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Impact of fine particulate matter air pollution ($PM_{2\cdot5}$) on Nigerian children's performance on tests of cognitive and neurobehavioral development at age seven years

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Declaration of competing interest

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Abstract

Background: Elevated exposures to fine particulate matter ($PM_{2\cdot5}$) air pollution threaten child health and development. Kerosene and biomass cooking fuels are a source of $PM_{2\cdot5}$ in sub-Saharan Africa. Potential impacts on child cognitive and neurobehavioral development require investigation.

Methods: In a cross-sectional observational study, September 2021 – March 2023, we assessed cognitive and neurobehavioral development in 208 Nigerian seven-year-old children using the performance-based KABC-II (neurocognition) and two parent questionnaires: VABS-3 (adaptive behavior) and SDQ (psychological adjustment). We collected data on sociodemographic covariates. We conducted 48-hour $PM_{2\cdot5}$ (μg/m^3) exposure monitoring twice using two RTI MicroPEM™ sensors: indoor (in-home) and personal (body-worn). We examined the relationship between mean $PM_{2\cdot5}$ exposures and child developmental assessment scores using multiple linear regression, adjusting for child's age and sex, mother/caregiver's age and education, and household wealth.

Findings: A two-fold increase in mean personal $PM_{2\cdot5}$ exposures was associated with 3·04-unit lower (95 % CI: −4·62, −1·46; $p < 0\cdot001$) KABC-II scores and 2·18-unit lower (95 % CI: −4·79, 0·43; p = 0·10) VABS-3 scores, after adjustment for covariates. Children in households using clean fuels scored higher on both assessments, although the differences were not significant after adjustment. Those in households using exclusively polluting fuel had lower KABC-II scores after adjustment (−4·07, 95 % CI: −8·12, −0·02; p = 0·049). We found no associations between $PM_{2·5}$ levels or fuel types and SDQ scores.

Interpretation: Elevated personal $PM_{2·5}$ exposures during middle childhood are associated with lower developmental assessment scores in Nigerian seven-year-old children. Household use of polluting cooking fuels contributes to these exposures.

Keywords

Particulate matter; Air pollution; Child; Cognition; Neurodevelopmental outcome; KABC-II; Nigeria

1. Introduction

Around the world, 93 % of children under the age of 15 breathe polluted air every day, putting their health and development at risk (World Health Organization, 2018). A 2024 report by the Energy Policy Institute at the University of Chicago states that, “fine particulate air pollution ($PM_{2·5}$) is the greatest external threat to public health, with the average person on the planet losing more than two years of life expectancy, according to the Air Quality Life Index, with the loss even higher (3·1 years) outside Organization for Economic Co-operation and Development countries (Greenstone et al., 2024).” According to the World Health Organization (WHO), an estimated 3.2 million deaths per year in 2020, over 237,000 of them children, were attributable to household air pollution (HAP) from using biomass, kerosene, or other polluting fuels for cooking and heating (World Health Organization, 2024). These fuels burn inefficiently, producing $PM_{2·5}$, black carbon (BC), and other toxicants. People in low- to middle-income countries (LMIC) experience the highest levels of $PM_{2·5}$ from such sources (Lim et al., 2022). Women, infants, and children in LMIC suffer the most exposure to HAP. Sub-Saharan Africa is the region of the world most reliant on polluting fuels for household energy needs. In Nigeria, 28 % of urban residents cook with kerosene and two-thirds of households cook with biomass fuel (Roche et al., 2024). Beyond HAP, growing children encounter numerous sources of $PM_{2·5}$ exposure from ambient air pollution (AAP), including vehicular traffic, waste incinerators, burning of crop residue, petroleum fuels-powered electricity generators, and industry, each bearing a particular array of toxicants (Sukumaran et al., 2024). The impact of elevated $PM_{2·5}$ exposures on respiratory, cardiovascular, and neurologic health across the lifespan are well documented in LMIC. A small but growing body of research identifies potential harmful effects on infant and child cognitive and neurobehavioral development, as well, in those countries (World Health Organization, 2018).

Here we report on analyses stemming from a longitudinal study ongoing in Nigeria, a follow-up to our randomized controlled trial (RCT) conducted from 2012 to 2015 in Ibadan, Nigeria: the “HAP and Pregnancy Outcomes Study” (ClinicalTrials.gov: NCT02394574) (Alexander et al., 2018). The RCT monitored the HAP exposures of 324 women from their pregnancies until they gave birth. Our follow-up “HAPCOG Study” is investigating the longitudinal impact of exposures to $PM_{2\cdot5}$, black carbon (BC), and other toxins in HAP and AAP on the RCT participants' children, almost all of whom appear to be generally healthy and developing on a par with their peers. We report findings on the children's cognitive and neurobehavioral development, assessed at enrollment into HAPCOG around the time of their seventh birthdays, in relation to $PM_{2\cdot5}$ levels experienced during their seventh year (Fig. 1). Twice over this one year, we measured the $PM_{2\cdot5}$ ($\mu g/m^3$) levels in the children's households along with their personal $PM_{2\cdot5}$ exposures, to yield an estimate of their typical, middle childhood, all-source, year-round exposures. We also collected data on maternal education and household socioeconomic status (SES), known covariates of children's health and development (Boyle et al., 2006). Based on research demonstrating diverse ill effects of $PM_{2\cdot5}$ exposure, we hypothesized that elevated exposures would be associated with lower scores for these children on assessments of cognitive and neurobehavioral development. In line with some recent reviews, (Castagna et al., 2022; Alter et al., 2024) we thought it unlikely we would encounter clinically significant neurocognitive developmental disorders such as autism or ADHD in our sample, associated with their $PM_{2\cdot5}$ exposures. In the Discussion, we consider how to evaluate small but statistically significant point decrements in scores on standardized tests of neurocognitive development; their implications for children as individuals and at the population level.

