

Field Evaluation of Human Exposure to Pesticides and Comparison with Exposure Assessment Models: Drone and Wide-area Sprayer Applications

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Abstract: International agencies have developed guidelines and predictive models to assess human exposure of pesticides during the application. However, these models are typically based on limited empirical data and may not accurately represent real-world spraying conditions. Moreover, they do not account for spraying equipment such as drones or wide-area sprayers, which limits their applicability under current field conditions. In this study, we quantified pesticide exposure among operators, residents, and bystanders during applications using drones and wide-area sprayers. Subsequently, the pesticide exposure test results were evaluated using exposure models developed in this study. Measured operator exposure was substantially higher during wide-area spraying than during drone-based application, primarily due to reduced working distance and differences in spray delivery mechanisms. Exposure levels among residents and bystanders were also elevated during wide-area spraying, although drone-based applications demonstrated potential for long-distance drift under specific meteorological conditions. Existing models, including EFSA, UK-POEM, BREAM2, and EUROPOEM, did not adequately account for spray aerodynamics or field variability, resulting in frequent underestimation or overestimation of exposure. Despite a limited dataset, this study provides clear insights into exposure patterns associated with both technologies and highlights the need for model refinement to accommodate emerging application methods.

Keywords: Aerial spraying, Exposure assessment, Exposure models, Human exposure, Spray drift

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Introduction

The decline in the agricultural labor force has accelerated the adoption of precision agriculture and smart pest-control technologies aimed at ensuring a stable supply of high-quality agricultural products. In Korea, the use of agricultural drones and wide-area sprayers has expanded rapidly, as these systems can treat large areas within a short time [1]. Drone applications reduce working time by approximately 60% compared with conventional motorized sprayers [2], while wide-area sprayers

enable long-distance pesticide dispersion through high-capacity air-blast systems, making them suitable for large-scale open-field operations. Despite these advantages, both drone-based aerial spraying and high-pressure discharge systems can generate extensive drift of fine droplets [3]. Such drift increases the risk of unintended pesticide exposure among nearby workers and residents [4], with reported acute symptoms including headaches, dizziness, and irritation of the skin and mucous membranes [5]. Therefore, quantitative assessment of human exposure to pesticide drift is essential.

International regulatory bodies, including the European Food Safety Authority (EFSA), the Organisation for Economic Co-operation and Development (OECD), and the United States Environmental Protection Agency (US EPA), have developed standardized non-dietary exposure assessment models for operators, workers, residents, and bystanders [6-8]. EFSA recommends different models for specific groups, such as UK-POEM for operators, EUROPOEM for workers and bystanders, and BREAM for residents. EFSA also introduced an updated assessment scheme in 2022, incorporating revised default parameters derived from studies conducted between 1994 and 2009 [6]. The BREAM2 model further improves drift prediction by applying drift-reduction factors and integrating empirical exposure datasets with spray drift simulations [10]. However, OECD has emphasized that empirical drift exposure data remain insufficient, and existing models do not fully account for environmental variability, particularly fluctuations in wind speed, nor do they adequately represent worst-case scenarios [7]. These limitations contribute to substantial uncertainty in model predictions [9]. Moreover, most previous studies have focused on orchard environments [10, 11], and research on exposure characteristics across different pesticide-application technologies under open-field conditions remains limited.

Given these limitations, empirical field-based assessments are necessary to generate reliable drift exposure data and evaluate the performance of existing exposure models under domestic conditions. Therefore, this study aimed to quantify pesticide drift exposure among operators, residents, and bystanders during drone and wide-area spraying in Korean open-field agricultural settings. We further evaluated the applicability of major international exposure models—EFSA, EUROPOEM, UK-POEM, and BREAM2—by comparing their predictions with empirical measurements, to assess their suitability for domestic conditions and to identify the need for model calibration.

Results and Discussion

Pesticide Exposure of Applicators

Fig. 1 presents dermal and inhalation exposure of pesticide applicators during mixing/loading (ML) and spraying with drones and wide-area sprayers. Total dermal exposure was 2.70 mL for drone operators and 26.05 mL for sprayer operators, while inhalation exposure was 0.17 mL and 1.53 mL, respectively. Overall, wide-area sprayer operators experienced approximately eight-fold higher pesticide exposure than drone operators. This difference reflects both the smaller volume of pesticide handled during drone ML and the physical separation between the applicator and spray zone during remote-controlled drone application.

