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Particle-phase collection efficiency of the OVS and IFV Pro personal pesticide samplers

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Abstract

The inhalable aerosol sampling criterion has been developed to characterize the efficiency of particles entering the nose and/or mouth. However, pesticides can exist in the air in both vapor and particulate phases, which complicates exposure assessments. The American Conference of Governmental Industrial Hygienists (ACGIH) has established an IFV (inhalable fraction and vapor) endnote for chemicals such as many pesticides that need to be evaluated for both their inhalable fraction and vapor concentrations to fully characterize worker exposures. The purpose of this study was to evaluate the particle-phase collection efficiency of a commonly-used pesticide sampler, the OSHA Versatile Sampler (OVS) as well as a recently developed sampler, the IFV Pro. The OVS was not designed as an inhalable aerosol sampler, whereas the IFV Pro contains a sampling head scaled to that of the Institute of Medicine (IOM) sampler, which is known to closely follow the inhalable sampling criterion.

Laboratory experiments involving a vertical-flow, low velocity scheme and finely graded test dusts with known median aerodynamic diameter were used to determine sampler collection efficiencies. The collection efficiency of the OVS was evaluated as recommended by the manufacturer and after two modifications made to potentially improve its collection efficiency. The OVS was found to substantially under-sample relative to the inhalable criterion, and the two modifications did not provide substantial improvements to the original configuration. Conversely, the collection efficiency of the IFV Pro was found to compare closely to that of the IOM, although collecting 9% more mass. When applied side-by-side with the OVS sampler in a chamber into which ethylene glycol was sprayed as a proxy for a pesticide, the IVF Pro collected an average of 1.9-fold more mass than the OVS for the same flow rate and sample time.

Keywords

Efficiency; inhalable; pesticides; samplers

INTRODUCTION

Many pesticides have low vapor pressures (10^{-14} to 10^{-4} atm) and boiling points (240°-400°C). Thus, when sprayed as droplets, they exhibit both a particle and vapor phase

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given typical atmospheric temperatures and pressures (Hornsby et al. 1995; Raffy et al. 2018). Occupations such as professional painters, lawn care workers, grounds maintenance workers, and agricultural workers may use a spray applicator during work. Depending upon the applicator nozzle, a spray applicator may produce droplets with a median diameter of 4 μm to 15 μm classified as "very fine" by the ASABE S572.1 standard (ASABE, 2020; Bémer 2007). Others have found that spray aerosols may range from 24 μm to 543 μm diameter with speeds ranging from 0.5 m/s to 12 m/s depending on the nozzle, therefore leading to a wide size range of particles that may be present for human exposure (Minov 2016). However, the overall exposure to pesticides is difficult to quantify because of the dual-phase nature of pesticides, where both phases might constitute a health risk.

To provide guidance on the proper sampling of pesticides and other dual-phase compounds for which both phases contribute a significant portion of the dose, the American Conference of Governmental Industrial Hygienists (ACGIH) has designated such compounds with the Inhalable Fraction and Vapor (IFV) endnote (ACGIH, 2020). The IFV endnote is assigned by comparing the saturation vapor concentration (SVC) to the threshold limit value (TLV) time weighted average (TWA) concentration. Compounds that possess an SVC/TLV ratio of 0.1 to 10 are assigned the IFV endnote (ACGIH, 2020). As of 2020, there are currently 79 compounds assigned to the IFV designation, many of which are pesticides (ACGIH 2020).

Although not specifically described as such, the "inhalable fraction" of the IFV endnote suggests that a size-selective sampler designed to collect according to the inhalable fraction convention (Soderholm 1989, CEN 1993) be used when sampling compounds given that designation. Many IFV-designated compounds require the use of the OSHA Versatile Sampler (OVS) when following OSHA and NIOSH sampling and analytical methods for pesticides, including OSHA Analytical Methods 62 and 63 (OSHA 1991) and NIOSH Methods 5600, 5601, and 5602 (NIOSH 1994). The OVS sampler consists of a glass tube that contains a filter to capture the particle-phase and a two-section sorbent bed to adsorb the vapor-phase. However, the OVS was not originally designed to be size-selective for the inhalable fraction and therefore may not fully satisfy the IFV designation.

Recently, two all-in-one size-selective and vapor-capturing personal samplers to accommodate the unique dual-phase properties of pesticides and other semi-volatile organic compounds (SVOCs) were developed. The Gesamtstaub-Gas-Probenahme (GGP) inhalable dust and vapor sampler was developed as a modification to the Gesamt Staub Probenahme (GSP) inhalable dust sampler to accommodate the lower flow rates required for a sorbent tube while maintaining a scaled inhalable sampling head (Breuer et al. 2015). Likewise, the IFV Pro sampler developed by SKC Inc. (Eighty-Four, PA) consists of a sampling head scaled from that of the Institute of Medicine (IOM) inhalable dust sampler to operate at a lower flow rate to accommodate the addition of a sorbent tube (SKC 2021). However, evidence of the size-selective sampling capabilities of the IVF Pro could not be found in the literature. Additionally, its efficiency as a dual-phase sampler has not been compared to the traditionally used OVS sampler. Furthermore, there is no published literature on the particle-phase collection efficiency of the OVS.

