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Opportunities and Challenges in Reducing Personal Inhalation Exposure to Air Pollution among Electronic-waste Recovery Workers in Ghana

Zoey Laskaris[1], **Stuart A. Batterman**[2], **John Arko-Mensah**[3], **Bhramar Mukherjee**[4], **Julius N. Fobil**[3], **Marie S. O'Neill**[1,2], **Thomas G. Robins**[2]

[1]Department of Epidemiology, University of Michigan School of Public Health, Ann Arbor, MI, United States of America

[2]Department of Environmental Health Sciences, University of Michigan School of Public Health, Ann Arbor, MI, United States of America

[3]Department of Biological, Environmental and Occupational Health Sciences, University of Ghana School of Public Health, Accra, Ghana

[4]Department of Biostatistics, University of Michigan School of Public Health, Ann Arbor, MI, United States of America

Abstract

Background: Informal sector electronic-waste (e-waste) recovery produces toxic emissions resulting from burning e-waste to recover valuable metals.

Objectives: To identify high-risk worker groups by measuring relative levels of personal inhalation exposure to particulate matter (PM) of fine (≤2.5 μm) and coarse (2.5-10 μm) fractions ($PM_{2.5}$ and $PM_{2.5\text{-}10}$, respectively) across work activities among e-waste workers, and to assess how wind conditions modify levels of PM by activity and site location.

Corresponding author and institution at which the work was performed: Zoey Laskaris, laskaris@umich.edu, University of Michigan School of Public Health, Department of Epidemiology, 1415 Washington Heights, Ann Arbor, MI 48109-2029.

Author Contributions

Zoey Laskaris is the lead author on the manuscript. She conceptualized, designed and carried out the methods described in this paper, performed the analysis, interpreted the results and wrote the paper. Julius Fobil (PI-parent study), Thomas Robins (co-PI) and Stuart Batterman collectively conceptualized and oversaw the execution of the parent study from which the raw data used in this study originate.

Stuart Batterman additionally oversaw the exposure assessment and provided input into the methods and analyses described in the paper. John Arko-Mensah oversaw data collection in the field and provided input on the writing of the manuscript. Bhramar Mukherjee contributed to the statistical methods used in this paper. Marie O'Neill contributed to the manuscript development through draft revisions and input into the methods and analyses described in the manuscript. Thomas Robins (Co-PI of parent study) served as the senior author on the paper and contributed to the manuscript development through draft revisions and input into the methods and analyses described in the manuscript

Institution and Ethics approval and informed consent

All study protocols were approved by the University of Ghana and University of Michigan Institutional Review Boards. Informed consent acquisition and data collection were conducted by trained, local interpreters in the participant's native or preferred language.

Disclosure

The authors declare they have no actual or potential competing financial interests.

Disclaimers

There are no disclaimers to report.

Methods: At the Agbogbloshie e-waste site, 170 partial-shift PM samples and time-activity data were collected from participants (N=105) enrolled in the GeoHealth cohort study. Personal sampling included continuous measures of size-specific PM from the worker's breathing zone and time-activity derived from wearable cameras. Linear mixed models were used to estimate changes in personal $PM_{2.5}$ and $PM_{2.5-10}$ associated with activities and evaluate effect modification by wind conditions.

Results: Mean (± standard deviation) personal $PM_{2.5}$ and $PM_{2.5-10}$ concentrations were 80 μg m^{-3} (±81) and 123 μg m^{-3} (±139), respectively. The adjusted mean $PM_{2.5}$ concentration for burning e-waste was 88 (μg m^{-3}), a 28% increase above concentrations during non-recovery activities (e.g., eating). Transportation-related and burning activities were associated with the highest $PM_{2.5-10}$ concentrations. Frequent changes in wind direction were associated with higher $PM_{2.5}$ concentrations when burning and high wind speeds with higher $PM_{2.5-10}$ concentrations when dismantling e-waste downwind of the burning-zone.

Discussion: The greatest reductions in personal exposure for all workers will come from the replacement of burning practices with safer and more efficient methods of metal extraction viable in low and middle-income countries.

Keywords

electronic-waste; air pollution; particulate matter; personal inhalation; informal sector; Ghana

1.1 Introduction

The disease burden from ambient particulate matter (PM) pollution disproportionately falls on individuals in low- and middle-income countries (LMICs) [1]. Workers, especially those in LMICs where enforcement of occupational safety regulations often is minimal, are exposed to both environmental and occupational sources of PM. The Global Burden of Disease study estimates that 488,000 deaths were attributable to occupational exposure to "particulate matter, gases and fumes" in 2017, representing 42% of deaths attributable to *all* occupational risks [2]. The actual number of deaths may be higher considering the number of informal workers worldwide who are unaccounted for and endure high exposures with little to no protection or regulatory enforcement [3].

The informal electronic-waste (e-waste) recovery sector emits PM from the burning electronic wastes in open fires in order to extract valuable metals. Sub-Saharan Africa is home to several of the world's largest and most studied informal e-waste recovery sites [4]. At the Agbogbloshie e-waste site in Accra, Ghana, unprotected workers and surrounding populations have high potential for exposure to e-waste associated pollutants (e.g., heavy metals, organic chemicals, PM, and pollutant mixtures) [5]. The scope of health effects associated with exposure to e-waste associated pollutants is extensive; e-waste associated pollutants and their mixtures can adversely affect the reproductive, endocrine, cardiovascular, developmental and central nervous systems[6]. Health effects associated with e-waste recovery among workers and nearby communities include adverse neonatal outcomes, reduced pulmonary function, physical injuries, DNA damage, and increased risk of cancer[6-9].

The main methods used at Agbogbloshie for recovering reusable parts and metals from e-waste include manual dismantling and burning [10-13]. Dismantling methods, including pounding with hammers or similar devices, release airborne chemical mixtures, potentially including heavy metals (e.g., Pb, Cd, Cr), organic chemicals (e.g., brominated flame retardants (BFRs), and polychlorinated biphenyls (PCBs)) contained within electrical and electronic products. Burning e-waste, a simple and low-cost method for removing plastic insulation and circuit boards, allowing for copper and other metals to be retrieved, is performed at relatively low temperatures in open surface fires and often with non-traditional fuel sources (e.g., Styrofoam, discarded car tires). Particulate and gas-phase emissions from burning e-waste can include dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), carbon monoxide, carbon, nitrogen oxides, sulfur dioxide and volatile organic compounds including formaldehyde [14]. PM from e-waste emissions may be of higher toxicity than PM from biomass fuel emissions and traffic-related emissions due to the high concentrations of industrial chemicals and metals in e-waste [15].

PM with an aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) can readily reach the gas-exchange region of the lungs. Most of the coarse fraction ($PM_{2.5-10}$: 2.5 - 10 μm in aerodynamic diameter) is retained and deposited in the lungs' thoracic region. Health effects associated with PM sizes ≤ 10 μm in diameter include cancer and cardiovascular, respiratory and cerebrovascular morbidity and mortality [16]. Toxic constituents of PM from burning e-waste include persistent organic pollutants and heavy metals, and include known human carcinogens or central nervous, endocrine and/or reproductive systems toxicants [6].

Measurements of air pollution at Agbogbloshie or other informal e-waste sites around the globe are limited. Caravanos et al. (2011) characterized personal inhalation among e-waste workers (n=5) at Agbogbloshie and found levels of Al (5.5 - 6.5 mg m^{-3}), Cu (1.2 mg m^{-3}), Fe (5.6 - 17.0 mg m^{-3}) and Pb (0.98 mg m^{-3}) that exceeded the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) of 1.0, 1.0, 5.0 and 0.05 mg/m^3, respectively [17]. Hogarh et al. (2018) measured atmospheric PCB concentrations at two Agbogbloshie locations and across 16 other sites throughout Ghana; PCB concentrations at Agbogbloshie reached 11.1 ng m^{-3} in comparison to a median concentration of 0.48 ng m^{-3} across all other urban sites [18]. The authors concluded that burning practices at Agbogbloshie were a probable source of airborne PCBs across Accra [18].

In China, at the Guiyu informal e-waste site where burning e-waste is also performed, $PM_{2.5}$ concentrations from area sampling ranged from 50 to 62 μg m^{-3}, exceeding concentrations in reference populations and China's national recommendations (24-hr mean $PM_{2.5}$ target: ≤ 35 μg m^{-3}) [19-21]. PM samples from the Guiyu e-waste site included high concentrations of heavy metals (including Pb and Cd), PAHs, and flame retardants [9,19,22-25]. Surrounding illegal e-waste sites in India, the mean PM_{10} concentration averaged over three months was 233 μg m^{-3} (± 19); the PM constituents included high concentrations of Pb, Cu, Zn, Ni and Cr, which were mostly attributed to the burning of printed circuit boards [26]. Even in studies of formal electronic recycling facilities in Europe and the United States, which are typically licensed operations that should comply with occupational and environmental regulations, personal and indoor air quality sampling indicated significant exposures to inhalable dust containing metals, brominated flame retardants and organophosphate esters [27-30].

In our previous research at Agbogbloshie among the GeoHealth cohort (N=142), continuous measures of $PM_{2.5}$ (a total of 32,439 minutes) from the breathing zone of workers during 171 partial-shifts were highest (mean: 203 µg m^{-3}) among the workers burning e-waste [31]. Non-work-related activities, however, were also associated with exposure to high concentrations of personal $PM_{2.5}$. For example, the mean personal $PM_{2.5}$ measured during eating and drinking was 80 µg m^{-3} [31]. Activity-specific exposure measures and estimates provide an opportunity for targeted risk-mitigating interventions among highly exposed worker groups. Characterizing inhalation exposures among workers may also shed light on potential environmental and health risks among communities living and working nearby, especially when prevailing wind direction places communities downwind from e-waste emission sources (e.g., burning).