2. Methods

2.1. Participants

From August 2021 through March 2023, we recruited 212 of the RCT children into HAPCOG, along with either their biological mother or current primary caregiver as co-participant. To form an age-homogenous study sample, we enrolled each child as close to their seventh birthday as possible, resulting in a sample average age of seven years, two months (7;2, with a range of 6;9 to 7;11 and SD of 2.88 months) at time of developmental assessment (see Table 1). For 33 children, the co-participant was an adult other than their biological mother. Two of the 212 children were enrolled too late to be included in these analyses. Another two were lost to follow-up, leaving a total of 208 participants for the analyses we report here.

HAPCOG received approval from the University of Ibadan Institutional Ethics Committee and the University of Chicago Biological Sciences Division Institutional Review Board. Informed consent forms were created in both English and Yoruba, the language of southwestern Nigeria. Mothers/caregivers were consented in the language in which each was most conversant. We obtained consent using the written form. The consenting procedure was interactive. A colleague went through the form with each participant, discussed concerns and answered any questions. This oral protocol also allowed us to accommodate participants who had less than a secondary school education. The participant's signature or mark was witnessed and the witness signed the form.

2.2. Location

The city of Ibadan (7° 22′ 39″N, 3° 54′ 21″E; elevation 300–360 m) is in Oyo State in southwestern Nigeria. At 3,080 km^2 it is the largest city in Nigeria by landmass (Land mass, 2023). It is Nigeria's third largest city in population, estimated in 2022 (when most data for this report were gathered) at 3,756,000 (Ibadan, 2025). Nigeria's southwest region has monthly temperatures averaging from 25–30 °C and relative humidity hovering around 80 %, year round (Climate in Southwest Nigeria, 2025). Akinyemi et al. (2020) report Ibadan's rainy season (roughly May-October) daily precipitation at 150–350 mm and dry season (December-February) precipitation at below 50 mm (Akinyemi et al., 2020). Fig. 2 is a map of Ibadan showing the city's perimeter and 11 local government areas within. Blue dots indicate the locations of all of HAPCOG's participating households.

2.3. $PM_{2·5}$ monitoring

We monitored indoor $PM_{2·5}$ levels and children's personal $PM_{2·5}$ exposures (μg/m^3) using RTI MicroPEM™ air quality sensors (RTI International, Research Triangle Park, NC, USA), as in our earlier study (Alexander et al., 2018). We measured $PM_{2·5}$ levels for 48-hour intervals at two time points during each child's seventh year. The first exposure monitoring was conducted within a month after the child's recruitment into HAPCOG and the second one an average of 7·5 months (SD = 1·4 months) later. Typically, our Nigerian team members set up for exposure monitorings on a Tuesday and returned two days later to retrieve the MicroPEMs on Thursday. At set-up for each 48-hour interval, team members placed the indoor MicroPEM in the home, at a location away from cooking activities, in the area where household members spend the most time. Indoor MicroPEMs were positioned 1 to 1.5 m above floor level in all but a very few cases where this was not possible. The personal MicroPEM was given to the child to wear in a small backpack while going about all their daily activities, indoors and out. Care was taken to not block airflow into the device, for unobstructed sampling. The child wore the backpack at all times other than when bathing or sleeping, during which the personal monitor was placed nearby, within 1 m of the child.

Children's wearing compliance of the personal monitors was instrumentally assessed based on data logged every five seconds by the device's onboard accelerometer with an algorithm to determine when the device was moving or not moving.

Indoor $PM_{2·5}$ levels and each child's personal $PM_{2·5}$ exposures were determined by gravimetric analysis of the filters removed from the MicroPEMs, averaging values over the two monitoring intervals conducted with each child. Further details on our procedures for QA/QC of air quality data and gravimetric analysis of the MicroPEM filters may be found in the supplement to this paper.

2.4. Developmental assessment

Few instruments for assessing cognitive and neurobehavioral development have been developed for language/cultural populations in LMIC (Abubakar and van de Vijver, 2017). For HAPCOG, we followed the lead of several well-documented research efforts (Koura et al., 2013; Boivin et al., 2021; Bangirana et al., 2009; Chernoff et al., 2018) by employing assessment instruments originally developed for children in Western countries, with instructions adapted as appropriate for the Yoruba language/cultural context.

The Kaufman Assessment Battery for Children, 2nd Edition (KABC-II) is a performance-based assessment of child neurocognitive development (Kaufman and Kaufman, 2004).

KABC-II subscale tasks assess the basic domains of simultaneous and sequential processing, gross and fine motor skills, knowledge, learning ability, and planning. Adapted versions have been found suitable for use in several sub-Saharan African countries (Bangirana et al., 2009; van Wyhe et al., 2017). The assessment is administered by a trained assessor, one-on-one with the child, and requires the child's active engagement with tasks measuring a variety of neurocognitive domains. In line with published studies, we conducted the KABC-II assessments using the 15 domain subscales appropriate for our cohort of children, in accord with the Luria model, (Kaufman and Kaufman, 2004) calculating a global Mental Processing Index (MPI) measure of all-domain neurocognitive functioning, a general intelligence composite score.

Standardized instructions guide the child in engaging with each of the instrument's 15 subscale tasks. Our team of Nigerian colleagues, which includes our pediatric psychiatrist co-investigator, Dr. Yetunde Adeniyi, Nigerian and U.S. trained linguists, and native speakers of Yoruba and the Nigerian dialect of English, adapted these instructions for our Yoruba language/cultural context, aiming for close linguistic, functional, and cultural equivalence between the original and adapted versions. The adapted versions were piloted with child volunteers; revising and re-piloting with further volunteers until assessments were judged by Dr. Adeniyi to proceed smoothly and to accurately tap the target neurocognitive dimensions.

The Vineland Adaptive Behavior Scales, 3rd Edition (VABS-3) and Strengths and Difficulties Questionnaire (SDQ) are parent/caregiver questionnaires that have been used in studies of at-risk children in sub-Saharan Africa (Kusi-Mensah et al., 2022; Sparrow and Cicchetti, 2016; Hoosen et al., 2018). The VABS-3 is a comprehensive, multi-subscale assessment of adaptive behavior in the domains of communication, daily living skills, socialization, and gross and fine motor skills. The SDQ is a brief behavioral screening questionnaire that targets emotional symptoms, conduct problems, hyperactivity/inattention, peer problems, and prosocial behavior. It has been used in the Yoruba language/cultural context of southwestern Nigeria, including by members of our HAPCOG team (Adeniyi and Adeniyi, 2020; Adeniyi and Omigbodun, 2017; Adeniyi et al., 2021). (See supplement for further details on administration of the cognitive and neurobehavioral development assessments.).