To address these limitations in the scientific literature, the overall purpose of this study was to characterize the particle collection efficiencies of the IVF Pro and the OVS samplers. An initial study (Study 1) was conducted to determine the particle collection efficiency of the OVS sampler and in comparison to the collection efficiency of the IOM inhalable sampler, which has been shown to have a collection efficiency that compares well with the inhalable fraction definition (Mark & Vincent, 1986). This study also evaluated two simple modifications to the OVS sampler to determine whether they could enhance its ability to sample similarly to the IOM sampler. A second study (Study 2) was conducted to determine the collection efficiency of the IFV Pro sampler relative to that of the IOM sampler in calm-air conditions. An ancillary aspect of this research was to compare the combined particle- and gas-phase collection of the IFV Pro sampler relative to the OVS sampler.

METHODS

Aerosol Chambers and Generation

Although different chambers were used to conduct Study 1 and Study 2, they both produced a laminar downdraft of aerosol-laden air to the samplers compared in both studies. For Study 1, a laminar flow column (0.83 m of 0.2-m diameter ductwork) was placed inside a stainless-steel exposure chamber (1 m x 1 m x 1 m) to serve as a containment vessel (see Figure S1 in the online supplement). Using a thermal anemometer (TSI, Inc., Shoreview, MN), the velocity of air down through the column was measured between 0.02 – 0.04 m/s. Wind speeds inside chambers that have air movement below 0.05 m/s can be described as "calm air" (Aitken et al. 1999).

During Study 2, samplers to be compared were placed in a newly-fabricated vertical-flow chamber (Figure S1). Along with the supply air, a port in the top section of the chamber allowed for the injection of the test aerosol with the use of a Wright Dust Feeder II (CH Technologies, Westwood, NJ). The laminar flow of aerosol then passed down into a sampling area accessible by a door. The flow rate through the chamber was 400 L min^{-1}, which created a downward velocity of 0.025 m/s, was within the calm-air range.

In both studies, sieved aluminum oxide dusts (Washington Mills, Niagara, NY) were used as test aerosols (Table 1). Aluminum oxide dusts have been used in other experiments testing the performance of inhalable samplers (Mark et al. 1985). Based on the manufacturer's information, the median aerodynamic diameter of the three grit sizes used, F1200, F500, and F320, were 6, 26, and 58 µm, respectively. Additional information was obtained to determine the range of particle diameters comprising each dust type (Gritomatic 2021) and shown in Table 1. Furthermore, an eight-stage personal cascade impactor (290 Series, Tisch Environmental, Cleves, OH) was used to verify the size distribution of the two smaller grit sizes resulting in a geometric mean (GM) of 6.2 µm and geometric standard deviation (GSD) of 2.8 for the F1200 dust, and GM of 34 µm and GSD of 3.42 for the F500 dust. The F320 dust was too large to measure accurately with this device. The dust sizes were selected in order to represent the lower, middle, and upper ranges of the particle sizes included in the ACGIH-CEN-ISO inhalable convention curve (Soderholm 1989) with a range of 0 – 100 µm.

Aerosol Samplers

Four aerosol samplers were used during the study: the IOM (No. 225-76A, SKC, Inc., Eighty Four, PA), a 25-mm conductive polyurethane open-faced asbestos cassette (No. 225-321, SKC, Inc., Eighty Four, PA), the OVS (No. 226-30-16, SKC, Inc., Eighty Four, PA) and the IFV Pro sampler (No. 225-49, SKC, Inc., Eighty Four, PA). The IOM was operated with a flowrate of 2 L min^{-1} in accordance with manufacturer's instructions to achieve size-selective particle collection that meets the inhalable fraction criterion. The 25-mm open-face cassette was used as an isokinetic reference sampler by placing it in the chamber facing upward and operated with a flow rate to achieve an inlet velocity equivalent to the downward velocity of air through the chamber.

The OVS consists of a glass tube (11-mm inner diameter and a 13-mm outer diameter) containing a 13-mm filter to capture aerosols and a two-section sorbent bed to adsorb vapor (Figure S2). The filters are either glass fiber for OSHA methods or quartz fiber for NIOSH methods, and the adsorbent is typically Amberlite® XAD®-2 or XAD®-7 resin. In its normal configuration, the OVS is placed within a hard plastic tube with its inlet facing vertically downward and sampled with flow rates ≤ 1 L min^{-1}.

The IFV Pro sampler is equipped with a scaled IOM-style sampling head with a 11-mm inlet containing a 25-mm cassette facing horizontally followed by a sorbent tube housed in a hard plastic tube held vertically (Figure S3). To prevent rapid breakthrough of the sorbent tube, the IFV Pro operates at a flow rate of 1 L min^{-1}. To achieve a particle aspiration efficiency that matches the inhalable criterion while operating at that flow rate, the sampling head was developed as a scaled version of the IOM using methods developed by Vincent and his collaborators (Brixey et al. 2002; personal communication with the manufacturer). When collecting both particle and vapor phase, a separate filter sampling cassette (No. 225-4903, SKC, Inc., Eighty Four, PA) and 6 x 110 mm dimension XAD®-7 sorbent tube (No. 226-95, SKC, Inc., Eighty Four, PA) were used as directed by the manufacturer (SKC 2021) for each sample of ethylene glycol as further explained below. Analysis of the sorbent tube was performed in accordance with NIOSH Method 5523 (ALS Labs, Salt Lake City, Utah).