Body-region-specific dermal exposure is shown in Fig. 2. During ML, the major exposure sites for drone operators were the hands (7.28 mL), legs (3.69 mL), and trunk (2.42 mL). For sprayer operators, exposure was highest on the trunk (0.50 mL) and legs (0.37 mL). The need to board the spray vehicle during tank loading resulted in greater contact with contaminated surfaces. Hand exposure during drone loading could not be quantified due to glove loss during the experiment; however, the similarity of loading procedures suggests hand exposure was comparable to that observed during sprayer loading. In both technologies, considerable pesticide was spilled onto the feet during pouring, but because patches were not attached to this area, actual exposure was likely underestimated.

During spraying, the wide-area sprayer generated substantial exposure, with 4.45 mL of pesticide deposited on the trunk and 1.27 mL inhaled. This elevated exposure was due to the operator applying pesticide from the vehicle with the windows fully open while monitoring field conditions and operating the fan and spray system, which resulted in greater deposition on the trunk and arms. In contrast, drone operators experienced minimal exposure because they remained physically distant from

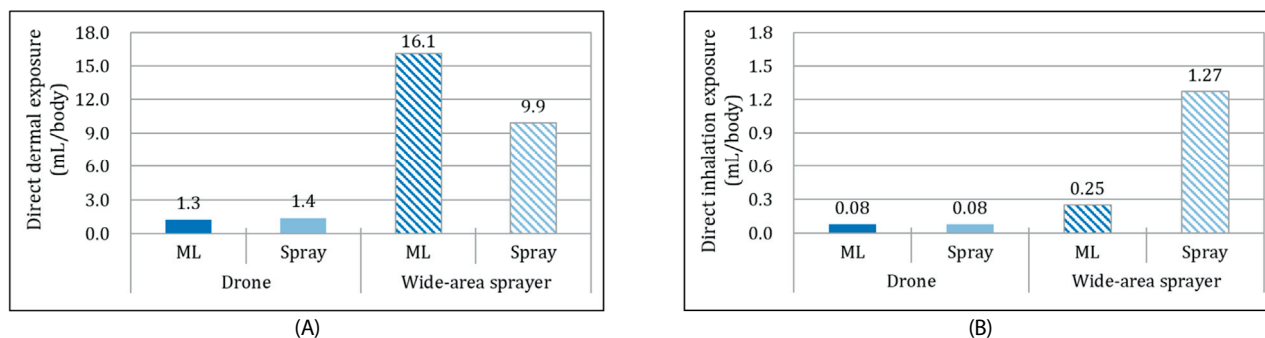


Fig. 1. Dermal (A) and inhalation (B) pesticide exposure of operators during mixing/loading (ML) and spraying (Spray) using drone and wide-area sprayers.

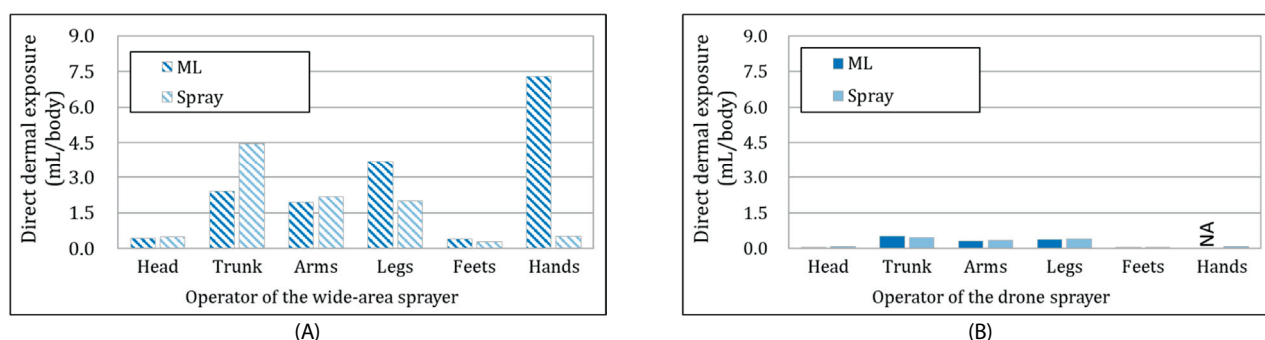


Fig. 2. Body-part-specific dermal pesticide exposure of operators during mixing/loading (ML) and spraying (Spray) using a drone sprayer (A) and a wide-area sprayer (B).

the spray zone. Although trained commercial applicators may reduce ML exposure by using hose-connected filling systems, appropriate protective equipment remains essential during wide-area sprayer use.