2.5. Sample characteristics survey

We used structured survey instruments developed for the earlier RCT to collect demographics data, including child's sex and age, maternal age and education; also, data on residence and neighborhood characteristics and household assets. Items relevant to SES included parental employment and marital status; assets such as livestock, household appliances, motorized vehicles; years of residence; residence construction details including building materials and number of windows; household fuel type usage and expenditures; sanitation practices; and waste disposal. Following the Demographic and Health Survey (Rutstein et al., 2004), we formulated a household wealth index appropriate to the southwestern Nigerian context, comprising five levels or quintiles: 1 (poorest) to 5 (wealthiest). (See supplement for more information on formulation of the household wealth index.) During a visit to our campus facility at time of recruitment and a home visit soon thereafter, sample characteristics data were gathered from mothers/caregivers. Our Nigerian field workers supplemented these self-report data with on-site observations of residence and neighborhood characteristics. To learn more about the sources of each child's $PM_{2·5}$ exposures, the survey also included items on residence proximity to roadways, petroleum fuels-powered electricity generators, waste incinerators, and factories. Field workers captured GPS coordinates of all participants' places of residence, along with those of nearest roadways, any waste incinerator nearby, and so on.

2.6. Statistical analysis

We performed a base-2 logarithmic transformation of indoor $PM_{2·5}$ levels and children's personal $PM_{2·5}$ exposures, due to their skewed distributions. We calculated the average of log-transformed values of the gravimetric measures over both $PM_{2·5}$ exposure monitoring intervals. We calculated children's personal monitor wearing compliance from the monitors' internal accelerometers as moving/(moving + not moving), resulting in a percentage of time the device was considered moving, or "worn" by the child during each 48-hour monitoring interval. Raw scores for each KABC-II or VABS-3 subscale were scaled and standardized according to U.S. norms; that is, transformed into a standardized scale with a mean of 100 and standard deviation of 15 as is the convention for tests of cognitive ability such as, e.g., the Stanford-Binet IQ. From these, the KABC-II global mental processing index (MPI) (Suter et al., 2018) and VABS-3 adaptive behavior composite (ABC) (Sparrow and Cicchetti, 2016) were derived. We used multiple linear regression to investigate associations between developmental outcome measures KABC-II MPI, VABS-3 ABC, and SDQ scores and: (1) $PM_{2·5}$ levels (indoor and personal), (2) household cooking fuel type (polluting versus clean), and (3) primary/secondary fuels type (clean/clean, clean/polluting, polluting/clean, and polluting/polluting). Analyses of children's developmental assessment scores in relation to $PM_{2·5}$ levels and household fuels usage were adjusted for children's age and sex, mother/caregiver's age and education, and household wealth index. Homogeneity of the residuals from the regression fit was confirmed using the Breusch-Pagan test. Similar analyses were conducted to investigate associations between the $PM_{2·5}$ exposure levels (indoor and personal) and cooking fuel type. Two-sided p-values $< 0·05$ were considered statistically significant. Finally, we tested for a correlation between wearing compliance and the log-transformed $PM_{2·5}$ concentrations with Pearson's r and for a possible relationship between wearing compliance and children's assessment scores by running the multi-linear regression model with wearing compliance included as covariate.

3. Results

3.1. Sample characteristics

Table 1 summarizes sample characteristics, those of the 208 children, their mothers/caregivers, and households; also, personal and indoor $PM_{2·5}$ levels (averaging values over the two monitoring intervals conducted with each child), overall and at each visit, and outcome measures, overall and stratified by primary fuel type. Questionnaire responses concerning cooking fuel type revealed use of both clean and polluting fuels across the households in our sample. As defined by the International Energy Agency, polluting fuels are those that burn inefficiently, releasing a variety of toxic substances including $PM_{2·5}$ (IEA, 2025). Participants across our sample reported using three types of polluting fuels: firewood, charcoal, and kerosene. They reported using three clean fuels: liquid petroleum gas (LPG), electricity, and ethanol.

3.2. Household fuel type use and $PM_{2·5}$

Households were asked to self-report their primary and secondary cooking fuel(s) usage for the six-month interval preceding each exposure monitoring. Table 1 shows that 25·5% of households reported using exclusively clean fuels, 21·2% exclusively polluting fuels, and 52·9% both clean and polluting fuels, with one type reported as being primary. We examined the contribution of cooking fuel type (polluting vs. clean), to indoor $PM_{2·5}$ levels and to children's personal $PM_{2·5}$ exposures. In the univariate analysis, personal $PM_{2·5}$ exposures were 38 % higher for children living in households using primarily polluting cooking fuel (64·99, 95 % CI: 57·48, 73·48) than in those using primarily clean fuel (47·16, 95 % CI: 43·1, 51·6). After adjusting for covariates (Model 1, Table 2), the association between primary fuel and personal $PM_{2·5}$ levels remained significant (26 % higher for polluting fuel; 95 % CI: 6 %, 49 %, p = 0·008). Indoor $PM_{2·5}$ levels were marginally significantly higher in households that cook primarily with polluting fuels (51·97 vs. 44·91, p = 0·063) but this effect was not significant after adjustment for covariates (Model 1, Table 2). Male children registered 19 % higher indoor $PM_{2·5}$ levels (95 % CI: 3 %, 37 %; p = 0·02) and personal $PM_{2·5}$ exposures (95 % CI: 3 %, 38 %; p = 0·02) than female children in the multiple linear regression (Model 1, Table 2). Mother/caregiver education was significantly associated with lower indoor $PM_{2·5}$ (9 %; 95 % CI: 2 %, 15 %; p = 0·01) and child personal $PM_{2·5}$ exposures (7 %; 95 % CI: 1 %, 14 %; p = 0·04). Child's age was associated with lower personal $PM_{2·5}$ exposure (3 % per month; 95 % CI: 1 %, 10 %; p = 0·047) but was not associated with indoor $PM_{2·5}$ level. When both primary and secondary fuel types were considered, personal $PM_{2.5}$ exposure was higher in households that primarily used polluting fuel types and secondarily clean fuel types (64·31, 95 % CI: 52·79, 78·35) or exclusively used polluting fuels (65·42, 95 % CI: 55·89, 76·58) compared to households that used clean fuel types (44·7, 95 % CI: 38·73, 51·6). The effects of primary and secondary polluting fuels remained significant after adjustment for covariates (Model 2, Table 2). The effects of covariates were similar to Model 1.

