32)
Hand	0.0065(ND-0.28)	0.20(0.014-1.7)	0.060(ND-1.1)	0.034(ND-0.78)	0.15(ND-1.2)	0.29(ND-0.62)	0.039(0.0043-0.33)	0.017(0.0026-0.24)
Arm	ND(ND-0.49)	0.076(ND-2.1)	0.081(ND-1.1)	0.085(ND-3.1)	0.21(ND-2.0)	0.33(ND-2.0)	0.043(0.0073-0.14)	0.13(ND-9.7)
torso	ND(ND-0.68)	0.25(ND-5.5)	ND(ND-0.73)	0.58(ND-2.2)	0.18(ND-1.6)	0.27(ND-2.6)	0.062(ND-0.52)	0.17(0.019-17)
Total OCPs	0.39(ND-10)	4.0(0.039-20)	1.8(ND-18)	1.0(ND-4.7)	2.5(0.14-15)	3.4(0.21-11)	2.0(0.072-12)	6.0(0.82-68)
Hand-to-mouth exposure levels (ng/kg/d)								
Total OCPs	0.029(ND-1.3)	0.89(0.062-7.8)	0.044(ND-0.80)	0.025(ND-0.57)	0.11(ND-0.89)	0.21(ND-0.46)	0.029(0.0032-0.25)	0.099(ND-7.1)

Table 1. OCPs concentrations (median and range) in 4 selected body surface areas.

Isomeric ratios of DDT provide insights into the sources and persistence of these compounds. The ratio of DDT/(DDE + DDD) serves as an indicator for the age of DDT in the environment; a ratio of < 1 typically indicates older historical residues, while a ratio of > 1 suggests more recent input. However, it is important to note that the distinction between 'old' and 'new' DDT sources can be challenging to define. In this study, the detection frequencies of o, p'-DDE, p,p'-DDE, o,p'-DDD, and p, p'-DDD were higher compared to those of o, p'-DDT and p, p'-DDT. Additionally, the ratio of the total mass of DDT to the total mass of DDE + DDD in all skin wipe samples was found to be 0.65. These findings collectively suggest that OCPs contamination in Maoming City primarily originates from historical residues.

Concentrations of OCPs at different skin sites

Table 1 presents a statistical overview of the OCPs concentrations at the four skin sites across different age groups within the study population. The concentrations in the skin wipes ranged from ND to 7200 ng/m^2. The pattern of OCPs concentrations across sex and age groups consistently revealed the following order: face > hand > forearm > shank (Fig. 1; ANOVA, $P < 0.001$). This indicates that the OCPs levels on exposed skin were higher than those on clothed areas, likely because clothing acts as a barrier against airborne particles, thereby minimizing the accumulation of particulates and dust on the skin[29,30].

Notably, the facial skin samples showed significantly elevated OCPs concentrations, possibly linked to increased sebum production, particularly in the forehead region. The face, with its abundant sebaceous glands, is more prone to adsorbing OCPs from the air or other sources, as these compounds bind to sebum on the surface of the skin. Previous studies have demonstrated that polybrominated diphenyl ethers (PBDE) are absorbed by the sebum layer of the skin upon contact with PBDE-containing items[24,31]. Similarly, Pawar et al. (2017) reported that hydrophobic and lipophilic pollutants such as PBDE are more readily dissolved in and adsorbed by sebum on the skin[32]. Furthermore, the higher OCPs concentrations observed on the forearm than on the shank may have been due to the greater air exposure of the forearm during winter.

Previous studies have quantified the levels of halogenated flame retardants (HFR), PCBs[20,33], and phthalates (PHT)[34] across various skin sites, establishing a comparative framework for the distribution of OCPs. Uncovered areas typically harbor higher concentrations of these substances than areas covered by clothing. However, contrary to the findings of previous studies, which showed a higher level of contaminants on the hands than on the face, our results demonstrated that facial OCPs concentrations were substantially high than hand levels, by up to two orders of magnitude (Fig. 2). Notably, HFR and PHT, which are widely employed in consumer goods as flame suppressants and plasticizers, respectively, account for up to 30% of the weight of these products. This substantial percentage suggests that routine contact with commonly used items could lead to pronounced accumulation of these compounds on the hands. However, OCPs trends diverge markedly as these pesticides are not components of consumer merchandise, indicating alternative exposure routes.