Pesticide Exposure of Residents and Bystanders

Fig. 3 compares exposure levels for residents and bystanders at different downwind locations during drone and wide-area sprayer applications. Mean wind speeds were 3.39 m/s and 2.26 m/s for drone and sprayer trials, respectively, influenced by seasonal typhoon winds. Exposure levels were consistently higher for both adults and children during sprayer use, largely due to the substantially greater application volume (818 L/ha) compared with drones (59 L/ha). The wide-area sprayer treated three adjacent fields sequentially, and the farthest downwind site (W3) showed the highest dermal deposition: 9.57 mL for adults and 5.69 mL for children. This pattern was likely caused by accumulated drift resulting from the interaction of blower airflow and ambient wind.

Fig. 4 shows body-region-specific exposure patterns. Drone spraying produced less than 2.00 mL of dermal or inhalation exposure even under strong winds. In contrast, the wide-area sprayer produced the highest dermal deposition on the trunk (3.56 mL) at site W3 in the direction of sprayer travel. Across all locations, arms and legs received more deposition than the head. The average soybean height was 45 cm, and this vegetation partially shielded child mannequins, resulting in lower exposure—a trend consistent with findings by [12].

Fig. 5 presents dermal and inhalation exposure levels observed when 10 L of pesticide per hectare was applied using drones and wide-area sprayers. Although total exposure was higher for the wide-area sprayer, the drone application resulted in more than a 1,000-fold increase in human exposure under identical application-rate conditions. Aerial drone spraying disperses fine droplets at high altitude, which can drift long distances. Consequently, at site D3, adult mannequins showed dermal exposure

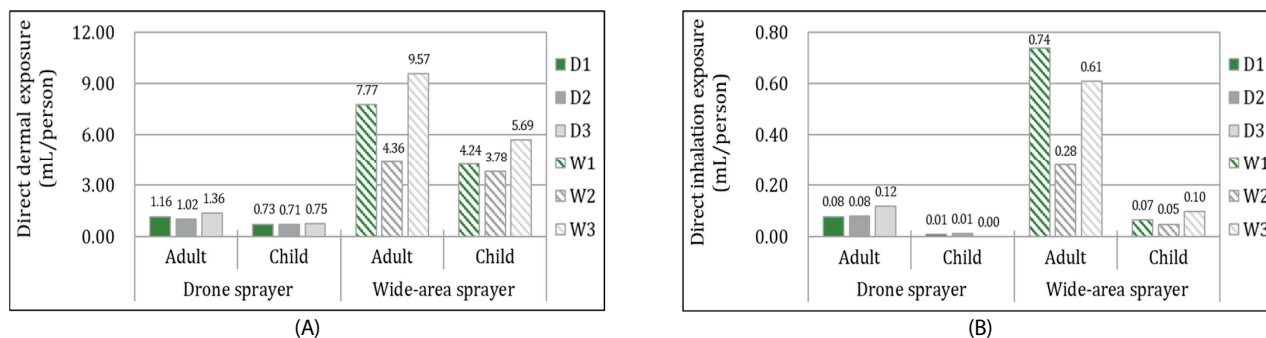


Fig. 3. Dermal (A) and inhalation (B) pesticide exposure of residents and bystanders at different locations during pesticide application.