3.3. Personal MicroPEM wearing compliance

Wearing compliance during the 48-hour monitoring intervals had a mean of 38·2%, SD 11·4, median of 41·0%. This indicates that the children wore the monitors for a mean of about 9·2 h per day; median of about 9·8 h. This is equivalent to a mean "waking" wearing compliance of 57·5% per day; median of 61·3%. Mean wearing compliance for female children was 37·7%, median 40·5%; for male children, 38·9%, median 41·8%. The result of a two-tailed t-test for difference of means was insignificant ($t(379) = -1·01$, $p = 0·31$), indicating that female and male children were similarly wearing compliant. We note that wearing compliance is almost always correlated with measured $PM_{2·5}$ exposures (Lawless et al., 2012; Gould et al., 2023) and so used Pearson's r to test for the correlation between all children's wearing compliance percentages and the log-transformed personal

$PM_{2·5}$ concentrations, revealing a highly significant correlation coefficient of 0·27(df = 379), p < 0·001.

3.4. KABC-II MPI – Neurocognition

$PM_{2·5}$ was negatively associated with MPI (Fig. 3a, 3b). The strength of association was greater for children's personal $PM_{2·5}$ exposures than for indoor $PM_{2·5}$ levels. A 2-fold increase in mean personal $PM_{2·5}$ was associated with a 4·43-unit reduction in MPI (95 % CI: −6·04, −2·81; p < 0·001) in the unadjusted analysis (Table 3) and with a 3·04-unit reduction (95 % CI: −4·62, −1·46; p < 0·001) after adjustment (Model 1, Table 3). Household wealth index (1·35, 95 % CI: 0·44, 2.26; p = 0·004) and mother/caregiver's education (2·24, 95 % CI: 1·05, 3.44; p < 0·001) were positively associated with MPI (Model 1, Table 3). In the univariate analysis, indoor $PM_{2·5}$ level was associated with significantly lower MPI (−2·70, 95 % CI: −4·41, −0·99; p = 0·002) but not so after adjustment (Model 2, Table 3). Household wealth index (1·58, 95 % CI: 0·66, 2·50; p = 0·001) and mother/caregiver's education (2·37, 95 % CI: 1·16, 3·59; p < 0·001) were positively associated with MPI (Model 2, Table 3). Finally, given the significant correlation between wearing compliance and personal $PM_{2·5}$ exposures noted above, we quantified the association between wearing compliance and KABC-II scores. We added wearing compliance to Model 1 as a covariate to further adjust for its effects. We found that a 2-fold increase in mean personal $PM_{2·5}$ was associated with a 4·73-unit reduction in MPI (95 % CI: −6·63, −2·83; p < 0·001) when adjusting for only wearing compliance, and with a 3·11-unit reduction (95 % CI: −4·97, −1·25; p = 0·0013) when adjusting for the complete set of covariates. The direction of the association between transformed personal $PM_{2·5}$ exposures and MPI remained unchanged, and the magnitude increased slightly, with an additional 0·3-unit decrease and 0·7-unit decrease in MPI associated with a 2-fold increase in mean personal exposure being reported after the inclusion of wearing compliance to the unadjusted and previously adjusted analyses.

MPI was lower, on average, for children in households that primarily used polluting fuels (Fig. 4a). The regression modelling confirmed this finding (62·92 vs. 68·01; p < 0·001). However, the difference was no longer significant after adjustment (Model 1, Table 4). In the adjusted analysis, household wealth index (1·39, 95 % CI: 0·41, 2·36; p = 0·006) and mother/caregiver's education (2·54, 95 % CI: 1·32, 3·76; p < 0·001) were positively associated with MPI (Model 1, Table 4).

Notably, children living in households that cooked exclusively with polluting fuels (both primary and secondary) had lower MPI, on average, than those in households that cooked exclusively with clean fuels (60·73 vs. 69·79; p < 0·001; see also, Fig. 3). This effect, though smaller in magnitude, remained significant after adjustment (−4·07, 95 % CI: −8·12, −0·02; p = 0·049; see Model 2, Table 4). In the adjusted analysis, household wealth index (1·18, 95 % CI: 0·19, 2·16; p = 0·02) and mother/caregiver's education (2·55, 95 % CI: 1·32, 3·77; p < 0·001) were positively associated with MPI. Male children's MPI was, on average, lower than female children's (−2·77, 95 % CI: −5·16, −0·38; p = 0·03).

3.5. VABS-3 ABC – Adaptive behavior

$PM_{2\cdot5}$ levels were negatively associated with ABC (Fig. 3c, 3d), with the strength of association slightly greater for children's personal $PM_{2\cdot5}$ exposures. A 2-fold increase in mean personal exposures was associated, on average, with 2·79 units lower ABC (95 % CI: −5·30, −0·29; p = 0·03) in the unadjusted analysis (Table 3). However, the effect was no longer significant after adjustment for covariates (Model 1, Table 3). Mother/caregiver's education was positively associated with ABC (2·70, 95 % CI: 0·73, 4·67; p = 0·008). Similarly, effects of indoor $PM_{2\cdot5}$ levels on ABC were significant in the univariate analysis (−2·63, 95 % CI: −5·20, −0·06; p = 0·046) but not significant after adjustment, and the effects of covariates were similar as for personal $PM_{2\cdot5}$ exposures (Model 2, Table 3). Additionally, we checked for association between wearing compliance and VABS-3 scores. A 2-fold increase in mean personal exposures was associated with a 2·46-unit decrease in ABC (95 % CI: −5·49, 0·56) in the wearing compliance-only adjusted analysis. Similar to MPI, the inclusion of wearing compliance maintained the direction of the relationship between exposure and ABC, and the magnitude of that relationship differed by 0·33 units, with the pre-wearing compliance-adjusted version reporting a slightly higher reduction in ABC per 2-fold increase in exposure. After including wearing compliance in the adjusted analysis, the effect remained insignificant.