OCPs concentrations on the faces of elderly were significantly higher than those of preschooler and thresholder ($P < 0.05$), but not when compared to middle-aged ($P > 0.05$). The increased facial OCPs levels in the elderly could stem from less frequent face-washing, especially among nursing home residents. Middle-aged subjects showed the highest OCP levels at hand, forearm, and shank, significantly surpassing the levels in preschooler ($P < 0.05$) (Fig. 2). For those in middle age, particularly canteen workers, elevated OCPs concentrations may be linked to occupational exposure, as their work entails more contact with agricultural products than the other groups studied.

Cao et al. (2019) identified gender-based differences in the deposition of HOP on skin, noting that males exhibited higher levels of less volatile substances, such as decabromodiphenyl ether and decabromodiphenyl ethane, while females were more prone to absorbing volatile compounds, including PCB and penta-BDE mixtures. Our study reveals significant gender-related differences in OCPs levels exclusively in shank samples, with female showing higher concentrations than male ($P < 0.05$) (Fig. 3). Upon examining age-related patterns, we observed that these gender-specific variances in OCPs concentrations were limited to the facial and hand samples of preschoolers (females > males, $P < 0.05$). Other age groups did not exhibit any significant gender disparities in OCPs levels across the examined skin sites. The underlying causes of the gender differences noted remain unclear and merit further investigation for a detailed explanation.

Dermal and hand-mouth exposure levels

The DAD_{derm} of OCPs for the entire study population varied from ND to 68 ng/kg/d, with a median of 2.4 ng/kg/d. The DAD_{oral} ranged from ND to 7.8 ng/kg/d, with a median of 0.088 ng/kg/d (Table 1). Notably, HCH was the main component of both DAD_{derm} and DAD_{oral}, accounting for 68% and 91%, respectively. No significant age-related differences in DAD_{derm} were observed ($P > 0.05$). The head and neck skin was the dominant contributor to DAD_{derm} at 74%, followed by the torso at 12%, arms at 7.7%, and hands at 6.3%. Figure 4 shows that preschoolers had significantly higher DAD_{oral} scores than other age groups ($P < 0.05$), likely due to more frequent hand-to-mouth activities.

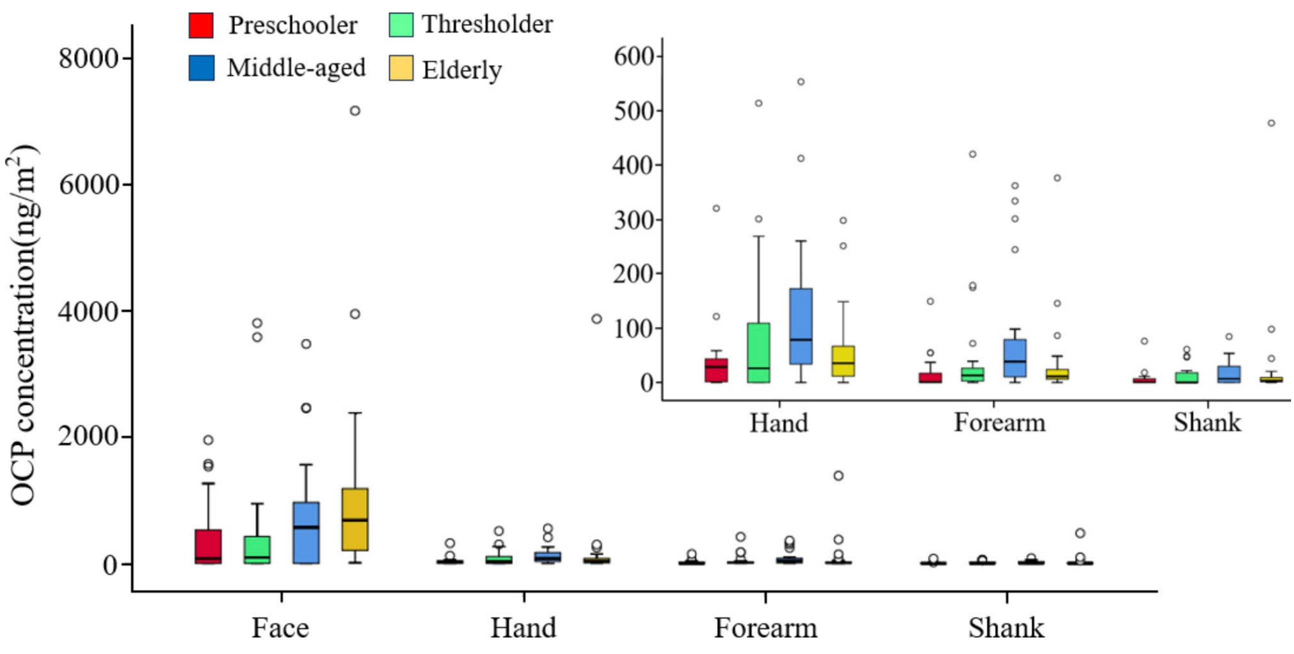

Fig. 2. The OCPs concentrations at different skin sites in samples from different age groups (lower and upper boundaries of the box represent the 25th and 75th percentiles, respectively, with the median depicted by the central line, and the circles denote outliers).