Our main objective is to compare levels of personal $PM_{2.5}$ and $PM_{2.5\text{-}10}$ exposures across work activities among e-waste recovery workers enrolled in the GeoHealth occupational cohort study in Accra, Ghana. Using a combination of continuous PM measures taken from worker breathing zones and time-activity data generated from wearable camera images, we estimate personal exposure by activity, adjusted for background levels of $PM_{2.5}$, study Wave, day of the week, and meteorological variables. A second objective is to examine the empirical relationship between wind conditions and personal PM inhalation for workers positioned downwind and at the main source of PM emissions, the e-waste burning zones. Measures of the joint effects of activity and wind conditions on $PM_{2.5}$ and $PM_{2.5\text{-}10}$ are presented. Winds in Accra primarily arise from the S, W and SSW, causing plumes from burning e-waste to travel across the Agbogbloshie site and along the river where many other workers and residents are located (see Figure 1). Assuming that plume rise will be low during conditions of high wind speed, we hypothesized that breathing zone PM concentrations would be high among dismantlers and other individuals who are frequently downwind of the emission source. With a shifting and meandering plume caused by low wind speeds and high variability in wind direction, we hypothesized that breathing zone PM concentrations would be high among burners who cannot move upwind of the emission source while tending the fires.

1.2 Methods

1.2.1 Study Sample

The GeoHealth occupational cohort study is an ongoing longitudinal study to assess environmental and occupational exposures and health effects among workers at the Agbogbloshie e-waste site. Details on the worker population and recruitment procedure are presented elsewhere [31]. In brief, 142 e-waste workers were enrolled into the GeoHealth study during the first (March 14 - May 2 2017) or second (August 4 - October 16 2017) Wave of data collection. Follow-up visits were scheduled for all participants during the second and third (January 8- April 20 2018) study Waves. All study protocols were approved by the University of Michigan and University of Ghana Institutional Review Boards. Informed consent acquisition and data collection were conducted by trained, local interpreters in the participant’s native or preferred language.

1.2.2 Background $PM_{2.5}$

Area monitoring of real-time ambient PM was conducted using a 5-channel optical particle counter (OPC) (Aerocet 831, Met One Instruments, Inc., OR, USA) at a fixed site approximately 6.5 meters above ground level and 1.35 km SSE of the Agbogbloshie e-waste site (see Figure 1). Given the prevailing wind directions, this fixed monitoring site is primarily upwind of Agbogbloshie, and thus is used to approximate “background” levels of $PM_{2.5}$, that is, levels unaffected by site activities. The OPC continuously measured per 1-minute concentrations of PM ≤ 1, 2.5, 4, and 10 μm in aerodynamic diameter and total suspended particulate (TSP) by converting particle counts into size-specific mass measurements (as $\mu g\ m^{-3}$). Continuous 1-minute data were averaged into hourly and daily measurements, on 50 days between June 2017 and February 2018. Hourly averages of PM_{10} that exceeded 2,000 $\mu g\ m^{-3}$ (<1%) were considered potentially biased due to coincidence error (i.e., when multiple small particles appear as larger particles resulting in an overestimate of large-channel particles) and censored. This decision was made based on our experience with these instruments and a comparison between OPC and gravimetric filter-based measurements collected at Agbogloshie [32]. Area monitoring did not occur during Wave I (March 2017) due to problems establishing electricity service at the site. The surrounding land-use includes a four-lane road with intermittent traffic, rubbish collection and occasional biomass burning. As of mid-October 2017, after the upwind monitoring site was established, changes in the surrounding land-uses were made, including intermittent fires and smoldering of dredged materials placed immediately to the SE and W of the monitoring site [32].

1.2.3 Personal PM

Continuous PM from the breathing zone of participants was measured using the same 5-channel OPC device as for area monitoring. $PM_{2.5-10}$ is derived by differencing PM_{10} and $PM_{2.5}$ measurements. Measures of PM_{10} that were potentially biased due to coincidence error (>2,000 $\mu g\ m^{-3}$) were censored; when aggregated to 15-minute averages, one observation needed to be censored. Sampling occurred on all days excluding Sundays and days with heavy precipitation. During Waves I and II, participants were asked to wear the backpack for 4 hours between 8 AM and 4 PM, in order to maximize the time during which workers were engaged in e-waste recovery activities. In Wave III, the sampling duration was reduced to two hours to avoid overloading other equipment in the backpack during the Harmattan season. PM concentrations in Ghana are highest during the Harmattan season (November-mid-March) when winds off the Saharan desert transport sand and dust across the region[33,34]. The sampling period averaged (± standard deviation (SD)) 198 minutes (± 83 minutes) across all three Waves.

1.2.4 Job activities

Participant activities were recorded using a wearable, wide-angle GoPro Hero4© camera. The camera was attached to the forward-facing shoulder strap of the monitoring backpacks and, like the personal PM device, set to take one image every minute. Trained reviewers processed the time-stamped images using a data collection instrument designed specifically for the GeoHealth study with input from seasoned workers. Details on image processing and design of the data collection instrument are described elsewhere[31]. In summary, the instrument records the type and length of each activity which is comprised of one or more consecutive images and can be categorized either as a work-related (burning, dismantling, sorting/ loading, buying and selling, transporting and other), non-work-related (not actively working, smoking), or transportation-related activity (walking, bicycling, motorbike or car). “Not actively working” includes sub-categories of sitting, eating or drinking, cell phone use, prayer, and communicating with others. Reviewers identified images as “unusable” if it was clear from the image that the participant removed the camera and monitoring backpack from their body. Participant location during sampling was not recorded; however, objects identified in the images (e.g., tools, broken electronics, tires) were used to classify whether the participant was on or off the Agbogbloshie study site.

1.2.5 Meteorological Variables

Meteorological data from the Kotoka International Airport in Accra, located approximately 10.2 km NE of the Agbogbloshie e-waste site, were obtained from the National Oceanic and Atmospheric Administration’s (NOAA) Integrated Surface Database (ISD) and the Global Historical Climatology Network (GHCN)[35,36]. These include hourly temperature, visibility distance, dew-point, wind speed and direction and daily precipitation. Relative humidity was calculated from temperature and dew-point. In order to calculate a measure of wind direction variability (degrees) that corresponded to the hours during which personal monitoring took place (typically between 8AM and 4PM), the circular SD of the hourly wind direction measurements, which can assume values between 0 and 360 degrees, was used. Wind speed (m/s) was defined by averaging the hourly measures of wind speed (m/s) for the same sampling periods. Two- and three-level categorical variables for both wind speed and wind direction were created; the two-level variable compared “high” (the upper fourth quartile ($>75^{th}$ percentile) with “low-medium” (the bottom three quartiles ($\leq 75^{th}$ percentile); the three-level variable compared tertiles. Meteorological variables were used both as predictors of background $PM_{2.5}$ for days with missing measurements and as covariates in adjusted analyses.

1.2.6 Data management

A minute-by-minute database of image-based and time-specific activity logs for each worker was merged with the minute-by-minute, continuous PM data by participant ID, date and time. This database was used to create a 15-minute averaged database. The 15-minute averaging period reduced sampling noise and variability associated with 1-minute PM measurements and aligned with short-term exposure limits used in occupational settings, typically set at a minimum of 15-minutes. In addition, the average duration for all activity types exceeded 15 minutes, as described previously [31]. Each interval was assigned mean $PM_{2.5}$ and $PM_{2.5\text{-}10}$ concentration for the activity that was performed longest during the interval. In the rare event of a tie, the activity that occurred first was chosen. Time intervals during which the camera and monitoring backpack were removed from the participant’s body for the majority of the interval were excluded.

1.2.7 Statistical analyses

Descriptive statistics of the type and duration of activities performed by the participants were calculated. Given missing directly-measured background $PM_{2.5}$ data on several days during which personal sampling occurred, background $PM_{2.5}$ was estimated using a prediction model based on the observed background $PM_{2.5}$ data (N=50 days) from the upwind fixed site (approximately 1 km from Agbogbloshie) and meteorological variables measured at the airport (approximately 10.2 km from Agbogbloshie). The choice of predictors was based on a model described by O'Neill et al. (2002) for predicting ambient $PM_{2.5}$ in Mexico City using visibility distance and other meteorological variables typically available from local airports [37]. The initial, full prediction model included: the extinction coefficient, a measure of "the total amount of light attenuated through adsorption and scattering by particles and gases" derived from visibility distance using the Koschmeider formula [38]; temperature (minimum, maximum, and mean); relative humidity (minimum, maximum, and mean); dew-point (minimum, maximum, and mean); wind speed; and interaction terms between the extinction coefficient and temperature, and separately with relative humidity. Variable selection and predictions were performed using elastic net penalized linear regression with five-fold cross-validation ("glmnet" package in R). Predictions were based on the model whose tuning parameters gave a mean squared prediction error (MSPE) within one standard error of the minimum. Elastic net provides good prediction accuracy with a parsimonious model in the presence of correlated predictors and reduces the variance associated with ordinary least squares (OLS) estimators at the cost of introducing potential bias[39].