ABC scores were higher on average for children in households that primarily cooked with clean fuels (Fig. 4c) but the difference was not significant (Table 4). In the adjusted analysis, only the effect of mother/caregiver's education was significant (2·98, 95 % CI: 1·03, 4·94; p = 0·003). Children from households using exclusively polluting fuels had lower ABC than children from households using exclusively clean fuels (−6·19, 95 % CI −11·98, −0·31, p = 0·041). This can also be seen in Fig. 4d; however, the effect was not significant after adjusting for covariates. In the adjusted analysis, only the effect of mother/caregiver's education was significant (Model 2, Table 4).

3.6. SDQ – Psycho-emotional and behavioral adjustment

Neither indoor $PM_{2\cdot5}$ levels nor children's personal $PM_{2\cdot5}$ exposures were associated with SDQ scores (Table 3) and neither were fuel(s) used for cooking (Table 4). The median composite (total difficulties) score for the entire cohort was 18 (mean 18·32, SD 4·6), in the "high" range relative to population-based norms established in the UK, (Goodman and Goodman, 2009) possibly indicating some measure of emotional and behavioral adjustment difficulty.

4. Discussion

4.1. Summary

For this cross-sectional observational study of the impact of $PM_{2\cdot5}$ air pollution on Nigerian children's cognitive and neurobehavioral development in middle childhood, we assessed development in a cohort of 208 seven-year-olds living in *peri*-urban and urban areas of Ibadan in southwestern Nigeria. At two time points over the year following assessment, we made 48-hour continuous measurements of $PM_{2\cdot5}$ levels in the children's homes and of their personal, all-source $PM_{2\cdot5}$ exposures. Personal monitor wearing compliance, calculated from

MicroPEM accelerometer data as the percentage of time the device was in motion, had a mean of 38·2% and median of 41 %; thus, a “waking” compliance mean of 57·5%; median 61·3%. This is well within the range, particularly for children, of what has been reported in other published studies that incorporate personal exposure monitoring (RTI International, 2013; Thornburg et al., 2021; Vanker et al., 2023; Shupler et al., 2024). Multiple linear regression analyses, adjusting for covariates, revealed that higher personal $PM_{2·5}$ exposures and household use of polluting cooking fuels were associated with lower scores on the KABC-II assessment of neurocognition and VABS-3 assessment of adaptive behavior, the associations being stronger for KABC-II. Children’s scores on the SDQ assessment of psychological and behavioral adjustment showed no relationship with their $PM_{2·5}$ exposures, nor with household fuel(s) usage. Household use of polluting cooking fuels was significantly associated with higher personal $PM_{2·5}$ exposures.

These findings align with a growing body of research, mostly epidemiological and focused on population-level cohorts, that have found detrimental effects of air pollution on child cognitive and neurobehavioral development (World Health Organization, 2018; Castagna et al., 2022; Alter et al., 2024; Suades-Gonzalez et al., 2015; Lopuszanska and Samardakiewicz, 2020). Few of these studies have been conducted in sub-Saharan Africa (Suter et al., 2018; Christensen et al., 2022) and almost none in Nigeria (Nduka and Jimoh, 2025) which, at more than 232 million people, is the continent’s most populous nation (World Bank, 2025). HAPCOG is distinguished not only by its geographic location but also in its alignment with studies seeking, as Alter et al. (2024) state in their systematic review and metanalysis, “… to quantify exposure at the individual level (e.g., biomarkers and wearable devices) to increase sensitivity and precision when generating exposure–response functions (Alter et al., 2024).” Alter’s et al. search of the literature identified only six such published studies, however, the body of research meeting their criteria is growing (Nduka and Jimoh, 2025; Reuland et al., 2025). The findings we report here contribute to this body of research.

4.2. Magnitude of point decrements

Castagna’s et al. (2022) systematic review found that adverse effects of air pollution on child cognitive and neurobehavioral development are most often reported for global intellectual and attention/executive functioning but notes that effects typically do not rise to the level of “clinically relevant performance deficits (Castagna et al., 2022).” Like-wise, our findings of a statistically significant, −3·04-point decrement (after adjustment for covariates) in KABC-II MPI and a −2·79-point decrement in VABS-3 ABC scores (before adjustment), would not be considered clinically significant; meaning, they would not trigger a recommendation for follow-up with a child developmental specialist. They do merit the attention of public health researchers, however. We note that the point decrements identified in our study are in the range of those covered in the Castagna et al. review, when these are reported with reference to a standardized assessment scale (mean 100; SD 15), as ours are. As cited in Castagna et al., for example, Edwards, et al. (2017) reported an estimated 3·8-point average decrease in IQ points and Wang et al. (2017), an average performance IQ decrement of 3·08 points, associated with increases in children’s air pollution exposures (Edwards et al., 2010; Wang et al., 2017).

Such point decrements are of no clinical significance for an individual child. However, we interpret them according to a framework in developmental neurotoxicology that acknowledges the incremental impacts of lead exposures on child neurodevelopmental outcomes; their potential economic and social sequelae at the population level (Alter et al., 2024; Weiss, 1997; Weiss, 2000; Perera et al., 2019). Alter et al. (2024) advocate for including subclinical IQ loss in children caused by environmental toxicants, including $PM_{2\cdot5}$ air pollution, in the Global Burden of Disease tabulations (Alter et al., 2024). Finally, we note that Calderón-Garcidueñas et al. (2020) and others caution that early $PM_{2\cdot5}$ exposures with seemingly negligible impact on child cognitive development may be associated with significant cognitive impacts later in life (Calderón-Garcidueñas et al., 2020).