For all experiments, the samplers were placed in close proximity to one another to minimize concentration differences spatially and were secured with a combination of ring-stand clamps and Velcro® to secure to a polyvinyl chloride (PVC) pipe. The inlets of all samplers were placed at the same height and were directed toward the middle of the laminar flow chamber for all experiments. PVC (No. 225-5-37, SKC, Inc., Eighty Four, PA) filters were used when performing collection efficiency studies. Sample flow rates for each sampler were calibrated using a tetraCal® (Mesa Laboratories, Inc., Lakewood, CO) or Gilibrator-2® Primary Flow Calibrator (Sensidyne, St. Petersburg, FL).

Study 1 Procedures

When sampling the aluminum oxide aerosols, the IOM, the OVS, and the isokinetic sampler were suspended by a ring stand in the middle of the sampling chamber and held by Velcro® horizontally at the same height in a row, side by side. During Study 1, only the filter of the OVS was used to assess the particle-phase collection efficiency of that sampler. The two-section sorbent bed was replaced with a piece of plastic tubing cut to support the bottom of the 13-mm filter at its typical location within the OVS tube (~14 mm from opening) while the polytetrafluoroethylene (PTFE) holding ring provided by the manufacturer supported the top of the filter. The 13-mm quartz filter provided by the manufacturer was also replaced with a 13-mm PVC filter to increase the precision of measurements when determining concentrations gravimetrically. The 13-mm filters were punched out of 25-mm filters (No. 225-5-25, SKC, Inc., Eighty Four, PA) using a cork borer. To best compare to the collection efficiency of the IOM sampler, the OVS flowrate was set to achieve the same entry velocity as that of the IOM sampler (19 cm/s). Given the 11-mm inside diameter of the holding ring supporting the filter, the corresponding flowrate of the OVS was 1.0 L min^{-1}, which also corresponded to the upper flowrate allowed by both NIOSH and OSHA sampling methods. Pre-trials were conducted with a filter placed downstream of the OVS with these adaptations, which confirmed that the aluminum oxide aerosol did not escape past the 13-mm filter.

The OVS was tested under its normal configuration and two other modifications to determine whether simple modifications could result in a collection efficiency close to that of the IOM. For the first configuration, the OVS was operated normally with a vertical, downward orientation and placed inside the tube holder. The first modification included removing the plastic holder, placing the OVS horizontally and attaching a flanged entry lip (Figure S4). This flange was made from the “hat cap” supplied with the OVS by cutting out the circular top cover and inverting it onto the OVS so that the flange was flush with the inlet of the OVS. Flanges block air from behind, which increase capture velocities in front of the inlet (ACGIH 2013). The inlet diameter of the flanged adapter was 14 mm, the flange was 24 mm, and the height of the flanged adapter was 10 mm. Such a flange also mimics the face of the IOM, which consists of a 35-mm diameter flange around a 15-mm diameter inlet. For the second modification, a conical piece was fabricated, attached to an OVS tube and pushed out slightly to create a sharper inlet edge. The conical inlet was designed to be similar to the inlet of the GSP sampler, an inhalable sampler (Kenny et al. 1997). The inlet, base, and height of the conical adapter were 13 mm, 25 mm, 11 mm, respectively and with a slant angle of the conical adapter similar to that of the GSP sampler.

Each comparison trial lasted for approximately 20 minutes, and for each OVS configuration, three trials were conducted per particle size. During pre-trials, an additional 9 trials for each particle size were conducted to further evaluate the IOM relative to the isokinetic cassette. All filters and filter-cassettes were weighed before and after a trial using a 6-place microbalance (Model MT5, Mettler Toledo, Columbus, OH) in a nearby dedicated room to determine a net mass on the filter. Laboratory blanks were kept inside the weighing room at all times, and all the net mass values were blank corrected. The temperature and relative humidity of the weighing room were identical to that of the chamber air stream to minimize environmental effects on filter weights. Filters were equilibrated in the weighing room for 24 hr prior to mass measurement.

In addition to weighing the IOM filter and cassette as a single unit, the filter associated with the IOM cassette was also weighed by itself. The OVS does not have a cassette to account for wall losses, and OSHA and NIOSH sampling and analytical methods for the

OVS do not analyze aerosol deposits inside the OVS tube. Therefore, the filter of the OVS was compared to the filter of the IOM by itself as well as the IOM filter and cassette as a unit. The isokinetic sampler concentrations also included mass from wall deposits. The net mass on the walls was determined by wiping a clean pre-weighed filter over the inside of the cassette walls and weighing the filter afterward.

Study 2 Procedures

Particle Collection Efficiency—When sampling dry powder aerosol in the vertical-flow chamber, the IOM, the IFV Pro sampling head with no sorbent attached, and the isokinetic sampler were suspended by a ring stand in the middle of the sampling chamber and held by Velcro® horizontally at the same height in a row, side by side. Testing procedures to determine the particle collection efficiency of the IFV Pro relative to that of the IOM were similar to those described above when comparing the OVS to the IOM. Eight trials were conducted per dust type. Between samples, the IFV Pro sampler head and IOM were exchanged from the left to right position, while the 25-mm cassette was left between them to negate potential spatial differences in concentration.