In two separate linear mixed models (see Equation 1), the changes in personal $PM_{2.5}$ and $PM_{2.5\text{-}10}$ concentrations associated with image-derived time-activity were estimated. Models accounted for the repeated measures design of the study and temporal autocorrelation in the 15-minute personal PM measurements by including random intercepts for participant-days and an auto-regressive (AR1) covariance matrix. *A priori* identified fixed effect covariates included background $PM_{2.5}$, study Wave, day-of-week, temperature and relative humidity. To account for the non-linear relationship between personal inhalation exposure and temperature and relative humidity, thin-plate regression splines were used. Covariates were added to the model one at a time in order to examine their effect on the outcome. Improvements in model fit were assessed using Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) and R^2 calculated for a linear mixed model[40]. Conditional R^2, percent changes in $PM_{2.5}$ and $PM_{2.5\text{-}10}$ associated with an activity ($(\exp(\beta) - 1) * 100$) and 95% confidence intervals (CIs) are presented. In sensitivity analysis, the final model was run without the AR(1) covariance matrix to evaluate the extent to which the association between change in personal PM exposure and change in activity could have been attenuated by over-controlling for temporal correlation.

Equation 1: Linear mixed model for estimating the association between activity and personal inhalation exposure to $PM_{2.5}$ and $PM_{2.5\text{-}10}$ in the GeoHealth study.

$$\ln(\boldsymbol{Personal\ PM})_{day,\,participant,\,time} = \beta_0 + \beta_1 \boldsymbol{Activity}_{day,\,participant,\,time} + \beta_2 \boldsymbol{Covariates}_{day,\,participant} + \delta(\boldsymbol{Background\ PM_{2.5}})_{day,\,participant} + S(\boldsymbol{Weather}_{day,\,participant,\,time}) + b_{day} + \tau_{participant} + \varepsilon_{day,\,participatn,\,time}$$

$$b_{day} \sim N(0, \sigma_b^2) \quad [1]$$

$$\tau_{participant} \sim N(0, \sigma_\tau^2)$$

$$\varepsilon_{day,\,participant,\,time} \sim N(0, \Sigma)$$

$$\Sigma = AR(1) = cor\left(\varepsilon_{day,\,participant,\,time_1}, \varepsilon_{day,\,participant,\,time_2}\right) = \rho^{-\,|\,time_2 - time_1\,|}$$

Equation 1 legend: In this model, time is nested within participant, which is nested within sampling day. Activity includes not actively working (reference category), smoking, burning e-waste, sorting/loading e-waste, dismantling e-waste, transporting materials, buying/selling e-waste, and other (work-related) activities. The model is adjusted for covariates (study Wave and day-of-week), background levels of $PM_{2.5}$, temperature and relative humidity. S() refers to a thin-plate smoothing spline, b is a random intercept for day, $\boldsymbol{\tau}$ is a random intercept for participant, β and δ are regression coefficients, $\boldsymbol{\varepsilon}$ is a vector of random errors and AR(1) signifies the specified first order autoregressive covariance structure.

The joint effects of activity and wind conditions (direction and speed) on personal exposure to $PM_{2.5}$ and $PM_{2.5\text{-}10}$ were examined for a subset of participants who performed burning or dismantling activities. These activities were chosen because the locations of both are consistent over time and dismantling activities are downwind of the two burning zones (Figure 1). The hypothesized changes in personal PM concentrations among workers performing dismantling and burning e-waste activities according to different wind conditions are summarized in Figure 2, which reflect assumptions regarding plume dispersion. Due to the lack of available data, the influence of other factors that determine plume dispersion and rise (e.g. emission rate, mixing height, insolation, etc.) were not considered in this analysis.

Two-way interaction terms between activity and wind direction variability (low, medium and high) and activity and wind speed (low, medium and high) were added to the fully adjusted models. Although wind speed and direction are typically inversely correlated (i.e., high wind speeds are correlated with low variability in direction), our data showed only a modest correlation (correlation =−0.25). Therefore, the joint effects of wind speed and direction variability on the association between activity and personal inhalation exposure had to be examined in separate models in order to avoid small cell sizes and conserve statistical power. Main effects of the interaction model are presented graphically to facilitate their interpretation[41]. Additionally, effect modification results are presented, for two-level variables only, on the multiplicative and additive scale in a table following the recommendations provided by Knol and Vanderweele (2012) [42]. “Super-additive” and “positive” multiplicative interaction are defined as changes in personal PM associated with the combined effect of activity and wind conditions that is larger than the sum and product, respectively, of changes associated with their individual effects.

1.3 Results

Among the 142 participants, 105 individuals wore backpacks containing a camera and personal PM monitoring device. Participants with personal sampling did not differ from the full cohort across socio-demographic characteristics. During Waves I, II and III, 51, 54 and 55 partial work shifts were sampled, respectively (N=160). The average length of shift samples per participant was 221, 214 and 160 minutes during Waves I, II and III, respectively. A total of 2,110 15-minute intervals were averaged from a total of 31,650 minutes. Data from three participants collected on a day during Wave I with a large urban fire adjacent to the Agbogbloshie e-waste site were excluded. No data were collected on the days immediately following the fire. Descriptive statistics on the GeoHealth cohort have been presented previously [31]. In brief, the all-male cohort is an average of 27 years old and reported working 6 to 7 days a week for an average of 10 hours per day (some of which is spent on-site, but not actively engaged in a work activity [31]).

1.3.1 PM and time-activity

Descriptive results of time-activity and their corresponding levels of measured personal $PM_{2.5}$ and $PM_{2.5\text{-}10}$, unadjusted for background levels, are shown in Table 1. The most common work activities were dismantling, sorting/ loading and burning (Table 1). For 50% of the recorded partial-shifts, workers were categorized as "not-actively working" (i.e., sitting, eating or drinking, cell phone use, prayer, and communicating with others). The average duration of activities ranged from 24 minutes (± 13) for walking to 80 minutes (± 90) for dismantling. Burning activities had the highest measured personal concentrations of both $PM_{2.5}$ (mean: 209 μg m^{-3}) and $PM_{2.5\text{-}10}$ (mean: 241 μg m^{-3}). Mean $PM_{2.5\text{-}10}$ concentrations were higher for transportation-related activities (131 μg m^{-3}) than for "other" activities (98 μg m^{-3}), but similar for $PM_{2.5}$.

1.3.2 Background $PM_{2.5}$

Observed background levels of $PM_{2.5}$ (N=50) from the upwind fixed site between June 2017 and February 2018 had an overall median and mean of 62 and 73 μg m^{-3} (± 53), respectively. During June through October (non-Harmattan season) 2017, the median was 34 μg m^{-3} (± 21); median levels increased to 80 μg m^{-3} (± 56) during November 2017 - February 2018 (Harmattan season). These observed values were used to predict missing daily averages of background $PM_{2.5}$ on days during which sampling took place (N=61). The prediction model with the minimum cross-validated MSE, which included visibility distance, minimum temperature, wind speed and an interaction between visibility distance and relative humidity, had an R^2 of 0.69 (Figure 3). Estimated background $PM_{2.5}$ concentrations for the study period had an overall median of 68 μg m^{-3} (± 112), and median concentrations were 69 (± 17), 61 (± 7), and 76 (± 140) μg m^{-3} for Waves I, II and III, respectively. The correlation between observed and fitted values was poorest for low levels of $PM_{2.5}$. The poor correlation may be due to: the lack of observed background $PM_{2.5}$ measurements during the non-Harmattan season; lack of measurements during Wave I (March-April) when visibility distance (the main prediction variable in the model) was high; and/or that measurements taken after October 27, 2017 were elevated due to local fires near the monitoring site.

1.3.3 Personal PM exposure for work and transportation-related activities

Changes in personal inhalation exposure to $PM_{2.5}$ and $PM_{2.5-10}$ associated with activity are presented in Table 2. The intercepts (67.3 and 97.4 μg m^{-3}, respectively) correspond to a 15-minute period of “not actively working”, with all other covariates in the model, including background $PM_{2.5}$, Wave of data collection, day-of-week, temperature and relative humidity, set to their reference levels (Table 2). Burning e-waste is associated with an adjusted personal $PM_{2.5}$ concentration of 86.3 μg m^{-3} (95% CI: 61.1, 121.9) or a 28.1% increase (95% CI: 10.7%, 48.2%) from levels when workers are not actively working. The presence of tobacco smoke is also associated with a large percent increase in $PM_{2.5}$ exposure (22.3%, 95% CI: 5.4%, 42.0%). Personal $PM_{2.5}$ exposures during walking, dismantling, sorting/loading, transporting materials, and bicycling activities are all moderately higher exposure than when not actively working (5.4-6.7%), resulting in adjusted mean personal PM concentrations that ranged from 71.0 to 71.9 μg m^{-3}. For $PM_{2.5-10}$, bicycling followed by motorbike use and burning are associated with the largest increases in personal exposure (45.7%, 30.7% and 28.1%, respectively) in comparison to not-actively working. However, unlike for $PM_{2.5}$, sharp differences in $PM_{2.5-10}$ between burning and the other work activities were not observed. Personal $PM_{2.5}$ and $PM_{2.5-10}$ concentrations were lower during Wave III (Harmattan season) in comparison to Wave I (non-Harmattan). Higher personal PM concentrations during Wave I in comparison to II and III may be due to the higher number of burning activities performed by the participants; in Wave I, 50 burning events were recorded in comparison to 32 during Waves II and III combined. Furthermore, it is unlikely that Harmattan winds contributed to personal or background PM measurements; out of a total of 27 days during which possible Harmattan dusts were identified using satellite data for the Dec 2017 – Feb 2018 period[32], only 7 overlapped with days of personal sampling. Among the days of the week, Mondays are associated with the highest, and Thursdays and Fridays with the lowest, concentrations of $PM_{2.5}$ and $PM_{2.5-10}$, although the confidence intervals are wide. Models run without accounting for temporal autocorrelation had similar results with respect to the rank order of associations between activities and personal PM exposure. However, the magnitude of the relative risk associated with each activity was larger, as expected.