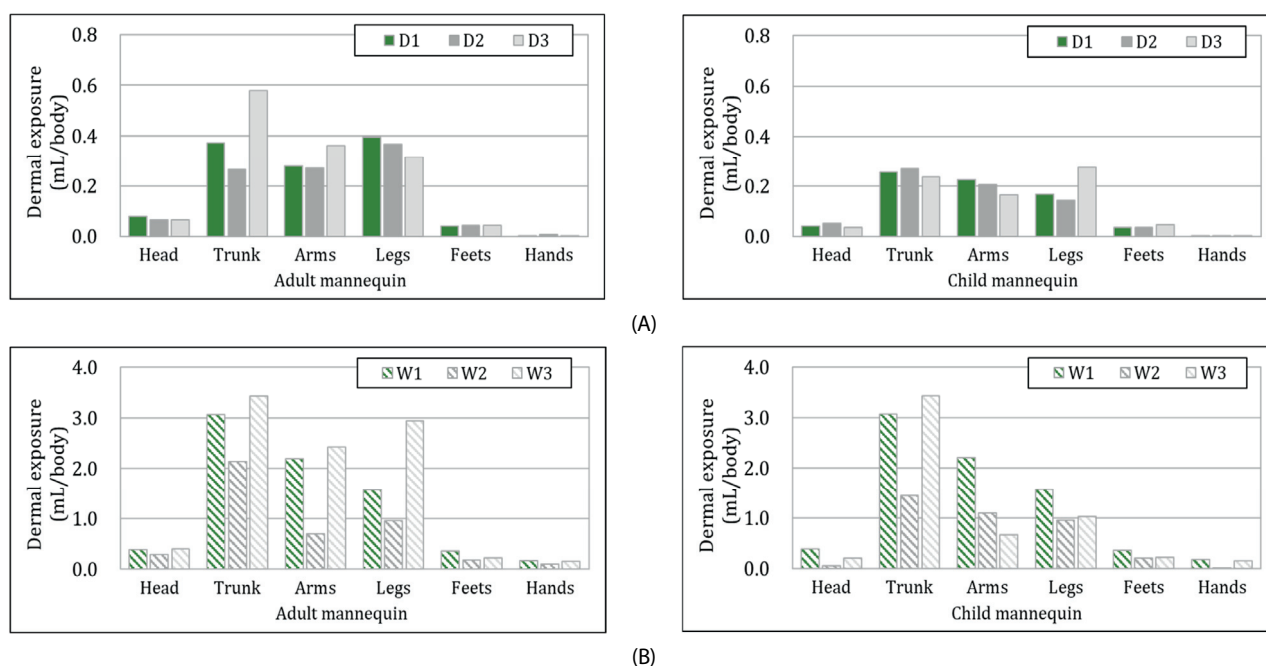


Fig. 4. Body-part-specific pesticide exposure of residents and bystanders, including adults and children, at different locations during pesticide application using a drone sprayer (A) and a wide-area sprayer (B).

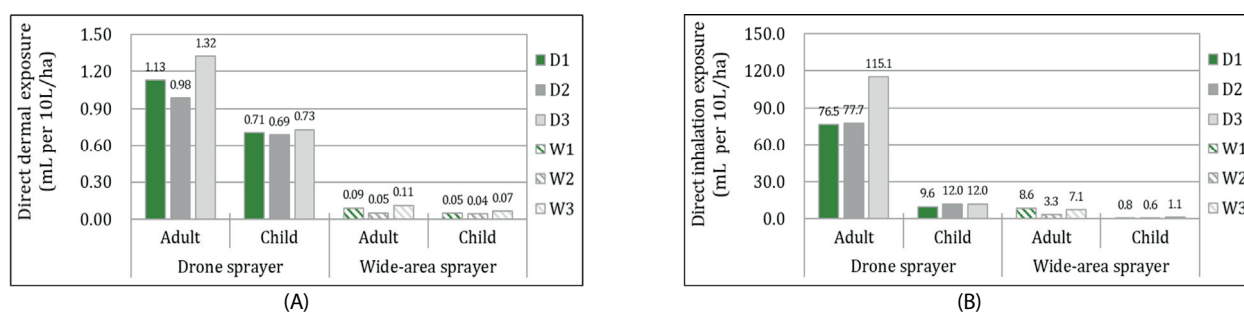


Fig. 5. Dermal (A) and inhalation (B) pesticide exposure of residents and bystanders during pesticide application at a rate of 10 L/ha.

of 1.32 mL per 10 L/ha and inhalation exposure of 115.10 mL per 10 L/ha, indicating a greater potential for long-range drift compared with ground-based equipment.

Evaluation of Exposure Models for Domestic Application

Operator exposure estimates from the EFSA and UK-POEM models were compared with measured values (Table 1). For the drone-based application, predicted exposures were 0.014 mg/kg bw/day (EFSA) and 0.020 mg/kg bw/day (UK-POEM), whereas the measured exposure was 0.005 mg/kg bw/day. Thus, both models overestimated exposure, likely because they do not account for remote-controlled drone operation, which substantially reduces operator contact during ML and spraying. In contrast, for wide-area sprayer use, measured exposure exceeded model predictions, indicating underestimation. This discrepancy reflects the models' assumption of fixed posture and uniform exposure, whereas actual field operations involve operator movement, posture changes, and varying proximity to equipment, all of which may contribute to greater pesticide deposition on clothing. Limited repeated measurements in this study also constrained model calibration.