Dual-Phase Comparison—A cylindrical steel drum with a tight, removable lid (D 45 cm x H 74 cm) was adapted as a chamber to compare the IFV Pro to the OVS for simultaneous particle- and gas-phase collection (Figure S1). To create dilution air and some mixing within the chamber, a vacuum pump pulled 60 L min^{-1} of room air through an inlet port halfway down one side and out through a fitting on the top lid of the chamber. Additional ports were added to the lid to connect vacuum pumps to the two samplers arranged within the chamber to be located slightly above the inlet port.

Ethylene glycol (99% Anhydrous, Sigma-Aldrich) was used as the test compound. Glycols have previously been used to verify a sampler to collect dual-phase compounds (Breuer, et al. 2015). Ethylene glycol was also selected due to its vapor pressure of 7.89 x 10^{-5} atm, which is within the range of vapor pressures of common pesticides. Initially, a commercially-available portable pesticide sprayer was adapted for spraying into the chamber, but preliminary trials demonstrated that the sprayed volume was much higher than needed for these tests. Therefore a handheld spray bottle was used that injected approximately 1 mL of liquid per trigger depression into the ambient air inlet port of the chamber. The concentration over time and size distribution of the droplet aerosol was measured using an optical particle counter (GRIMM 11-C, GRIMM Aerosol, Ainring, Germany) to verify the generation of a polydisperse aerosol with droplet sizes typical of a commercial sprayer (Bémer et al. 2007). This aerosolization method produced a pulse of droplet aerosol after each injection characterized by a sudden increase that exponentially decayed to background levels within 90 s.

Trials began by placing the OVS with XAD®-7 adsorbent (No. 226-57A, SKC, Inc., Eighty Four, PA) in its holder in a downward facing position. The IFV Pro filter cassette was loaded with a 25-mm quartz fiber filter (No. 225-1825, SKC, Inc., Eighty Four, PA) and XAD®-7 sorbent tube (No. 226-95, SKC, Inc., Eighty Four, PA) and was placed so that its sample inlet was at the same elevation as the OVS inlet. Both samplers were placed off-center to avoid being hit directly with the droplet spray. To minimize any orientation bias that may occur from the placement of the samplers within the chamber, sampler placement was alternated between trials. A total of three sprays per trial were injected at time 0, 1:30, and 3:00 min over the course of a 5-min sampling duration timed by stopwatch providing a 5-liter air sample for each sampler. Upon completion of sampling, the samples were removed and placed in freezer (−80 °C) for storage prior to shipment to the lab for analysis.

Both samplers were analyzed following NIOSH Method 5523 by an American Industrial Hygiene Association accredited lab (ALS Laboratories, Salt Lake City, Utah). The OVS tubes were shipped with the supplied end caps. As per Method 5523, the front sorbent section and the filter were desorbed in methanol together and analyzed. The IFV Pro filter cassettes were shipped in holders designed for that purpose (No. 225-4901, SKC, Inc., Eighty Four, PA) together with the corresponding sorbent tubes after capping. During six preliminary trials, the lab was directed to follow Method 5523 applied to the filter and corresponding sorbent tube of the IVF Pro separately. Eight additional trials were then analyzed after combining the separate filter with the sorbent tube contents prior to desorption. For both the OVS and the IVF Pro sorbent tube, the back section of adsorbent media was analyzed to test for vapor breakthrough. The lab did not rinse the inside of the cassette to retrieve particles that may have deposited in that area. Unlike when using the OVS, the stainless steel filter cassettes shipped to the lab had to also be returned after analysis upon request. A blank OVS tube, quartz fiber filter, and sorbent tube were also analyzed.

Data Analysis

For both studies, concentrations measured with the IOM sampler and the co-located sampler (OVS or IVF Pro) were compared to those obtained from the 25-mm cassette used as an isokinetic sampler and related to the proposed calm air inhalability curve (Aitken et al, 1999) and the ACGIH/CEN/ISO inhalability curve. For Study 1, descriptive statistics were generated to compare each OVS configuration to the IOM filter and associated cassette as a single unit, and the IOM filter by itself at the three different particle sizes. In addition, a two-sample t-test was conducted to determine whether the measurements of the IOM filter and cassette as a single unit were different from the measurements of the IOM filter by itself.

Study 2 sampler measurements were compared using a paired t-test across all particle sizes. Additionally, orthogonal regression analysis was performed to test agreement and constant bias between the two samplers. When conducting this regression analysis, the error variance of the IOM measurements was assumed to be equivalent to the error variance of the IVF Pro measurements given identical sources of measurement variability for both samplers for which gravimetric analysis of filter weights was conducted (Leng et al. 2007). Descriptive statistics were generated and a paired t-test was conducted for measurements taken when comparing the OVS and IFV Pro. All data analysis was performed using Microsoft Excel and Minitab (v. 17.3.1, Minitab, Inc., State College, PA). An $\alpha < 0.05$ was considered significant. Data sets to be compared with the use of t-tests were first tested for normality using the Anderson-Darling test. All data sets were found to have a distribution not different from the normal distribution ($p > 0.05$).

RESULTS

OVS Evaluation

The collection efficiency of the IOM sampler relative to particle aerodynamic diameter is given in Figure 1(A). The collection efficiency of the OVS when operated in its normal vertically-downward configuration, and when the two modifications were applied, is shown in Figure 1 (B-D). To compare OVS measurements directly to those of the IOM, Table 2 displays the average concentration ratios of the two samplers based on IOM measurements developed from the filter and cassette as a single unit and the IOM filter by itself. The overall average OVS/IOM concentrations percentage across all particle sizes when in the typical vertical position was 34%. Adding the flange (33%) and conical (27%) adapters did not improve the overall average. Because the IOM cassette was weighed with its filter and the filter was weighed separately, the mass of particles adhering to the cassette walls could be determined. The average mass collected on the IOM cassette as a percentage of total mass collected was approximately 8% at 6 μm, 25% at 26 μm, and 47% at 58 μm.