1.3.4 Joint effects of activity and wind conditions on personal inhalation exposure

Figures 4 and 5 show wind conditions and the joint effects of activity and wind conditions on personal exposure to $PM_{2.5}$ and $PM_{2.5-10}$, adjusted for background $PM_{2.5}$, Wave of data collection, day-of-week, temperature and relative humidity. Based on Kotoka weather station data from days and hours that coincided with personal monitoring (n=304 h), hourly wind speeds ranged from 1.0 to 10.3 m/s with an average of 5.2 m/s (± 1.7), and winds originated predominantly from the S (25 %), W (24%) and SSW (20%) (Figure 4). Daily variation in wind direction ranged from 4 to 55 degrees with a mean and median of 26 degrees (± 12). Throughout the sampling period, direction shifted from the W to the S and speed increased by approximately 1 m/s from the morning to late afternoon. Average wind speeds were highest during Wave II, and direction variability was highest during Wave III (Figure 4).

Wind conditions modified inhalation exposures of dismantlers and burners (Figure 5). Personal $PM_{2.5}$ and $PM_{2.5-10}$ concentrations for burning activities increased with high wind direction variability. When plumes meander and their direction is harder to predict, burners may have greater difficulty avoiding the smoke (Figure 5). Personal $PM_{2.5}$ exposure for burners was lowest during high wind speeds (Figure 5); however, a clear downward trend in $PM_{2.5}$ or $PM_{2.5-10}$ exposure associated with increasing wind speeds was not observed (Figure 5). Personal $PM_{2.5-10}$, but not $PM_{2.5}$, for dismantling activities increased with wind speed (Figure 5); entrainment of surface dust and particles generated during e-waste dismantling may also contribute to $PM_{2.5-10}$ exposure. Dismantling activities were associated with higher concentrations of $PM_{2.5-10}$ than burning activities, except during periods of high wind variability.

Effect modification by wind conditions on personal $PM_{2.5}$ and $PM_{2.5-10}$ for participants exposed to burning e-waste in comparison to dismantling e-waste is presented in Table 3. The results provide preliminary evidence that high wind direction variability increases inhalation hazards among workers who are burning e-waste and high wind speeds increase inhalation hazards among those dismantling e-waste. For example, burning e-waste during conditions of high wind direction variability resulted in a 163.1% (95% CI: 81.7, 280.9) increase in personal $PM_{2.5}$ concentrations in comparison to a 32.3% (95% CI: −44.2, −17.9) decrease during conditions of low-medium wind variability. In other words, burners have higher PM exposures when the wind direction is variable. Evidence of a positive interactive relationship between burning e-waste and high wind direction variability was observed on the additive and multiplicative scales for both $PM_{2.5}$ and $PM_{2.5-10}$. The alternative negative interaction between burning e-waste and high wind speeds for $PM_{2.5}$ and $PM_{2.5-10}$ (i.e., a decrease in exposure for burners when wind speeds are high) was also observed on both the additive and multiplicative scales (Table 3). For dismantlers, point estimates of personal $PM_{2.5}$ and $PM_{2.5-10}$ exposure increased by 28.6% (95% CI: −13.1, 89.8) and 12.0% (95% CI: −25.0, 67.2), respectively, during high wind speeds in comparison to low and medium speeds; however, the results were not statistically significant at the 0.05 alpha level (Table 3).

1.4 Discussion

1.4.1 Main findings

This study contributes to the limited data on inhalation exposure among e-waste workers, identifies highly exposed worker groups by work activity, and contributes to our understanding of sources and causes of exposure among these workers. The mean $PM_{2.5}$ (80.2 μg m^{-3}) and $PM_{2.5-10}$ (123.2 μg m^{-3}) concentrations measured in the breathing zone of e-waste workers at the Agbogbloshie site in Accra, Ghana considerably exceed the WHO $PM_{2.5}$ and PM_{10} ambient air quality guidelines. Image-based time-activity data helped establish differences in personal PM by specific activity; during 15-minutes of burning e-waste activities, personal $PM_{2.5}$ and $PM_{2.5-10}$ concentrations increased from background levels on the site by 28.1% and 30.7%, respectively. Although burning e-waste exceeded any other activity's $PM_{2.5}$ concentrations, the concentrations of $PM_{2.5-10}$ during burning were similar in magnitude to measured concentrations that occurred during transportation-related activities (bicycling or motorbike and car use). Our analysis of associations between activity and personal inhalation exposure by wind conditions strongly suggest that, in the setting of

Agbogbloshie, plumes from burning e-waste are a source of PM exposure for downwind workers, and that with more variable winds, workers performing burning activities are unable to avoid smoke exposure, leading to peak exposures among these workers.

1.4.2 $PM_{2.5}$ and $PM_{2.5\text{-}10}$ breathing zone concentrations by job activity

Higher personal $PM_{2.5}$ concentrations during burning activities and higher $PM_{2.5\text{-}10}$ exposures during transportation-related activities in comparison to periods during which e-waste workers were not actively working were as expected. Personal $PM_{2.5}$ concentrations were similar among walking, transporting, sorting/ loading and dismantling activities, possibly because these activities occur in close proximity to one another in areas unprotected from smoke associated with burning. At Agbogbloshie, workers transport materials by foot between the e-waste processing area and the burning zones using carts and wheelbarrows. Buying and selling activities were associated with the lowest levels of $PM_{2.5}$ and $PM_{2.5\text{-}10}$; buyers and sellers typically have higher incomes and sit in sheds, some of which have fans, removed from the burning zones. Activities that occur mostly off-site, including bicycling and motorbike use, were associated with higher levels of $PM_{2.5\text{-}10}$ concentrations. This coarse PM fraction likely includes entrained soil, dust and exhaust emissions from vehicles.

1.4.3 Local dispersion from e-waste burn pits

Wind direction and wind speed represent two factors involved in dispersion, transport and transformation of e-waste emissions. Additional factors influencing plume trajectory, plume rise and dilution include parameters related to the emission's source (e.g., type, size, number, emission rate, heat flux), meteorological and micrometeorological factors (e.g., cloud cover, insolation, humidity, mixing height), and orographic and topographical factors (e.g., surface roughness, and land/water interfaces).

Emissions from open e-waste burning at Agbogbloshie are a ground-level area source. Considering the S, W and SSW prevailing winds that occurred during sampling hours, most workers are at a downwind distance of 200 to 400 m and a crosswind distance of less than 300 m from the plume centerline. Other than the location of the emission source, the number of fires, their size, type of accelerants used and materials burned, much less the emission rate and temperature, are unknown, and many of these factors will change on a daily or hourly basis. Agbogbloshie has a relatively flat terrain with the highest structures being small sheds and mosques (approximately 5 m tall), and the adjoining lagoon, drainage canal and terrain have limited relief (approximately 10 m). The Gulf of Guinea coastline is approximately 3 km away, far enough to limit some effects associated with land-sea interfaces.

Local exposure to workers downwind of the burning area depends on the fire's emission rate, plume rise, dispersion, and other factors, all of which can be affected by winds. As depicted in Figure 2, with high wind speeds, plume rise may be very limited and the plume is essentially at or near ground level, thus increasing the potential for exposure among e-waste workers downwind. High wind speeds and low variability in direction may also increase the burning rate, potentially increasing emissions, or alternatively diluting the plume. In any event, workers who are burning waste under such conditions are able to stay upwind and thus decrease their exposure. Anecdotal and photographic evidence from the wearable cameras demonstrates how burners avoid smoke exposure by modifying the location of their fires on days with steady and strong winds. However, if winds are meandering and plume rise is limited (likely with low temperature, dispersed or smoldering open fires), then wind shifts can cause the plume to move in multiple directions, causing exposures among burners to vary widely. Workers further downwind and over a wide swath of the e-waste recovery site will also be exposed. Low wind speeds, however, also have countervailing effects: with a sufficiently large and hot fire, plume rise will increase with low speeds, and pollutants will be transported well above the breathing zone of workers, leading to relatively low exposure on-site. At the urban scale, i.e., considering off-site exposure in Accra, even elevated plumes will contribute to exposure, although the maximum concentrations may be experienced at a further distance and concentrations will be lower. Still, e-waste burning may add to the PM exposure experienced by Accra residents.