Table 1. Comparison of measured and modeled pesticide exposure of operators during pesticide application using drone and wide-area sprayers

		Operator (mg/kg bw/day)		
		Experimental	EFSA model	UK-POEM model
Drone sprayer	Dermal	0.004	0.005	0.015
	Inhalation	0.001	0.009	0.005
	Total	0.005	0.014	0.020
Wide-area sprayer	Dermal	1.881	0.400	1.193
	Inhalation	0.041	0.040	0.025
	Total	1.922	0.440	1.217

Resident and bystander exposure was estimated using EFSA, BREAM2, and EUROPOEM models, with comparisons to measured values for adults and children under drone and wide-area sprayer conditions (Tables 2 and 3). All three models were originally developed for ground-based spraying and showed limitations when applied to drone scenarios. For example, BREAM2 requires 6–996 nozzles and cannot be directly applied to the four-nozzle drone used in this study. Furthermore, EFSA models provide estimates only for children aged 1–3 years, while this study evaluated children up to 14 years of age, limiting comparability.

During drone application, measured adult exposure (0.121 mg/kg bw/day) was most closely matched by EUROPOEM (0.178 mg/kg bw/day). EFSA overestimated exposure by approximately 0.200 mg/kg bw/day due to assumptions about pesticide drift behavior, vapor inhalation, ground deposition, and post-application re-entry, none of which reflect drone-specific aerosol dynamics. Drones generate small droplets that disperse upward or laterally and rapidly diffuse under propeller downwash—processes not captured by ground-sprayer-based models.

For wide-area sprayer application, EFSA overestimated adult exposure by approximately two-fold, whereas BREAM2 and EUROPOEM underestimated measured values. BREAM2 produced particularly low estimates (~20% of measured exposure), reflecting its inability to account for horizontal, high-velocity spray characteristics. For children, measured dermal exposure exceeded model predictions, likely due to their higher surface-area-to-body-weight ratio and closer proximity to ground-level deposition. Existing exposure models assume uniform spray distribution, constant distance, and static operator behavior. In practice, dynamic factors, including operator movement, varying proximity to equipment, and aerodynamic dispersion, strongly influence exposure. Applying these models to drones or wide-area sprayers, whose spray mechanisms differ substantially from conventional ground sprayers, results in significant divergence between predicted and measured values. Therefore, systematic accumulation of field-based exposure datasets is required to support model calibration and to inform the development of new exposure assessment models or correction factors that incorporate spray technique, droplet size, airflow patterns, and operator movement specific to drone and wide-area spraying systems.

Table 2. Comparison of measured and modeled pesticide exposure of bystanders during pesticide application using a drone sprayer

		Bystanders (mg/kg bw/day)			
		Experimental	EFSA model	BREAM2 model	EUROPOEM model
Adult	Dermal	0.119	0.310	-	0.167
	Inhalation	0.002	0.003	-	0.011
	Total	0.121	0.313	-	0.178
Child	Dermal	0.0118	-	-	-
	Inhalation	0.0002	-	-	-
	Total	0.0120	-	-	-

Table 3. Comparison of measured and modeled pesticide exposure of bystanders during pesticide application using a wide-area sprayer

		Bystanders (mg/kg bw/day)			
		Experimental	EFSA model	BREAM2 model	EUROPOEM model
Adult	Dermal	0.511	0.831	0.141	0.313
	Inhalation	0.008	0.197	0.008	0.002
	Total	0.519	1.028	0.149	0.315
Child	Dermal	2.650	2.181	0.560	-
	Inhalation	0.035	0.080	0.028	-
	Total	2.685	2.262	0.588	-

Materials and Methods

Study Area

This study was conducted in a soybean cultivation field in Gimje, Jeollabuk-do, South Korea. A site without physical obstructions was selected to ensure controlled experimental conditions. The experiment was performed on 28 August 2024, with soybean plants averaging 46 ± 3.6 cm in height. Because the experiments were conducted in a commercial farming area, repeated applications within a single plot were not feasible. Therefore, separate experimental zones were designated according to the type of application equipment (Fig. 6). Drone application was carried out in a half-plot area (35 m $\times$ 50 m), while wide-area sprayer application was conducted across three contiguous plots (105 m $\times$ 100 m). The sprayer moved sequentially across these plots during spraying.

A weather station (Onset Computer Corporation, Bourne, USA) was installed at a height of 1.8 m to record air temperature, wind speed, and wind direction at one-second intervals. During the experiments, the mean wind speed was 3.39 ± 0.79 m/s for the drone application and 2.26 ± 0.60 m/s for the sprayer application. The mean air temperatures were 27.4°C and 30.4°C, and the relative humidities were 74.3% and 66.5%, respectively.