IFV Pro Evaluation

Size-selective Comparison—The collection efficiency of the IVF Pro sampler relative to particle aerodynamic diameter is given in Figure 2(A) in comparison to the collection efficiency of a co-located IOM sampler. Figure 2(B) provides a direct comparison of the ratio of the collection efficiency of the IVF Pro to the efficiency of the IOM by particle aerodynamic diameter. The overall average across all three particle sizes was 109%. A paired t-test comparing mean concentrations of samples using the IOM and IFV Pro demonstrated a significant difference ($p = 0.021$) across all samples ($n = 24$ for each sampler). An orthogonal linear regression of the IOM sampler vs the IFV Pro sampler as a function of concentration is given in Figure 3. That analysis resulted in a significant slope of 1.33 ($p < 0.001$) and an $R^2 = 0.94$. As an indication of agreement between the two samplers, the 95% confidence interval about the slope was computed and found to not bound unity (CI = 1.198 – 1.470) indicating that the slope is > 1.0. Likewise, the intercept of the regression was significant ($p = 0.012$) indicating a potential constant bias between the two samplers (Wang et al. 2016; Yanosky et al. 2002).

Dual-phase Comparison—The particle diameter distribution by mass of the spray generated with the spray-bottle technique revealed the presence of a distribution of particles ranging from 2 μm to >32 μm with a mass median diameter (MMD) of 13 μm and geometric standard deviation of 1.7 (Figure S5). These results verify that a model aerosol was achieved that has droplet sizes typical to those created with a standard field applicator having MMDs in the range of 4 - 15 μm (Bémer et al. 2007).

The front and back section mass collected by each sampler type for the eight paired trials is given in Table S1. There were no samples for which breakthrough occurred, which is indicated by a back-to-front mass ratio >10% according to NIOSH Method 5523, Figure 4 shows the mass measured for each of the eight OVS samples and their paired IVF Pro sorbent tube measurements. Sample mass is comparable between the two samplers given identical sample flow rates and times. The OVS sampler collected an average mass of 0.25

mg/sample while the IFV Pro collected an average 0.48 mg/sample resulting in a 1.9-fold increase in mass collected by the IFV Pro. However, the IVF Pro sample mass was not consistently greater than that of the OVS with 2 samples having greater OVS mass collected (Figure 4). Despite a higher average mass collected by the IVF Pro, analysis by paired t-test showed that the means were not significantly different ($p = 0.063$). Additionally, with data obtained when the IFV Pro filter and sorbent tube were reported separately, it was determined that roughly seven-fold more mass was collected in the sorbent tube compared to the filter, but this result was dependent on test conditions.

DISCUSSION

OVS Characteristics

Study results demonstrate that the particle collection efficiency of the OVS was lower with respect to the ACGIH-CEN-ISO inhalable convention curve. However, the measured IOM sampler efficiency values were higher than the ACGIH-CEN-ISO inhalable convention curve, which was expected given prior studies in low-air flow experimental conditions (Aitken et al. 1999; Kenny et al. 1999; Sleeth and Vincent 2012; Görner et al. 2010; Witschger et al. 2004) that also showed higher collection efficiencies for the IOM sampling in that condition.

As expected, the efficiency of all OVS configurations matched the efficiency of the IOM filter by itself closer than the efficiency of the IOM filter and cassette as a single unit because particles adhering to the inner walls of the OVS were not weighed. Likewise, the standard method of sampling when using the OVS (oriented vertically and placed inside its tube holder) under-sampled when compared to the IOM sampler. This agreed with our expectation given that a downward-facing inlet would not aspirate particles with the efficiency of the horizontal-facing inlet of the IOM. However, even though the face velocity of the OVS was matched to the face velocity of the IOM sampler, the OVS also under-sampled when configured to sample horizontally with the flange and conical adapters applied.

In addition to unweighed losses within the OVS sampler tube, differences in inlet size between the IOM sampler (15-mm) and the OVS (11-mm) may have contributed to particle capture efficiency differences. Curvilinear motion of a particle can be characterized by Stokes number, a dimensionless number which is inversely proportional to the characteristic diameter of an object perpendicular to airflow (Hinds 1999). Because the inlet diameter of the IOM sampler is larger than the inlet diameter of the OVS, the Stokes number for the IOM sampler is smaller than the Stokes number for the OVS for all particle sizes. Thus, more particles are likely to follow the air streamlines when air turns into the IOM sampler than when air turns into the OVS. A much larger ratio of inlet diameter to filter depth within the sampler of the IOM (0.99) than that of the OVS (0.38) may also have contributed to the poor collection of the OVS despite sampling in a horizontal position and operating with the same inlet velocity as the IOM. Likewise, the outer edge of the OVS tube is rounded and the inner ring holding the filter in place is “blunt”, unlike the sharp edge of the IOM, which may diminish its aspiration efficiency (Brixey et al. 2002). The addition of the sharp-edged conical adapter did not substantially increase collection efficiency. However, the flanged adapter improved the efficiency of the OVS, but still under-sampled relative to the IOM. Flanges block air from behind, which increase capture velocities in front of the inlet (ACGIH 2013), but not to the level resulting in sampling efficiencies similar to the IOM sampler.