1.4.4 Toxicity of particulate matter generated from e-waste

The concentrations of personal $PM_{2.5}$ and $PM_{2.5\text{-}10}$ exposure among these e-waste workers far exceed ambient air quality guidelines. However, they do not exceed the permissible exposure limit (PEL) for “otherwise unregulated” particulates defined by the U.S. Occupational Health and Safety Administration (OSHA) (15 mg m^{-3} for total particulate and 5 mg m^{-3} for the respirable fraction)[43]. However, personal protective equipment (PPE), e.g., masks or respirators, would typically be utilized to minimize exposure with such PM levels. Moreover, PM emissions from burning e-waste are comprised of highly toxic constituents. In air samples of TSP and $PM_{2.5}$ from the Guiyu e-waste site in China, concentrations of PAHs, dioxins, flame retardants and metals (e.g., Cr, Zn, Cu, Pb, and As) were higher when compared with urban and rural regions [19,25,44]. Cesaro et al. (2019) modelled the chemical reactions that occur during open e-waste burning and found that the potential hazards from open burning of cables made of copper, thermoplastic elastomers, polyvinyl chloride, and polyethylene foils were higher than for computer and mobile printed circuit boards, and above the threshold limit values [15]. This result was driven by the high content of chlorine-containing plastics in cables that generate dioxin (specifically, 2,3,7,8-tetrachlorodibenzo-p-dioxin) [15]. Further research into the severity and range of health effects from occupational exposure to PM emissions with high concentrations of metals and persistent organic pollutants is needed.

1.4.5 Implications, interventions, and policy options

A key finding of the current study is that, on a site where open burning is routinely used to recover metals from e-waste, and other workers dismantling e-waste are typically located downwind of burning sites given prevailing wind patterns, a combination of wind speed and variability in wind direction is highly predictive of personal exposures to PM. This finding reinforces the significance of open burning as a source of potentially toxic exposures to workers. Thus, interventions aimed at reducing personal inhalation exposures among e-waste workers should focus on burning activities as a critical PM emission source affecting essentially all workers on the site. Other activities, such as dismantling of e-waste and draining of oils, are also problematic and should be addressed by hazard reduction strategies. Many interventions attempted at informal e-waste sites around the globe, e.g., educational campaigns, training, and distribution of PPE, have provided minimal protection on their own and have not provided economic incentives for the workers. Effective engineering solutions should be designed with input from the workers, and should simultaneously improve the efficiency and capture of raw materials. Interventions at Agbogbloshie or other e-waste recovery sites have the difficult challenge of balancing pollution controls with job availability. Ongoing monitoring of exposure and worker's health is recommended to help validate the effectiveness of an intervention. A hierarchy of strategies aimed at air pollution prevention, their opportunities and potential challenges specific to Agbogbloshie and other informal e-waste sites is shown in Table 4.

The creation of informal and formal sector partnerships is a proposed solution to eliminate environmental exposures from informal e-waste recovery [45]. Under this scenario, informal recyclers collect, dismantle, and repair e-waste, while formal sector facilities, subject to occupational and environmental regulations, perform raw material recovery and waste disposal. Although this model has strong potential to reduce occupational and environmental exposures in settings like Agbogbloshie, it may not be sustainable if the earnings among informal workers are reduced through their loss of control of the final product. Strong regulatory oversight is also needed to ensure safe conditions in the formal facilities.

On a national scale, a variety of Extended Producer Responsibility (EPR) policies for e-waste management have been implemented in the European Union (EU), Switzerland, Japan, United States and Canada [46,47]. An EPR policy approach extends the responsibility to take back used products to the manufacturer. Different management approaches and take-back schemes have resulted in varying degrees of compliance and collection efficiency [46]. A 2011 EU directive placed further restrictions on use of hazardous substances in the design of electronic and electrical equipment[46]. India and Thailand have also drafted e-waste management regulations. However, black markets and informal recycling sectors that do not fall under the regulation's jurisdiction are limiting factors of such policies that are yet to be overcome. In countries with large informal economies, a different set of management principles sensitive to the local social, cultural, political, and economic tapestry are needed.

1.4.6 Strengths and limitations

A strength of this research is the unique and highly time-resolved data on personal inhalation exposure to $PM_{2.5}$ and $PM_{2.5-10}$ in combination with photo-validated time-activity data among informal e-waste workers. The use of available airport weather data to estimate background levels of $PM_{2.5}$ in a place where directly measured concentrations are not readily available can be replicated in other studies with the same data limitations. Comparisons of breathing zone PM concentrations by activity helped identify burning e-waste and transportation-related activities as the greatest sources of personal $PM_{2.5}$ and $PM_{2.5-10}$, respectively. Examining the joint effects of activity and wind conditions on personal inhalation exposure provided a useful step in understanding whether and how emissions from burning e-waste contribute to personal inhalation among different groups of workers. Another strength is that we suggested air pollution control strategies viable in LMIC settings.

Optical measurements of size-specific personal PM concentrations are limited in that they can diverge from gravimetric (e.g., filter-based) mass measurements, considered the reference approach. Optical measurements can be affected by particle characteristics, instrument response, inlet and sampling configurations, and humidity, and thus site-specific correction factors are often recommended. Based on a related study at the Agbogbloshie site where both optical measurements (using the same instrument as in the present study) and gravimetric measurements were collected at fixed monitoring sites, optical $PM_{2.5}$ measurements were biased downwards by 21% from gravimetric measurements [32]. The backpack samplers, however, differed from the tested configuration in that the sampling inlet on the chest strap was connected to the instrument in the backpack using a length of tubing. Numerical and field experiments conducted to understand penetration through the tubing indicated losses of up to 19% for $PM_{2.5}$ and 23% for $PM_{2.5\text{-}10}$. These preliminary results suggest that PM concentrations reported in this paper may be underestimated. However, this would not change comparisons of relative exposure concentrations by activity since these biases scale across all measurements in the study, regardless of the activity.

Data screening was used to exclude other biases. Half (n=13) of the observations exceeding the Aerocet optical device's maximum concentration range (1000 μg m^{-3} as stated by the manufacturer) occurred during burning e-waste activities. By censoring measurements exceeding 2000 μg/m^3, the most severe cases of bias due to coincidence error were avoided. In a sensitivity analysis, our main results did not differ after censoring values exceeding 1000 μg m^{-3}. The lower cut-off, however, would have the effect of underestimating concentrations for activities associated with high PM exposures.

Models were adjusted for fitted rather than observed measures of background $PM_{2.5}$. Unknown measurement error may have resulted in an over- or underestimate of fitted background $PM_{2.5}$ values. Overestimates of background $PM_{2.5}$ may have occurred due to the lack of observed background $PM_{2.5}$ observations from Wave I of the study during the non-Harmattan season and elevations in observed background $PM_{2.5}$ concentrations after October 26, 2017 due to changes in land-use (e.g. smoldering excavation materials) near the monitoring site. Adjusting for such over- or under-estimates of background $PM_{2.5}$ in the statistical models might falsely reduce or enlarge, respectively, the estimated proportion of PM from occupational sources. In a sensitivity analysis stratified by Wave, the moderate associations between personal PM (both sizes) and background $PM_{2.5}$, was highest during Wave I, followed by Waves III and II; however, when using an interaction term between background $PM_{2.5}$ and study Wave, the differences by Wave did not reach statistical significance. Similarly, in models unadjusted for background $PM_{2.5}$, the associations between personal PM (both sizes) and activities did not change significantly. Evidence on the joint effect of wind conditions and activity on personal inhalation exposure relied on measures of wind speed and direction from the Kotoka International airport, which may not have accurately represented conditions at Agbogbloshie, where winds are slightly lower in velocity and more variable in direction[32]. Lastly, we were unable to account for numerous potential non-work related sources of personal PM exposure on the site (e.g. nearby cooking with wood and charcoal, waste burning, unpaved road traffic and diurnal changes).

1.4.7 Conclusions

The greatest reductions in personal exposures for all e-waste workers will likely come from the replacement of current burning practices with safer and more efficient methods of metal extraction viable in low and middle-income countries. Our preliminary evidence suggests that burning activities not only result in elevated personal PM concentrations for those performing the activity, but also contribute to elevations in personal $PM_{2.5}$ and $PM_{2.5\text{-}10}$ concentrations among downwind workers who are performing different tasks. Reducing the amount of time that workers spend on the site without actively working (50% of the monitored work-shifts in this sample) could reduce unnecessary exposure to occupational sources of PM, among other pollutants with high toxicity. However, with the knowledge that many of the workers live on site out of necessity, this is not feasible without substantial, long-term structural changes in Accra. Development and implementation of air pollution control strategies requires a collaborative effort among diverse stakeholders, including workers, engineers, industry, government, academia and local organizations, in order to overcome challenges in designing effective interventions for an informal site characterized by a lack of economic capital and technically trained workers. Effective interventions will balance the reduction of occupational and environmental exposures with the maintenance of job availability for workers who depend on e-waste recovery for their livelihoods.

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Data availability statement

The data are not publicly available due to privacy or ethical restrictions.