Experimental Conditions

The equipment specifications and spraying conditions for the drone and wide-area sprayers are summarized in Table 4. Two commonly used pesticide application systems were employed: a drone (Korea Samgong SG-10P octocopter, Iksan, Korea) and a wide-area sprayer (Han Sung T&I HSU-3000/4000-VI, Asan, Korea). Both systems applied the same pesticide mixture, consisting of a suspension concentrate (azoxystrobin, hexaconazole 11.5% [6.5 + 5%]) and an emulsifiable concentrate (etofenprox 10%), as typically used by local growers. The application rates were 59 L/ha for the drone and 818 L/ha for the sprayer. Drone flight



Fig. 6. Layouts of the experimental setup for human exposure assessment to pesticides using a drone sprayer (A) and a wide-area sprayer (B).

Table 4. Drone and wide-area sprayer specifications and experimental conditions

	Drone	Wide-area sprayer
Size (L × W × H, mm)	2,075 × 2,075 × 700	6,710 × 2,230 × 2,660
Tank capacity (L)	10	3,000
Nozzles	XR11002 (Teejet, Technologies, Springfield, IL, USA) × 4 pcs	
Nozzle pressure (bar)	3.0	
Spray volume (L/ha)	59	818
Airflow rate (m ³ /h)		4,000
Wind speed (m/s)	4.17	
Spray height (m)	3.0	

and spraying operations were conducted in accordance with the safety guidelines for unmanned aerial application established by the Rural Development Administration.

Exposure Groups

Human exposure assessment was conducted by classifying subjects into three groups based on exposure characteristics: operators, bystanders, and residents. Workers refer to individuals who enter treated areas or handle treated crops. However, workers were excluded from this study because their tasks typically exceed one hour, during which sample loss or evaporation may occur during prolonged collection.

For applicators, exposure was evaluated separately during the ML stage and the spraying stage, as these represent periods with the highest likelihood of pesticide contact. Bystanders and residents were defined as individuals located near the treatment area during spraying. Based on exposure duration, bystanders were considered acute-exposure individuals with contact durations of 30 min or less, whereas residents were considered short-term exposure individuals with potential exposure over the course of a day.

Operator exposure was assessed using actual human operators, while exposure for bystanders and residents was measured

using adult (A) and child (C) mannequins. The adult mannequin represented a 60 kg general adult, including women and adolescents, as commonly used in risk assessment. The child mannequin represented individuals under 14 years of age, with a standard body weight of 10 kg [7].

Pesticide Exposure Measurement

Human pesticide exposure was measured following EFSA standard guidelines for exposure assessment [6]. To simulate exposure among residents and bystanders, adult and child mannequins were positioned at three downwind locations within the application area, as illustrated in Fig. 7. The first point was located at the downwind boundary line during wide-area sprayer application (W1) and at 50 m from the boundary during drone application (D1). The second point (W2 or D2) was positioned directly on the downwind boundary. The third point (W3 or D3) was located approximately one plot (35 m) beyond the downwind boundary.