An ancillary result obtained from this study was the observation that the mass of particles collected on the wall of the IOM cassette can be substantial and increases with particle size. This result agrees with the study by Witschger et al. (2004) who found that IOM cassette wall losses were particle size dependent and increased from approximately 20% at 7 μm to 55% at 76 μm. This result has implications for the use of an IOM-like inlet as part of the IVF Pro that is later analyzed for a pesticide using methods such as NIOSH 5600 or 5601 (NIOSH 1994). Those methods do not require the inner walls of the OVS sampler to be washed with reagent to release adhered pesticide residue. Therefore, if either method is used to analyze a sample taken with the IVF Pro, it will fail to include inhalable pesticide mass adhered to the inner walls of the cassette and underestimate inhalable exposure concentrations.

IFV PRO Characteristics

Analytical methods for IFV-designated pesticides such as Methods 5600 and 5601 (NIOSH, 1994) require sorbent tubes to be operated at flow rates of ≤ 1 L min^{-1}, which negates the use of an IOM in series at this flowrate given the need to operate the IOM at 2 L min^{-1}. Therefore, to correctly apply a sorbent tube in series with a size selective sampler, SKC engineers scaled down the sampling head of the IOM to operate at 1 L min^{-1} while still maintaining its size selective capabilities. Proper scaling of a size-selective sampler inlet occurs by maintaining the ratio, R, of freestream velocity to sampling velocity (Ramachandran et al. 1998, Durham and Lundgren 1980). At its operating flow rate and inlet diameter of 15 mm, the IOM inlet velocity is 0.19 m s^{-1}, which was matched by the IFV Pro given its sample flow rate and inlet diameter of 10.6 mm. The IFV Pro also has the same ratio of inlet diameter to filter depth as the IOM (0.99). However, the aspiration efficiency of a sampler is also affected by the ratio, r, of the outer diameter of the sampler body to its inlet diameter (Ramachandran et al., 1998), which is 2.3 for the IOM but is 3.0 for the IFV Pro. The larger body diameter relative to inlet diameter of the IFV Pro is most likely due to the constraint imposed by the standard size of the filter applied, 25 mm, which forced a higher ratio.

The results of this study demonstrated that the IFV Pro has a size-selective inlet that conforms with the ACGIH/CEN/ISO inhalable curve (Figure 1A), but slightly over-estimates (9%) the inhalable dust fraction (Figure 2B). This observation is supported by the results of the paired t-test analysis showing that, across all particle sizes, the average IOM and IFV Pro concentrations are statistically different. Likewise, the confidence interval about the slope resulting from a linear regression relating concentrations obtained from the two samplers did not bound unity, which suggests that the IFV Pro oversamples relative to the IOM within the vertical-flow, calm-air conditions of this study. Measurements made in the vertical-flow chamber associated with this aspect of the study (Study 2) resulted in IOM and IVF Pro collection efficiencies closer to the ACGIH/CEN/ISO inhalable curve than those obtained with the chamber used in the first study. This suggests that the second chamber may create eddies of horizontally flowing air in order to better mimic results obtained utilizing a wind tunnel similar to that used originally to validate the IOM (Mark and Vincent 1986).

The IFV Pro sampled 1.9-fold more ethylene glycol mass per sample than the OVS across all trials. With no reported breakthrough of ethylene glycol vapors through the OVS front sorbent section, this difference in mass per sample is best explained by the lower collection efficiency of the OVS relative to an inhalable sampler (Table 2). The unique ability of the IFV Pro to capture the particle phase and vapor phase simultaneously, but separately, also gave insight into how the chemical behaved when aerosolized. The ethylene glycol droplets readily evaporated, most likely while in the air and also while trapped on the collection filter, which resulted in higher mass collected in the sorbent tube than on the filter.

CONCLUSION

When used in its typical configuration, the particle collection efficiency of the OVS sampler rapidly diminished below 50% with particle size and, therefore, did not achieve a collection efficiency comparable to that of an inhalable sampler, which remains ≥ 50% for particles with aerodynamic diameter < 100 μm. For this reason, the OVS sampler cannot be used to satisfy the IFV designation established by the ACGIH for many pesticides given the need to collect the inhalable fraction. Two simple adaptations to the OVS sampler were likewise unable to achieve a collection efficiency curve comparable to the inhalable convention. However, the IFV Pro sampler was found to have a collection efficiency that was close to, but somewhat over-sampled relative to, the inhalable convention when operating in the calm-air conditions developed in this study. The increased particle capture efficiency of the IFV Pro resulted in a considerable (1.9-fold) increase in mass of a test semi-volatile organic compound, ethylene glycol, compared to the OVS and, therefore, provides a much more conservative estimate of exposure to IFV-designated compounds. However, given that droplets may adhere to the inner walls of the IFV Pro filter cassette, we recommend that analytical methods used to determine the sampled pesticide mass include a step to wash the inner surface of the cassette to result in a more accurate measure of the inhalable fraction of airborne pesticide spray droplets.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability statement:

The data that support the findings of this study are available from the corresponding author, P. T. O'S., upon reasonable request.