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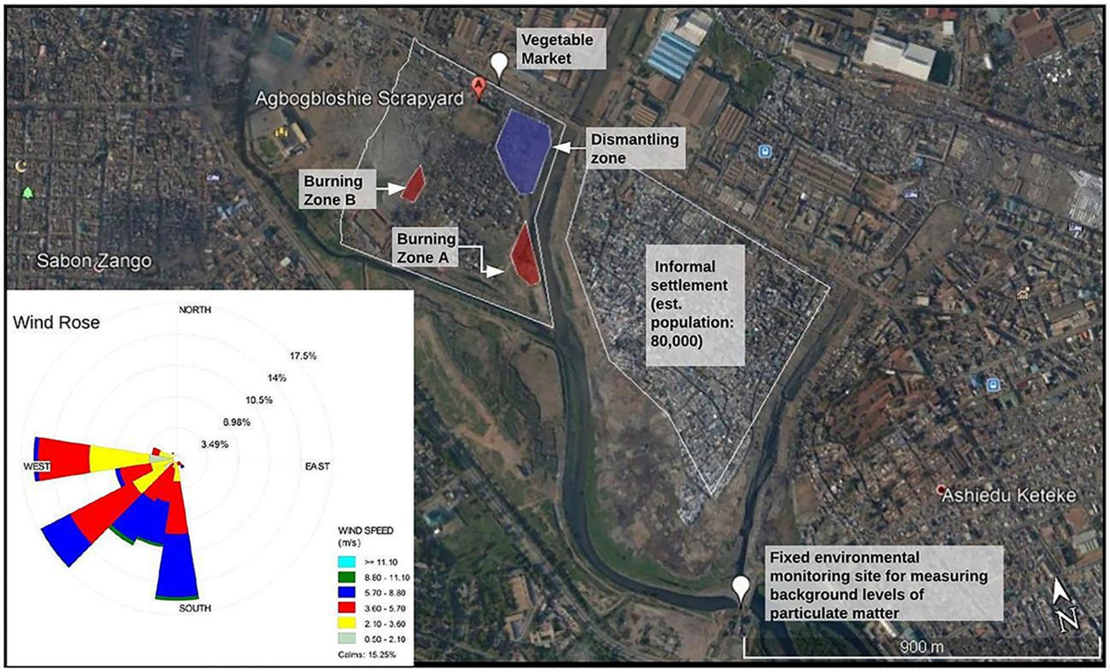

Figure 1: Map of the Agbogbloshie scrap and e-waste recovery site and surrounding area.
The Agbogbloshie site is approximately 0.5 km^2 in area. The highlighted polygons indicate the main zones where e-waste burning takes place: "Burning Zone A" and a secondary, smaller and newer burning zone "Burning Zone B", and the dismantling zone where most e-waste processing occurs (e.g., sorting, loading, weighing). Pins indicate locations of the fixed environmental monitoring station for background levels of $PM_{2.5}$, and the adjacent vegetable market. The wind rose (date range: 1/1/2017- 5/1/2018, timeframe: 8AM – 4PM) shows that prevailing winds during the timeframe of personal sampling originated primarily from the S, W and SSW. Map created using Google Earth Pro V 7.3.$_{2.5}$776. (10/7/2015). © Google 2018. Wind rose created by WRPLOT View (ver. 8.0.2) provided by Lakes Environmental.

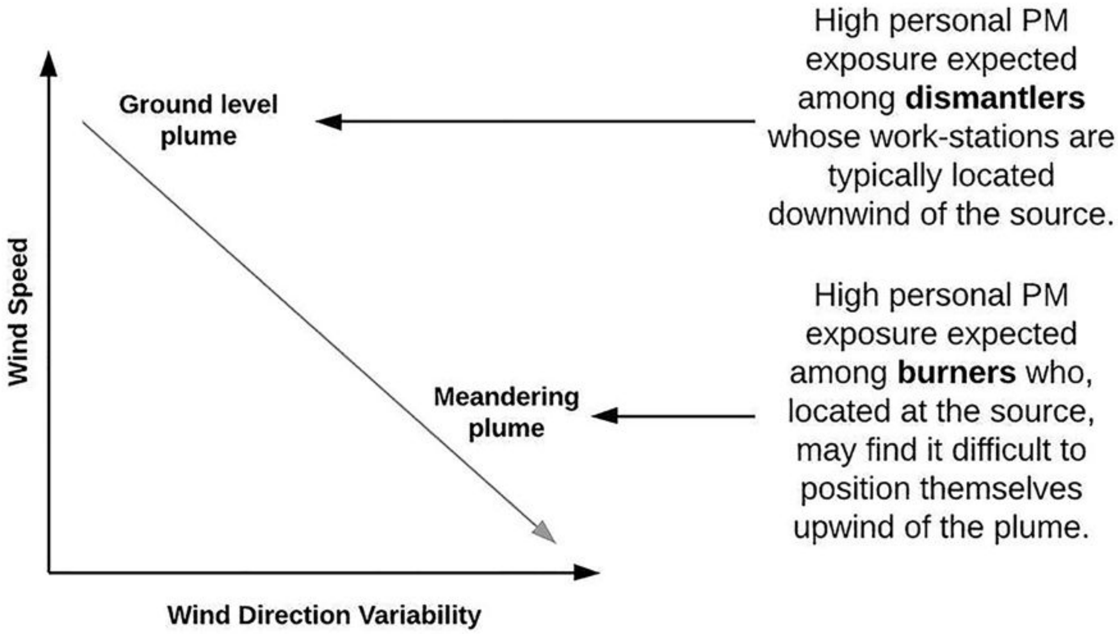

Figure 2:

Hypothesized effects of wind speed and direction variability on PM exposure among workers performing dismantling and burning activities at Agbogbloshie electronic waste recovery site, Accra, Ghana.

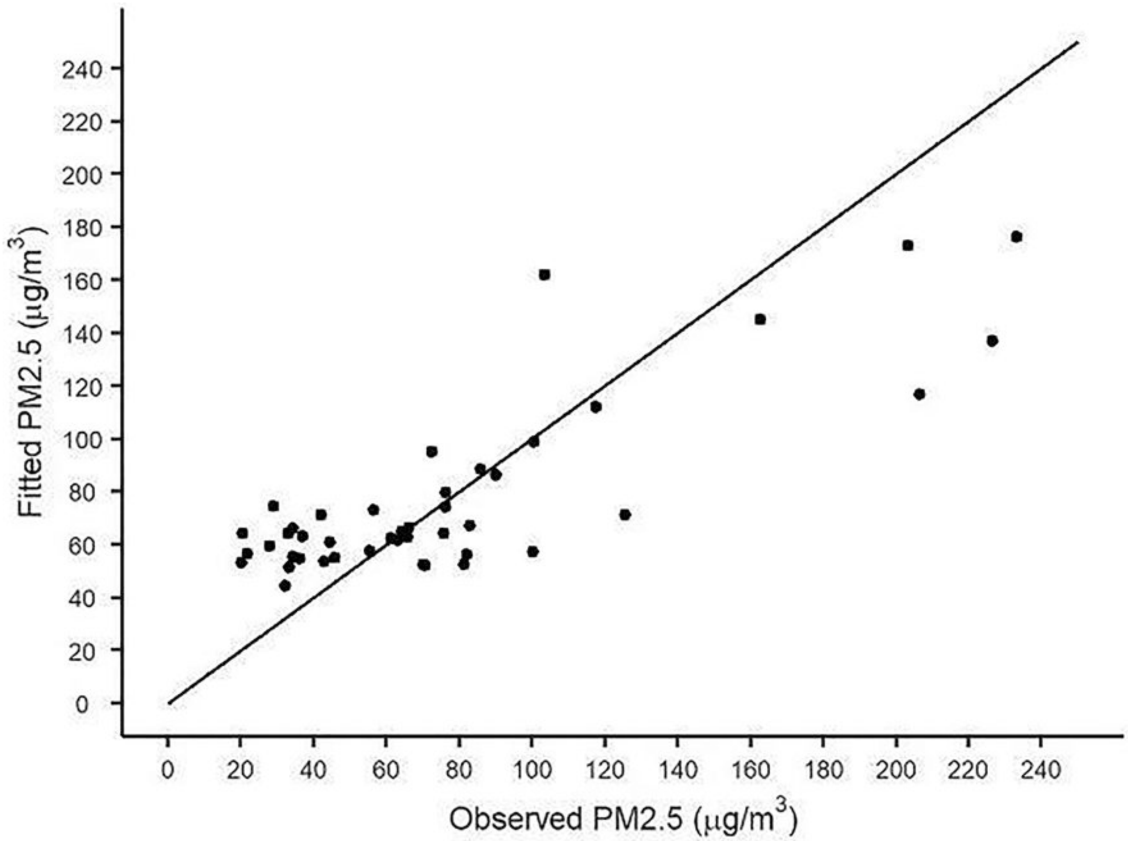

Figure 3: Correlation between fitted and observed background $PM_{2.5}$ measured between June 2017 and February 2018.

Observed concentrations of background $PM_{2.5}$ were measured at a fixed site 1.35 km upwind of the Agbogbloshie e-waste site on 50 days between June 2017 and February 2018. Variable selection and predictions were performed using elastic-net penalized linear regression. Models were adjusted for visibility distance, temperature, wind speed and an interaction term between visibility distance and relative humidity.

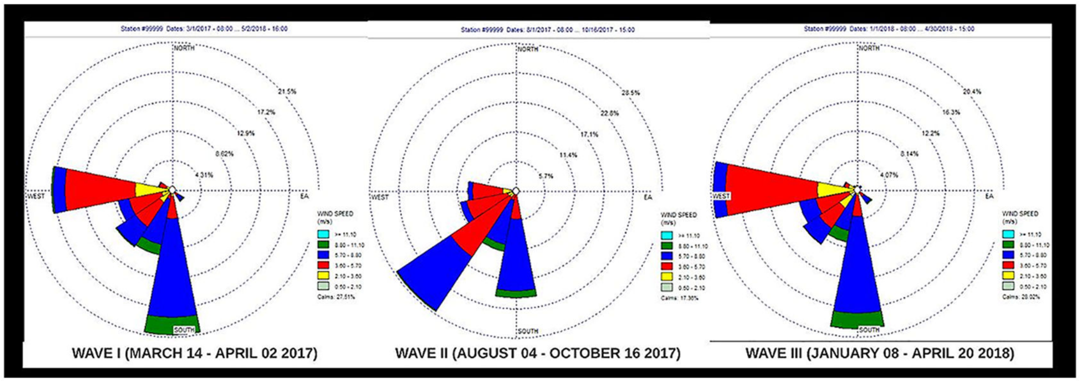

Figure 4: Wind roses from Kotoka International Airport by Wave of data collection, 2017-2018.
Wind rose were created by WRPLOT View (ver. 8.0.2) provided by Lakes Environmental.