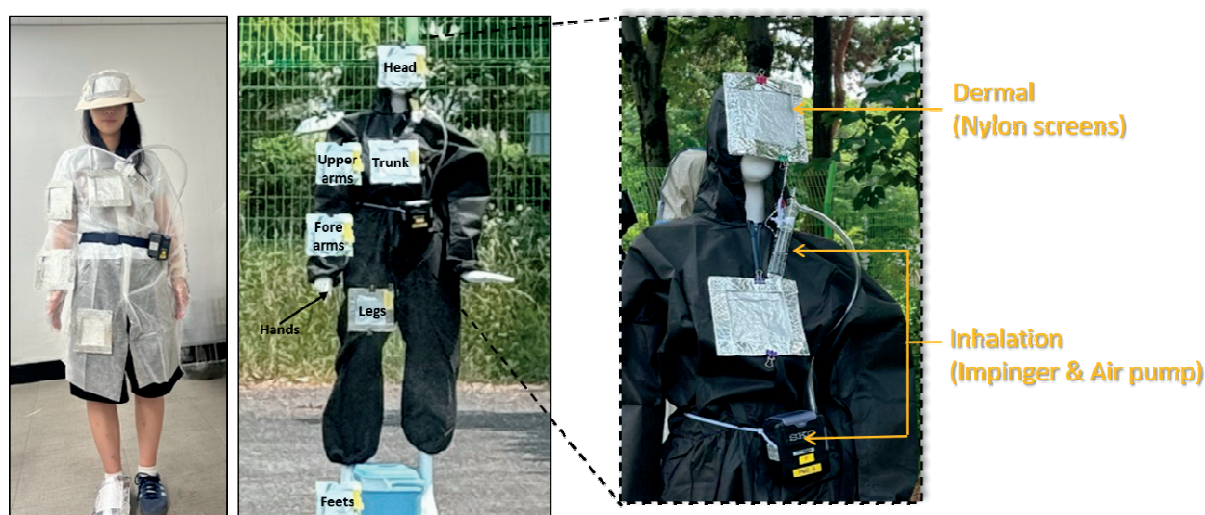


Fig. 7. Locations of pesticide sampler attachment for dermal and inhalation exposure experiments. Left: operator; right: residents and bystanders.

Prior to spraying, exposure during ML was measured from operators handling the pesticides and filling the tanks of the drone or wide-area sprayer. After completing the ML stage, new samplers were attached to collect exposure during spraying. The drone application was conducted remotely from a nearby roadway, whereas the wide-area sprayer application was performed by an operator driving the equipment. Following pesticide application, all sampling patches and inhalation samplers attached to applicators and mannequins were retrieved for analysis. Exposure samples were collected in accordance with guidelines established by EFSA, OECD, and the US EPA, with separate assessments for dermal and inhalation exposure.

Dermal Exposure Assessment

Dermal exposure from pesticide deposition was quantified using the patch method, which assumes uniform deposition across the collection area [7]. During spraying, operators wore protective clothing, including coveralls, masks, hats, and gloves. Patches were attached to the outer surface of the clothing to measure pesticide deposition. Nylon screen patches (10 × 10 cm) were used as collection media and mounted in open-frame aluminum holders to ensure standardization. The collection efficiency of the nylon screen has been validated at up to 88% [13].

Dermal sampling followed OECD and EU guidelines and included seven body regions: head, trunk, upper arms, forearms,

legs, feet, and hands [6, 7]. However, patch loss was anticipated on the hands during pesticide handling and equipment operation. To address this, hand exposure was simulated by having applicators wear vinyl gloves, following US EPA (1987) guidelines.

Inhalation Exposure Assessment

Inhalation exposure was measured using an impinger (Midget Impinger, 1820-01, Chemglass Inc., USA) connected to an air sampling pump (AirCheck Sampling Pump, 220-5000TC, SKC Inc., USA). Although adsorbent-based samplers generally provide more reliable results under laboratory conditions, previous studies have shown that impingers yield greater accuracy under field conditions [14]. Accordingly, the impinger was attached at neck level, corresponding to the breathing zone of the applicator, while the pump was worn at the waist and connected to the impinger. This configuration simulated realistic inhalation and captured airborne pesticides during spraying.

Quantification of Pesticide Deposited in Collection Samplers

After spraying, the patches used for dermal exposure assessment were collected in 100-mL glass bottles, and the samples captured in impingers were transferred into vials for storage. To prevent pesticide degradation, all samples were transported to the laboratory in an icebox. The recovered samples were rinsed with triple-distilled water, and the total pesticide collected (mg) was quantified using the Total Organic Carbon (TOC) analytical method. The accuracy of the TOC method was validated against liquid chromatography-tandem mass spectrometry (LC-MS/MS), yielding an R^2 value of 0.99 [13]. Dermal and inhalation exposure levels were calculated using Eqs. (1) and (2).

$$D_{\text{dermal}} = \frac{(C_{\text{nylon screen}} - C_{\text{blank}}) \times V_{\text{sample}} \times 1,000}{C_{\text{tank}} \times A_{\text{nylon screen}}} \times A_{\text{body}} \quad (1)$$

$$D_{\text{inhalation}} = \frac{(C_{\text{impinger}} - C_{\text{blank}}) \times V_{\text{sample}} \times 1,000}{C_{\text{tank}} \times Q_{\text{pump}}} \times IR \times \frac{BW}{60} \quad (2)$$