Concerning our finding of no association between $PM_{2\cdot5}$ levels and children's SDQ scores, one possible interpretation relates to this assessment's status as a basic screening instrument, designed to identify individuals who need referral for professional evaluation of mental health problems. Of the three instruments we used, the SDQ is likely the least sensitive. In line with our original expectation that this HAPCOG cohort comprises a sample of generally healthy children developing normally in their context and noting that our two sensitive, comprehensive assessments did not detect clinically significant differences between children with higher versus lower $PM_{2\cdot5}$ exposures, a null finding with the SDQ is not surprising. Indeed, a recent review of the literature on the association between air pollution ($PM_{2\cdot5}$ and nitrogen oxides) and mental health in children and young adults cites a number of studies that used the SDQ, all but one with sample sizes in the thousands (Mazahir et al., 2025). A number of these found no effect of air pollutants on SDQ scores. It remains to be seen whether, as the HAPCOG cohort increases in size longitudinally, the larger sample may afford statistical power sufficient to detect an effect of elevated $PM_{2\cdot5}$ levels on children's psychological and emotional adjustment in our study context.

Our finding that male children experienced higher $PM_{2\cdot5}$ levels was unexpected. Further explorations of our data revealed a likely contributing factor in households' choice of cooking fuels. Thirty-seven percent of male children's households reported use of polluting fuels (primary only, or primary and secondary) versus 31 % of female children's households, a difference that can only be due to chance variation. Other factors, such as use of home power generators or the practice of cooking indoors versus outdoors did not apportion more to either male or female children's households. Regarding male children's higher *personal* $PM_{2\cdot5}$ exposures, the 6 % greater household use of polluting fuels would be a contributing factor. We found no statistically significant difference between male and female children's monitor wearing compliance. Beyond such factors, some portion of the difference in personal exposures may be attributable to different patterns of daily activities; e.g., male children may spend more time in more contaminated outdoor areas. The International Energy Agency reports that girls in Africa may spend hours a day away from home, gathering firewood for cooking (IEA, 2025). Our questionnaire's did not gather data on children's activity patterns sufficient to account for the observed difference. In the absence of such data or inclusion of technologies such as GPS tracking, any account will be limited and speculative.

4.3. Possible mechanisms of effect

Biological mechanisms via which air pollution may affect cognitive and neurobehavioral developmental domains are under investigation. Chronically elevated $PM_{2\cdot5}$ exposures likely induce oxidative stress, promoting systemic inflammation and epigenetic changes (Yan et al., 2024) in the body that could engender developmental deficits. Another biological mechanism is suggested by demonstrations of fine particulate matter deposition in brain tissue, likely leading to disruption of neurologic functions (Calderón-Garcidueñas et al., 2020). Finally, $PM_{2\cdot5}$ is a vehicle for many toxicants such as black carbon and heavy metals such as lead, that are known threats to child neurodevelopment.

4.4. Future directions

Findings of a recent large-scale study in the United States suggest that the precise nature of air pollution's threat to cognitive and neurobehavioral development, and the biological mechanisms underlying it, may vary regionally based on local primary sources of $PM_{2\cdot5}$ pollution (Sukumaran et al., 2024). These varying sources, for example, combustion of cooking fuels and crops residue, vehicular traffic, industrial activities, and so on, emit particulate matter with distinct chemical compositions, including varying proportions of carbonaceous compounds, metals, trace elements, and other constituents. Exposure to varying $PM_{2\cdot5}$ compositions, along with individual differences in susceptibility, may drive the biological mechanisms responsible for adverse health outcomes, more than $PM_{2\cdot5}$ mass alone. MicroPEM filters may be analyzed for chemical composition of $PM_{2\cdot5}$, making this a logical future extension of the HAPCOG Study.

Our study's strengths include its moderately sized, well-characterized cohort, direct (rather than proxy) measures of child cognitive and neurobehavioral development, and two direct measures of $PM_{2\cdot5}$, personal and indoor. Gravimetric analyses of $PM_{2\cdot5}$ concentrations provided a sensitive and reliable measure of individual children's personal exposures to $PM_{2\cdot5}$ from HAP and AAP encountered outside the home as they went about their daily activities. We found that developmental assessment scores were more strongly associated with personal $PM_{2\cdot5}$ exposures than with household indoor $PM_{2\cdot5}$ levels and the impact of exposure was greater for male than female children. We also found that the use of household cooking fuel types, polluting versus clean, was significantly associated with personal $PM_{2\cdot5}$ exposures, and was marginally significantly associated with indoor $PM_{2\cdot5}$ levels. With regard to this last finding, we note that, for a portion of the households in this study, cooking was often done outside. Specifically, 49 % of households reported cooking outside either sometimes or always. This would tend to diminish the influence, in our analyses, of cooking fuel type on indoor $PM_{2\cdot5}$ levels. It also points to a limitation in some contexts of monitoring only household indoor $PM_{2\cdot5}$ levels as a means of quantifying individuals' personal exposures to $PM_{2\cdot5}$.