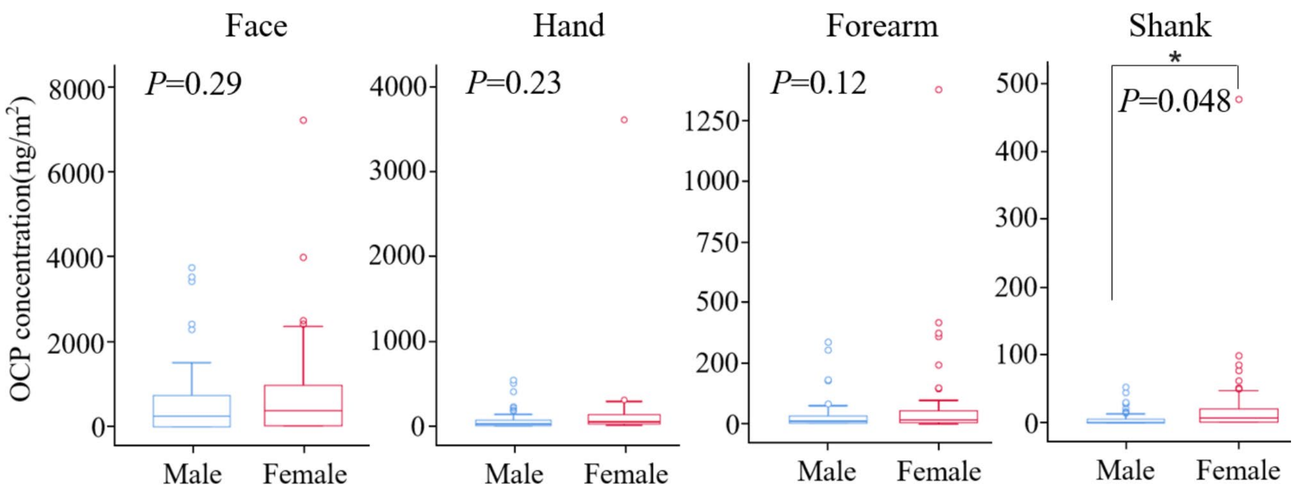

Fig. 3. Comparison of OCPs concentrations at different skin sites between males and females.

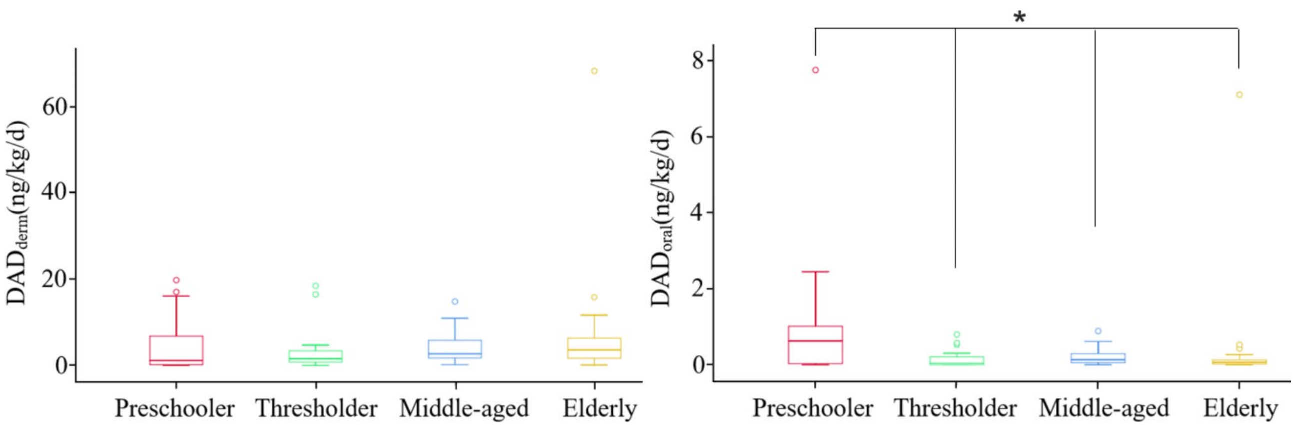

Fig. 4. Dermal OCPs exposure dose (left) and oral OCPs contact exposure dose (right) in different populations.