where, D_{dermal} represents the amount of pesticide deposited on the mannequin surface (mL/body), $C_{\text{nylon screen}}$ represents the TOC concentration of spray solution extracted from the nylon screen (mg/L), C_{blank} is the initial TOC concentration of the blank drift of the collection sampler (mg/L), V_{sample} is the total volume of the solution, including deposited spray and triple-distilled water (L), C_{tank} represents the TOC concentration of the spray solution in the application tank (mg/L), $A_{\text{nylon screen}}$ indicates the projected area of the nylon screen perpendicular to the wind direction (m^2), and A_{body} denotes the body surface area of the adult or child mannequin (m^2). For inhalation exposure, C_{impinger} represents the amount of pesticide collected by the impinger (mL/body), Q_{pump} is the pump flow rate (L/min), IR is the inhalation rate (m^3/h), and BW is the body weight of adults or children (kg). The total body surface areas of adults and children were assumed to be $16,600 \text{ cm}^2$ and $9,200 \text{ cm}^2$, respectively [6]. The air sampling pump was operated at a flow rate of 3 L/min. Inhalation rates were set as follows: $2.28 \text{ m}^3/\text{h}$ for adult bystanders, $3.18 \text{ m}^3/\text{h}$ for child bystanders, $0.33 \text{ m}^3/\text{h}$ for adult residents, and $0.68 \text{ m}^3/\text{h}$ for child residents [6].

Pesticide Exposure Modeling Approach

We evaluated the applicability of internationally recognized pesticide exposure models to application practices commonly used in Korean agricultural fields. For applicators, exposure was estimated using the EFSA model (European Food Safety Authority, Parma, Italy) and the UK-POEM model (UK Health and Safety Executive, United Kingdom). For bystanders, exposure was predicted using the EFSA model, the BREAM2 model (Bayer AG, Germany) [15], and the EUROPOEM II model (European Crop Protection Association, Belgium) [16].

Although the pesticide application equipment used in Korea does not fully correspond to the equipment types assumed in

these international models, field-measured parameters from the present study were incorporated into each model to evaluate their suitability for domestic drone and wide-area sprayer operations. The measurement procedures for bystanders and residents are identical; however, the EFSA guideline requires application of the 75th percentile for resident exposure assessment. Because the number of repeated measurements in this study was insufficient to derive percentile values, resident exposure could not be reliably estimated. Consequently, this study focused on an acute (short-term) bystander exposure scenario, assuming a single pass through the application zone during spraying. Model inputs for active ingredient deposition were based on the actual pesticide application rates used in the field trials, corresponding to 2.7 kg a.s./ha for drone application and 0.4 kg a.s./ha for ultra-low-volume sprayer application.

Conclusion

This study quantitatively assessed pesticide exposure among operators, residents, and bystanders during drone and wide-area sprayer applications and evaluated the applicability of existing exposure assessment models. Operator exposure was approximately eight-fold higher with the wide-area sprayer than with the drone, a difference attributed to close-range tasks during ML and increased direct contact with spray droplets during operation. In contrast, drone application substantially reduced dermal and inhalation exposure because operators remained physically separated from the spray zone through remote control.

Exposure levels for residents and bystanders were also higher during sprayer application. The greater spray volume per unit area and the horizontal, high-pressure discharge of the sprayer expanded drift dispersion and increased cumulative deposition at downwind distances. However, when normalized to an application rate of 10 L/ha, drone-based aerial spraying exhibited greater long-range drift potential, indicating the need for careful management of distant exposure risks.

Comparisons between measured exposure and predictions from EFSA, BREAM2, EUROPOEM, and UK-POEM revealed that existing models tended to either overestimate or underestimate exposure. These discrepancies stem from the models' assumptions of ground-based equipment and uniform deposition, which do not adequately capture the aerodynamic characteristics of drones and sprayers or the variability inherent in real-world field operations. This highlights the structural limitations of applying current models to fundamentally different spraying technologies and underscores the need to develop exposure assessment models tailored to aerial and wide-area spraying systems.

Although this study was limited by the lack of repeated measurements and could not encompass a wide range of environmental conditions, crop growth stages, or operator behaviors, it provides clear insights into exposure patterns associated with different types of application equipment and exposed populations. Accumulation of additional field data and further experiments across diverse multi-variable conditions will support the development of more accurate, field-reflective exposure models and evidence-based safety management guidelines.

Data Availability: All data are available in the main text or in the Supplementary Information.

Author Contributions: S.-w.H. and S.-y.L. conceived and designed the study; S.-y.L., J.-y.P., J.P., C.-r.L., .R.A.R. and Y.K. measured and collected the data; J.P., S.-w.H. and H.H.N. contributed analysis tools; S.-y.L. and J.-y.P. performed the analysis; S.-y.L., J.P. and S.-w.H. revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Notes: The authors declare no conflict of interest

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