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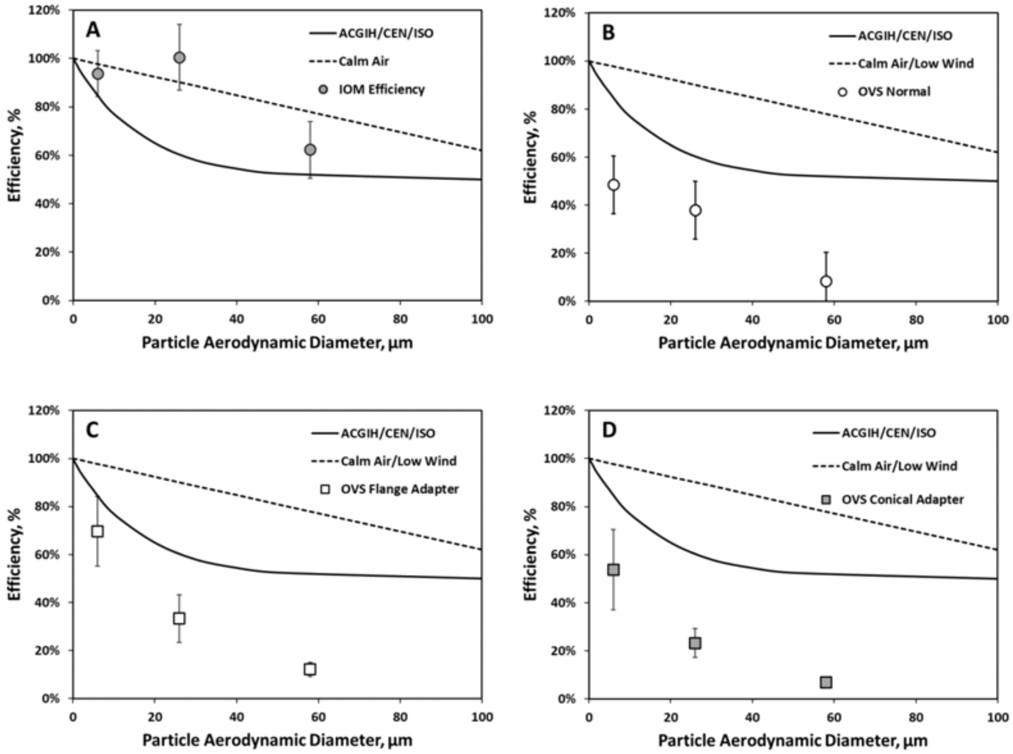

Figure 1.

Plots of average collection efficiency with standard error bars of the IOM (A) and the OVS when used normally (B), when a flange adapter was applied (C) and when a conical adapter was applied (D). Each plot also contains a line representing the ACGIH/CEN/ISO inhalability criterion and a line indicating the proposed calm air inhalability criterion (Aitken et al, 1999).

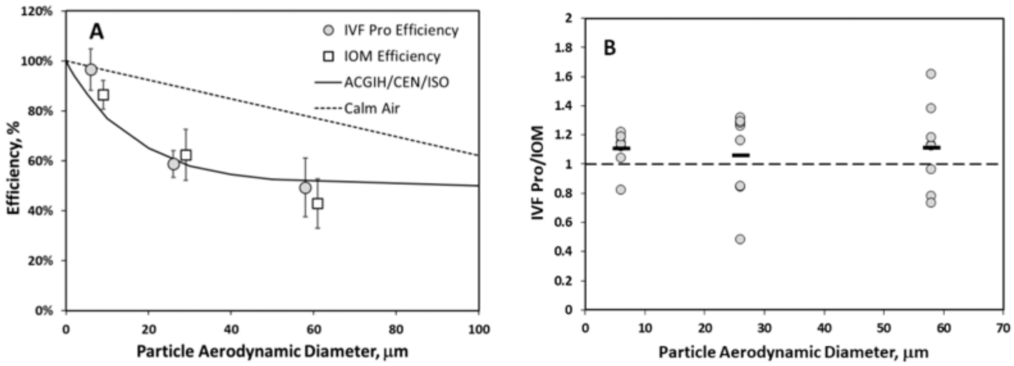

Figure 2.

The collection efficiencies of the IVF Pro sampler and IOM relative to particle aerodynamic diameter measured in the vertical-flow chamber (A). IOM efficiency was shifted to the right of the diameter measured for clarity. Comparable ratios of IVF Pro concentrations to IOM concentrations (B) relative to a 1:1 line. Horizontal bars represent ratio averages.