For the pooled samples of both sexes, DAD_{derm} ranged from ND to 18 ng/kg/d for males and from ND to 68 ng/kg/d for females, with medians of 1.8 ng/kg/d for males and 3.3 ng/kg/d for females. Meanwhile, DAD_{oral} varied from ND to 1.3 ng/kg/d for males and from ND to 7.8 ng/kg/d for females, with medians of 0.052 ng/kg/d for males and 0.21 ng/kg/d for females. Although there was no significant sex-based difference in DAD_{derm} ($P > 0.05$), a marked sex-based disparity was evident in DAD_{oral}, with females exhibiting higher exposure doses than males ($P < 0.05$).

Children in rural areas of Nepal had a median OCPs exposure dose of 14 ng/kg/d through dermal contact with indoor dust[14], which is approximately one order of magnitude higher than the DAD_{derm} of the preschooler group in this study (median value of 1.1 ng/kg/d). In Shanghai, the doses of HCH absorbed by the skin in adults and children were 9.6×10^{-4} and 6.8×10^{-4} ng/kg/d, respectively, and the doses of DDT absorbed by the skin were 5.3×10^{-3} and 3.8×10^{-3} ng/kg/d, respectively[35], which are approximately three and two orders of magnitude lower than the DAD_{derm} of HCH and DDT of different populations in this study, respectively. The median exposure doses of DDT through dermal contact with indoor and outdoor air for adults in rural areas of Qingyuan City were 3.9×10^{-3} and 7.1×10^{-5} ng/kg/d, respectively, and for toddlers, they were 1.7×10^{-2} and 2.3×10^{-4} ng/kg/d, respectively[15], which are approximately one to four orders of magnitude lower than the DAD_{derm} of DDT of different populations in this study.

Dietary consumption is an important route of human exposure to OCPs. Investigations have revealed that in Nanjing, the average daily dietary intakes of HCH and DDT were 17 and 38 ng/kg/d, respectively[36]. In Xiamen, consumption of shellfish resulted in varied intake levels of HCH and DDT, with figures ranging from 0.19 to 0.31 ng/kg/d and from 5.9 to 9.6 ng/kg/d, respectively, across different age groups. Notably, exposure was higher among females and children than among their male and adult counterparts[37]. The inhabitants of Beijing and Shenyang exhibited a consistent dietary HCH intake of 13 ng/kg/d[38]. Adults in Weihai, Qingdao, and Yantai in Shandong Province reported dietary intakes of HCH and DDT of 2.2 and 32 ng/kg/d, respectively[39]. Infants in New Zealand were exposed to HCH in breast milk at a rate of 33 ng/kg/d[40]. Individuals in northwestern Russia had dietary HCH and DDT intakes of 5.8 and 31 ng/kg/d, respectively[41]. Danish adults and children had dietary

HCH intakes of 0.67 and 1.2 ng/kg/d, respectively, and DDT intakes of 3.7 and 6.7 ng/kg/d, respectively[42]. Swedish adults had a dietary DDT intake of 7.5 ng/kg/d[43]. Furthermore, in the Chenab River Basin in Pakistan, the adult intake of OCPs through rice and wheat consumption was 39 and 40 ng/kg/d, respectively[44].

Internationally, research has focused on OCPs exposure through dust ingestion across diverse demographics. In Guangzhou, adults and children were exposed to OCPs through dust ingestion at doses ranging from 5.7×10^{-3} to 1.3 ng/kg/d and from 0.22 to 74 ng/kg/d, respectively. Meanwhile, in Hong Kong, the exposure ranged from 2.8×10^{-3} to 0.50 ng/kg/d for adults and from 9.9×10^{-2} to 0.92 ng/kg/d for children[45]. In Shanghai, adults and children had dust-derived HCH intakes of 1.2×10^{-3} and 7.6×10^{-3} ng/kg/d, respectively, and DDT intakes of 7.2×10^{-3} and 4.1×10^{-2} ng/kg/d, respectively[35]. In Qingyuan's rural locales, adults encountered DDT in indoor and outdoor dust at doses of 4.7×10^{-3} and 2.5×10^{-5} ng/kg/d, respectively[15]. The indoor dust OCPs intake of rural Nepalese children was 10 ng/kg/d[14]. In Kuwait, the OCPs exposure through dust ingestion was 6.5 and 94 ng/kg/d for adults and toddlers, respectively[46], while in eastern Romania, HCH and DDT exposure through indoor dust was 0.05 and 0.72 ng/kg/d for adults and 0.32 and 4.7 ng/kg/d for toddlers, respectively[47].