A further strength of our study was the depth and breadth of expertise in our team, including trained linguists, native Yoruba and English proficiency, deep local context knowledge, and African specialists in child cognitive and neurobehavioral development and methods of developmental assessment on our team to guide the work. We found differences in development that may be typical of children exposed to $PM_{2\cdot5}$ in this region of sub-Saharan Africa. Our study is the first undertaken in Nigeria of children's cognitive and neurobehavioral development in relation to their all-source, personal $PM_{2\cdot5}$ exposures during middle childhood. It contributes to building much-needed capacity for this kind of research in a country of 232 million in a region of sub-Saharan Africa where a significant majority of the population use polluting cooking fuels and particulate matter air pollution is a pressing public health concern. The study's limitations include its cross-sectional as opposed to randomized controlled trial design, reliance on assessments not normed for the study population, which necessitated using scores scaled to American norms; also, lack of teachers' reports of classroom learning, achievement, or behavior. An additional limitation is unmeasured confounders. These include factors such as home learning environment, sleep duration, school attendance, poor nutrition and presence of anemia, and exposures to pesticides and other pollutants common in the environment, for example, in soil and water, and in edible plants and animals. Another is exposures to heavy metals such as lead and manganese. While we acknowledge these limitations, we believe that the set of variables included in our analysis is sufficiently comprehensive to account for primary sources of potential confounding between the exposure groups. Finally, in regard to monitor wearing compliance, we note that our finding of a mean "waking" compliance of 57·5% hours per day (median 61·3%) means there is some uncertainty about the children's personal exposures for a mean 42.5 % of their waking hours (median, 38.7 %) and this is a limitation of our study. However, as noted above, this mean level of waking compliance is in the range reported for other studies with child participants. We note further that our 7-year-olds are in school for portions of each monitoring interval, presumably sitting still for periods of time. This may be true in other contexts of their days as well. Thus, uncertainty about waking wearing compliance stems also from limitations of accelerometer (movement) data as a measure of wearing. Finally, we addressed the possibility that low or variable wearing compliance might be a confounder in our assessment of the association of personal PM2·5 exposures and our measures of cognitive and neurobehavioral development. Inclusion of wearing compliance as a covariate in our multilinear regression model revealed that it was not.

4.5. Implications

Based on our results, we emphasize the virtue of employing direct measures of both personal $PM_{2\cdot5}$ exposures and indoor $PM_{2\cdot5}$ levels experienced by children whose neurodevelopmental outcomes are to be assessed and of estimating the contributions of each to adverse outcomes. To better understand biological mechanisms, additional studies are needed in varied geophysical regions of the world and diverse language/cultural contexts, with longitudinal perspectives from *in-utero* through adolescence and into adulthood. Further robust validation studies of developmental assessment instruments adapted for LMIC populations are also needed, together with systematic norming studies on target language/cultural populations.

This area of research promises improved understanding of the risks to child development posed by $PM_{2\cdot5}$ air pollution and of factors that may offer resilience in the face of burgeoning environmental threats to children's health. Broadening this research space to encompass a global perspective is essential for guiding LMIC public health policy making toward attainment of WHO goals for sustainable development.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

Data will be made available on request.

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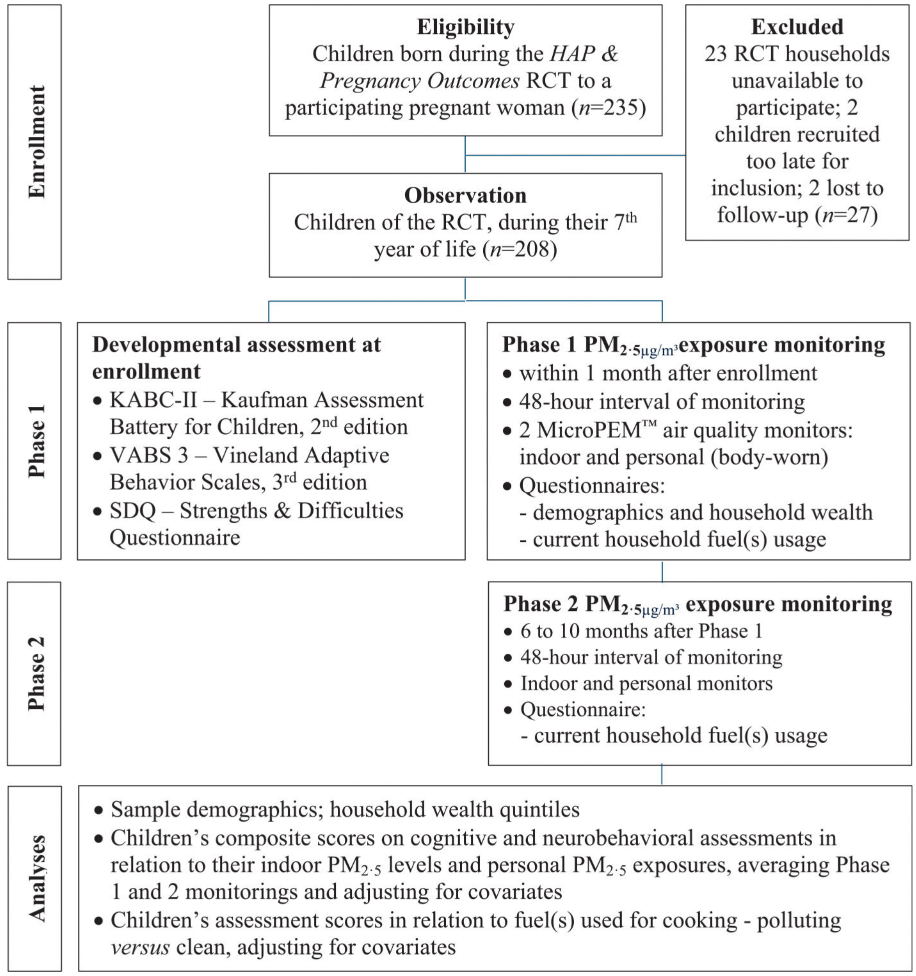


Fig. 1.

Study protocol.