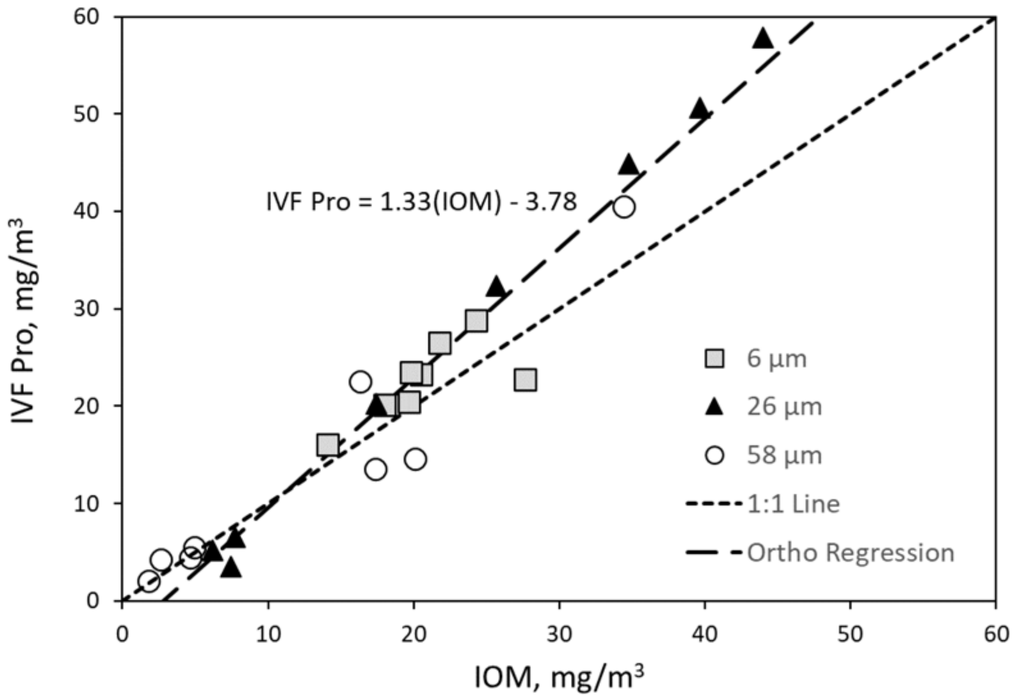

Figure 3.
Orthogonal regression analysis of IFV Pro concentrations relative to paired IOM concentrations.

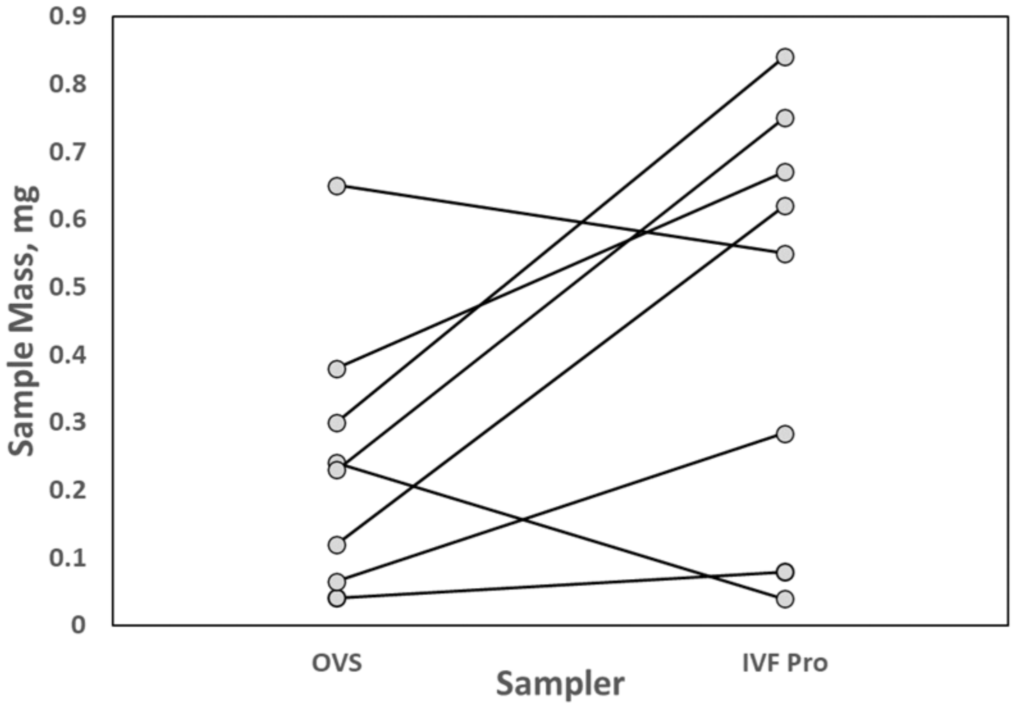

Figure 4.

Ethylene glycol mass collected by the paired OVS and IVF Pro samplers (as shown with connected line) for all eight trials performed in the steel drum chamber.

Table 1.

Characteristics of the aluminum oxide dust used in the experiments.[A,B]

Grade Designation	Physical Diameter and Range[C] (μm)	Aerodynamic Diameter (μm)
F1200	3 (1 – 4)	6 (2 – 8)
F500	13 (5 – 25)	26 (10 – 49)
F320	29 (17 – 49)	58 (34 – 97)

[A]Composition: 96.05% Al_2O_3, 2.7% TiO_2, 1.25% others

[B]Density: 3.92 g/cm^3

[C]Values in brackets are the particle diameters for which 94% are greater than, and 97% are less than, the given diameter (Gritomatic 2021)

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Table 2.

Average concentration ratios ($\bar{x}$) and standard deviation (s) comparing each OVS configuration to the IOM filter and cassette as a single unit and the IOM filter by itself for all particle sizes

	OVS/IOM		**OVS/IOM (Filter-Only)**	
OVS Configuration	$\bar{x}$	**s**	$\bar{x}$	**s**
Vertical	34%	10%	51%	19%
Flange Adapter	33%	10%	39%	19%
Conical Adapter	27%	14%	31%	15%