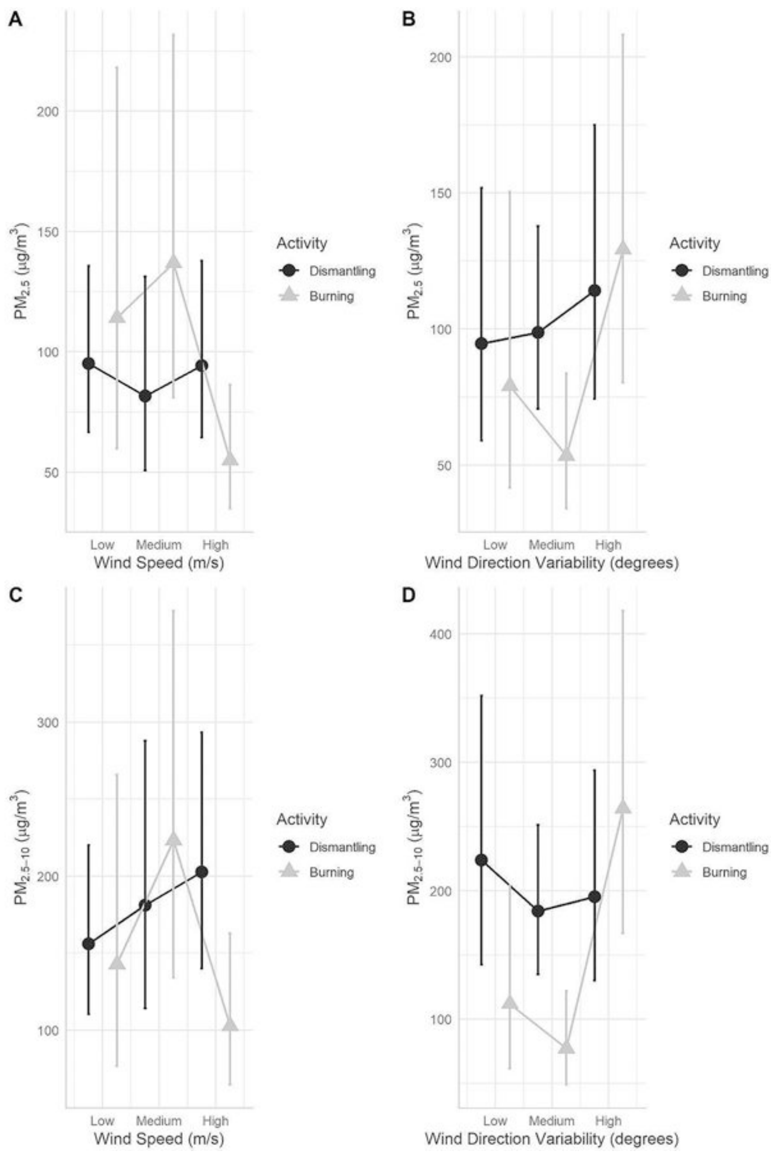

Figure 5: Predicted means of personal $PM_{2.5}$ (plots A and B) and $PM_{2.5-10}$ (plots C and D) exposure associated with changes in activity and wind conditions among e-waste workers, Agbogbloshie, Accra, Ghana, 2017-2018, (n=381).

Wind speed (plots A and C) cut-points are derived from the 33rd (4.6 m/s) and 66th (5.7 m/s) percentiles. Wind direction variability (plots B and D) cut-points for “Low”, “Medium”, and “High” are derived from cut-points at the 33rd (20.1 degrees) and 66th (30.2 degrees) percentiles. Marginal effects represent the expected change in personal exposure to $PM_{2.5}$ and $PM_{2.5-10}$ as a function of a change in activity and wind conditions while holding all other variables constant. Models were adjusted for background $PM_{2.5}$, study Wave, day of the week, temperature and relative humidity. Error bars represent 95% confidence intervals.

Table 1:

Time-activity and personal inhalation exposure to particulate matter averaged over fifteen minute intervals among 105 electronic-waste workers at Agbogbloshie e-waste recovery site, Accra, Ghana, 2017-2018.

		Activity Frequency		$PM_{2.5}$ (μg m^{-3})		$PM_{2.5\text{-}10}$ (μg m^{-3})	
	Activity Type	**Mean length of activity in minutes ± SD**	**Total minutes during which activity was performed (%)**	**Mean ± SD**	**Median (Range)**	**Mean ± SD**	**Median (Range)**
Work-Related		57 ± 64	8955 (28)	100.1 ± 130.2	66.1 (12.2, 1150.6)	166.5 ± 190.3	105.9 (9.5, 1702.8)
	Dismantling	80 ± 90	4485 (14)	90.0 ± 81.9	68.7 (13.4, 683.1)	145.9 ± 132.9	102.9 (17.7, 1101.7)
	Sorting, loading	45 ± 45	1530 (5)	81.4 ± 45.0	69.1 (14.4, 312.3)	169.4 ± 186.0	101.2 (23.7, 1000.8)
	Transporting materials	33 ± 25	825 (3)	71.4 ± 54.3	50.6 (18.2, 271.3)	160.5 ± 154.4	105.9 (22.5, 721.2)
	Burning	59 ± 44	1230 (4)	208.6 ± 283.2	71.7 (23.7, 1150.6)	240.9 ± 341.0	104.7 (22.0, 1702.8)
	Buying, selling, weighing	29 ± 18	315 (1)	58.9 ± 48.5	58.6 (12.2, 191.0)	161.9 ± 161.8	130.0 (9.5, 580.6)
	Other (Work)	52 ± 30	570 (2)	59.5 ± 23.3	58.1 (19.4, 121.1)	172.5 ± 164.9	126.5 (14.9, 858.5)
Transportation-Related		26 ± 17	5655 (18)	72.9 ± 46.0	62.0 (3.4, 468.0)	130.8 ± 124.2	100.0 (9.8, 1173.1)
	Walking	24 ± 13	4020 (13)	78.6 ± 49.6	66.5 (3.4, 468.0)	126.2 ± 122.3	98.9 (9.8, 1173.1)
	Motorbike or Car	31 ± 30	1155 (4)	57.2 ± 33.5	50.9 (16.3, 180.1)	145.6 ± 143.7	100.8 (12.5, 581.9)
	Bicycling	30 ± 11	480 (2)	62.5 ± 27.5	54.8 (15.9, 148.6)	132.9 ± 82.7	124.7 (23.2, 370.0)
Other		71 ± 78	16980 (54)	72.2 ± 47.9	64.3 (3.9, 558.2)	97.9 ± 100.0	71.1 (9.0, 1197.9)
	Not actively working[a]	74 ± 80	15915 (50)	71.1 ± 47.4	63.2 (3.9, 558.2)	99.5 ± 102.5	71.1 (9.0, 1197.9)
	Smoking	46 ± 48	1065 (3)	87.7 ± 52.1	78.0 (10.8, 253.1)	74.1 ± 44.8	70.7 (12.9, 238.3)
Total		51 ± 62	31590 (100)	80.2 ± 81.0	64.4 (3.4, 1150.6)	123.2 ± 138.8	83.5 (9.0, 1702.8)

Note: Activity type and length were derived from wearable cameras and continuous size-specific personal inhalation concentrations were measured using an optical device. Summaries are calculated from a grand total of 31,650 minutes (n=2,110 15-minute intervals), 60 minutes were "unusable" because the participant removed the camera and backpack with optical device for measuring PM during sampling. SD, standard deviation.

[a]"Not actively working" includes activities of sitting, eating or drinking, cell phone use, prayer, and communicating with others;

Table 2:

Estimated adjusted personal exposure and percent change in personal exposure to $PM_{2.5}$ and $PM_{2.5\text{-}10}$ by work and transportation-related activities in comparison to non-work related activities among 160 work shifts from 105 electronic-waste recovery workers, Agbogbloshie, Accra, Ghana, 2017-2018.