However, research on human exposure to OCPs through air inhalation is limited. Yu et al. (2012) discovered that in Shanghai, adults and children inhaled HCH doses of 6.9×10^{-4} and 1.3×10^{-3} ng/kg/d, respectively, and DDT doses of 1.8×10^{-3} and 3.4×10^{-3} ng/kg/d, respectively. In Turkey, adults inhaled OCPs at doses ranging from 1.6×10^{-4} to 1.2×10^{-2} ng/kg/d[28]. In Nanjing's Xianlin district, the OCPs inhalation dose varied between 0.022 and 0.16 ng/kg/d across different age groups and seasons[48]. Lv et al. (2022) reported that in Qingyuan's rural regions, adults breathed in DDT from indoor and outdoor air at doses of 8.6×10^{-3} and 1.7×10^{-4} ng/kg/d, respectively, while toddlers were exposed to higher doses of 3.4×10^{-2} and 4.8×10^{-4} ng/kg/d, respectively, indicating greater exposure for children than for adults.

In summary, global populations have been exposed to OCPs at rates of 0.19 to 40 ng/kg/d through diet and 0.025 to 94 ng/kg/d via dust ingestion, comparable to the dermal exposure doses (ND to 68 ng/kg/d) found in our study. Notably, the OCPs inhalation doses ranged from 1.6×10^{-4} to 0.16 ng/kg/d, which are lower than the dermal exposure levels recorded in the current study. This indicates that dermal contact with OCPs is as important as dietary intake and dust ingestion routes and surpasses inhalation exposure.

Exposure risk assessment

The HI_{derm} and HI_{oral} across all studied populations ranged from ND to 0.21 and from ND to 0.023, respectively, with all values remaining below the threshold of concern ($HI < 1$). This demonstrates the absence of significant non-carcinogenic health risks related to both dermal exposure and hand-to-mouth contact exposure in the populations under consideration. The CSR and COR values ranged from ND to 2.4×10^{-5} and from ND to 5.3×10^{-6}, respectively, with mean values of 1.9×10^{-6} for CSR and 1.8×10^{-7} for COR. Within the prevailing regulatory frameworks, risk estimates of $\leq 10^{-6}$ are generally deemed inconsequential or negligible, risk estimates ranging from 10^{-6} to 10^{-4} are characterized as low cumulative cancer risk, and risk estimates of $> 10^{-4}$ indicate substantial potential health risk[49]. Accordingly, we determined that all examined populations in this study were categorized within the low carcinogenic risk bracket ($< 10^{-4}$). Our analysis revealed distinct age- and sex-based disparities in the CSR. Specifically, the CSR values were significantly higher for older adults than for thresholders ($P < 0.05$). Additionally, the CSR value was significantly higher for females than for males ($P < 0.05$).

We compared our findings with those of previous research to elucidate the contextual importance of this study. Yang et al. (2012) reported that the cancer risks associated with dermal exposure to α-HCH and β-HCH in soil particles were notably lower among Beijing's urban dwellers than among rural residents, at 3.3×10^{-12} and 2.8×10^{-10}, respectively[50]. These figures are approximately six and three orders of magnitude lower than the respective risks from α-HCH and β-HCH exposure via dermal contact in the varied cohorts within our study (1.0×10^{-6} and 4.4×10^{-7}). Furthermore, in the Sulaibya region of Kuwait, the carcinogenic risk from OCPs exposure through soil-mediated dermal contact for both children and adults was reported to be less than 1.0×10^{-8}[51], which is approximately two orders of magnitude lower than the risk levels for OCPs encountered through dermal contact among the populations analyzed in our investigation.

Conclusions

This study provides a comprehensive assessment of dermal exposure to OCPs and related health risks in different population segments of a major agricultural city in southern China. Our results indicate variable detection levels of HCH and DDT on the skin across the sampled demographics, influenced by distinct living environments, hygiene habits, and behaviors among various age and sex groups. Notably, the skin of the head and neck constitutes 74% of the total dermal OCPs exposure, highlighting facial cleanliness as a key factor in reducing OCPs absorption. We determined that the OCPs dose from dermal uptake was on par with that reported from dietary intake and dust ingestion in previous studies and exceeded that reported from inhalation in previous studies, underscoring the need to consider dermal absorption in exposure assessments. These findings emphasize the importance of a nuanced evaluation of organic pollutant exposure and health risks across different population cohorts.

ND indicates not detected or below the detection limit.

Data availability

The core data for this study are provided in the article. For additional data, please contact the author at guojian@gdupt.edu.cn to request it.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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