		$PM_{2.5}$		$PM_{2.5\text{-}10}$	
		Conditional R^2: 0.47	**Adjusted**	**Conditional R^2: 0.51**	**Adjusted**
Exposure and covariates	**Period of exposure**	**% change in personal exposure (95% CI)[a]**	**estimated concentration (95% CI)**	**% change in personal exposure (95% CI)**	**estimated concentration (95% CI)**
Intercept	15-minute	N/A	67.3 (54.9, 82.5)	N/A	97.4 (73.0, 129.9)
Activity (reference = Not actively working)[b]					
Burning	15-minute	28.1 (10.7, 48.2)	86.3 (61.1, 121.9)	30.7 (10.1, 55.1)	127.5 (81.2, 202.1)
Presence of tobacco smoke	15-minute	22.3 (5.4, 42.0)	82.4 (58.1, 116.9)	−2.1 (−17.9, 16.6)	95.4 (60.5, 152.0)
Walking	15-minute	6.7 (0.3, 13.4)	71.9 (55.3, 93.3)	16.2 (8.2, 24.8)	113.4 (79.8, 162.7)
Dismantling	15-minute	5.9 (−3.8, 16.5)	71.3 (53.1, 95.9)	19.2 (6.4, 33.5)	116.2 (78.4, 174.0)
Sorting, Loading	15-minute	6.3 (−5.6, 19.7)	71.6 (52.1, 98.5)	15.6 (0.6, 32.9)	112.8 (74.2, 173.2)
Transporting materials	15-minute	6.4 (−7.9, 23.1)	71.7 (50.8, 101.2)	20.1 (1.4, 42.2)	117.1 (74.7, 185.4)
Bicycling	15-minute	5.4 (−11.7, 25.9)	71.0 (48.7, 103.6)	45.7 (18.5, 79.2)	142.1 (87.4, 233.5)
Motorbike or Car	15-minute	−2.0 (−13.2, 10.5)	66.0 (47.9, 90.9)	28.1 (11.3, 47.5)	124.9 (82.0, 192.2)
Buying, selling, weighing	15-minute	1.0 (−18.9, 25.7)	68.0 (44.7, 103.4)	7.7 (−16.6, 39.)	105.0 (61.5, 181.1)
Other (Work)	15-minute	−10.4 (−26.7, 9.6)	60.4 (40.4, 90.1)	−4.6 (−24.7, 20.9)	93.1 (55.5, 157.5)
Background $PM_{2.5}$ ($\mu g\ m^{-3}$) (reference= mean)	24-hour	0.5 (0.2, 0.8)	67.7 (55.2, 82.9)	0.8 (0.4, 1.3)	98.3 (74.0, 132.0)
Wave (reference = Wave I (non-Harmattan))					122.3 (80.5, 191.4)
Wave II (non-Harmattan)	Aug-0ct	−30.6 (−44.0, −13.9)	46.8 (30.9, 70.9)	−46.5 (−60.3, −27.9)	52.2 (29.3, 93.9)
Wave III (Harmattan)	Jan- April	−27.6 (−42.5, −8.7)	48.8 (31.7, 75.1)	−38.3 (−55.5, −14.3)	60.2 (32.8, 111.7)
Day of the Week (reference = Friday)[c]					
Monday	day	46.9 (13.7, 89.6)	98.9 (62.7, 156.0)	42.4 (−1.4, 105.5)	138.8 (72.7, 267.8)
Tuesday	day	11.5 (−12.1, 41.4)	75.1 (48.5, 116.3)	16.8 (−17.0, 64.3)	113.9 (61.2, 214.1)
Wednesday	day	18.6 (−6.3, 50.1)	79.9 (51.7, 123.5)	18.2 (−15.5, 65.6)	115.3 (62.2, 215.8)
Thursday	day	−0.4 (−21.4, 26.3)	67.1 (43.3, 103.9)	3.6 (−26.3, 45.7)	101.0 (54.3, 189.8)
Saturday	day	25.9 (−8.1, 72.7)	84.8 (50.7, 142.)	14.3 (−27.3, 79.5)	111.4 (53.6, 233.9)

Note: All estimates are from linear mixed effect models adjusted for background $PM_{2.5}$, study Wave, day-of-week, temperature and relative humidity.

[a]Percent change calculated by (exp (β) −1)* 100.

[b]"Not actively working" includes activities of sitting, eating or drinking, cell phone use, prayer, and communicating with others.

[c]Sampling occurred on all days excluding Sunday.

Table 3:

Percent change in exposure to $PM_{2.5}$ (A) and $PM_{2.5\text{-}10}$ (B) by joint effect of wind conditions and activity type among 381 e-waste recovery workers at the Agbogbloshie site in Accra, Ghana, 2017-2018

(A) Exposure to $PM_{2.5}$								
		Dismantler (n=299)		**Burner (n=82)**		**Burners v. dismantlers within strata of wind**	**Measure of effect modification on multiplicative scale[a]**	**Measure of effect modification on additive scale[b]**
Effect modifier		**N**	**% change (95% CI)[d]**	**N**	**% change (95% CI)**	**% change (95% CI)**	**% change (95% CI) of interaction term[c]**	**RERI (95% CI)[d]**
Wind direction variability	Low-Med[e] (0-34°)	252	REF	47	−38.8 (−53.8, −19.0)	−32.3 (−44.2, −17.9)	280.7 (87.4 , 673.4) p-value: <0.001	144.3% (54.3, 234.4), p-value: <0.001
	High (34-56°)	47	−20.7 (−49.6, 25.0)	35	84.9 (14.5, 198.4)	163.1 (81.7, 280.9)		
Wind speed	Low-Med (0-6.2 m/s)	220	REF	57	42.7 (−8.6, 122.8)	47.1 (14.8, 88.6)	−59.6 (−76.6, −30.1) p-value: <0.01	−90.1% (−165.1, −15.1), p-value: <0.05)
	High (6.2-10.3 m/s)	79	12.0 (−25.0, 67.2)	25	−35.4 (−59.3, 2.4)	−23.2 (−40.0, −1.7)		
(B) Exposure to $PM_{2.5\text{-}10}$								
		Dismantler (n=299)		**Burner (n=82)**		**Burners v. dismantlers within strata of wind**	**Measure of effect modification on multiplicative scale**	**Measure of effect modification on additive scale**
Effect modifier		**N**	**% change (95% CI)[d]**	**N**	**% change (95% CI)**	**% change (95% CI)**	**% change (95% CI) of interaction term**	**RERI (95% CI)**
Wind direction variability	Low-Med (0-34°)	252	REF	47	−47.0 (−61.0, −27.9)	−46.6 (−56.1, −35.0)	241.1 (68.0 , 592.5) p-value: <0.01	111.9% (39.6, 184.2), p-value: <0.01
	High (34-56°)	47	−19.8 (−48.4, 24.7)	35	45.1 (−9.61, 133.1)	92.2 (31.3, 181.4)		
Wind speed	Low-Med (0-6.2 m/s)	220	REF	57	13.0 (−26.7, 74.3)	10.6 (−13.4, 41.3)		
	High (6.2–10.3 m/s)	79	28.6 (−13.1, 89.8)	25	−36.0 (−59.9, 2.2)	−44.0 (−57.8, −25.6)	−55.9 (−74.9, −22.4) p-value: <0.01	−77.4% (−144.4, −10.5), p-value: <0.05

Note: All estimates are from linear mixed effect models adjusted for background $PM_{2.5}$, Wave of data collection, day-of-week, temperature and relative humidity. CI, confidence interval, RERI, relative excess risk of interaction.

[a] "Positive" effect modification on the multiplicative scale is defined as an RR > 1 for the interaction term and "negative" effect modification is defined as an RR <1 for the interaction term.

[b]"Super-additive" effect modification on the additive scale is defined as having a relative excess risk of interaction (RERI) >0 and "sub-additive" effect modification is defined as an RERI < 0. CI, confidence interval.

[c]Percent change calculated by (exp (β) −1)* 100

[d]RERI is calculated as RR11 – RR10 – RR01 +1. Confidence intervals and p-values are calculated using the delta method[48].

[e]"Low-Med" and "High" categories for wind direction variability and wind speed are derived from cut-points at the 75th percentile (34.0 degrees and 6.2 m/s, respectively).

Table 4:

Opportunities and challenges associated with a hierarchy of air pollution control strategies for reducing emissions from open e-waste burning on an informal e-waste site.

Intervention	Opportunities and challenges
Source elimination	Eliminating the need to engage in burning e-waste would require a method of metal extraction that is equally or more efficient than burning e-waste. An effort made by Pure Earth to reduce emissions from burning wires by providing an automated wire stripping machine highlights the challenges in eliminating burning; despite the new tool, workers at Agbogbloshie continued to burn finely gauged plastic-coated copper wires saying that they were not efficiently processed by the machine[49,50].
Pollution prevention	The replacement of tires and Styrofoam as accelerants could reduce emission toxicity. Alternative technology for burning e-waste (e.g. burn box, incinerator) would reduce byproducts of incomplete combustion and improve process control and metal recovery. Large capital investment, maintenance and technically trained workers are required. New technologies may reduce the number of available jobs.
Pollution control technology	The inclusion of particulate collection methods (e.g. settling chambers, fabric collectors, cyclones) into innovative engineering solutions for burning e-waste that include health and safety in the design could reduce occupational and environmental exposures. Capital investment, maintenance and technically trained workers are needed.
Source relocation and site reorganization of site layout	Geographic separation from receptors (people), stack height increases, reorganization of the worksite layout so that burning e-waste occurs downwind of all other types of work, and restrictions on times during which burning and other activities can be performed may protect nearby populations, but cannot guarantee a reduction in occupational exposures. Relocation would prevent exposure among the estimated 80,000 individuals living adjacent to the Agbogbloshie site[51], in addition to people shopping at the open-air food market and attending nearby primary schools. Prior research found that nearby residents and e-waste workers at Agbogbloshie had comparable risks of PCB exposure, although PCB toxicity among nearby residents could be from other sources (e.g. diet, waste incineration)[18].
Personal protective equipment (PPE)	Provision of basic PPE including boots, gloves and respirators would help reduce injuries and exposure but must be combined with higher order interventions, including proper selection of respirator types, training, fit-testing and PPE maintenance. Long-term capital investment to maintain and replace PPE is essential.
Education and behavioral changes	Education is a prerequisite for any form of intervention. Effective technical interventions and behavioral changes require occupational training and education on the risks associated with e-waste recovery practices. Education can further empower workers to advocate for themselves and reduce unnecessary exposures while on the job (e.g., while eating or drinking on site) and in their homes where women and children may be exposed.