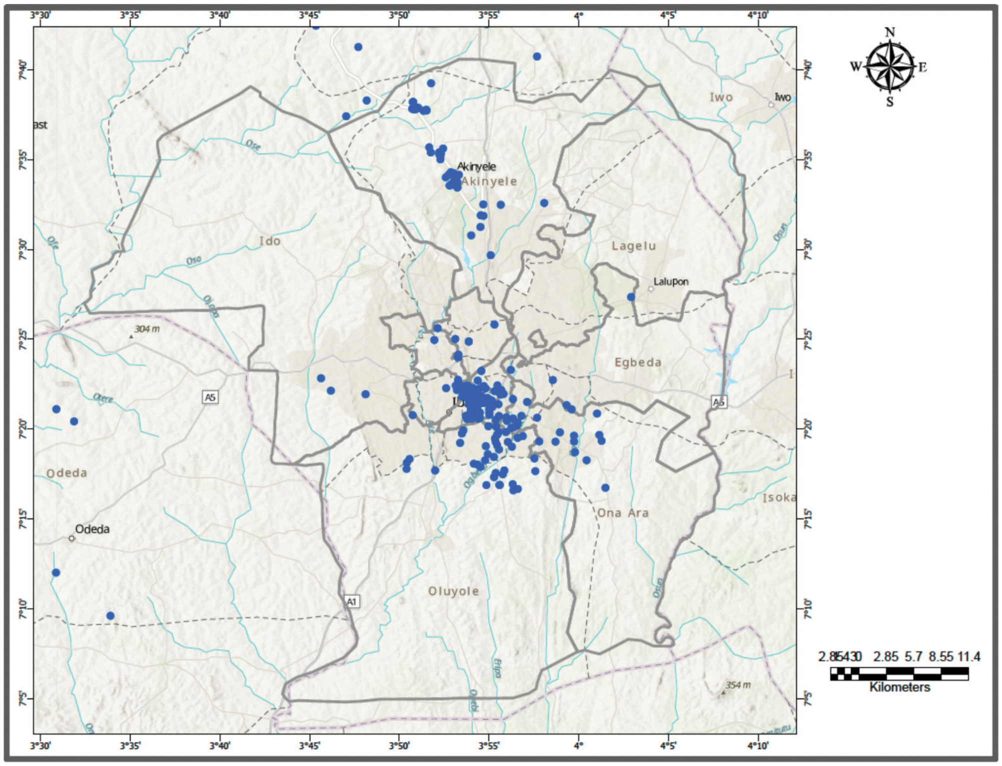
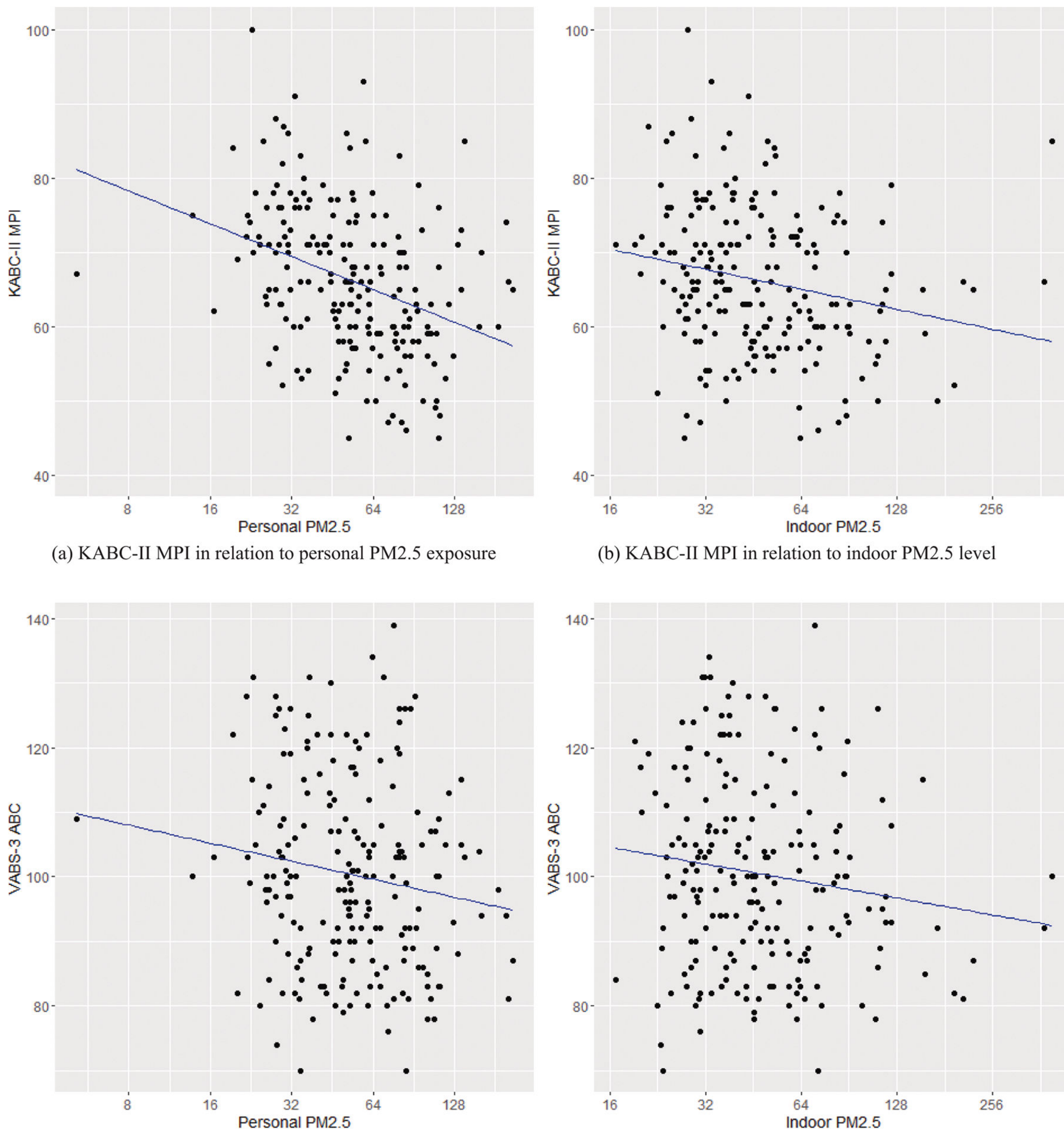


Fig. 2.

Locations of participating HAPCOG households on map of Ibadan, Nigeria, showing borders of the 11 local government areas (LGA) within the city's perimeter. (Software used: ArcGIS Pro 3.4. LGA boundaries obtained from Grid3.org. Elevation data from ESRI Atlas, esri.com.).



(a) KABC-II MPI in relation to personal PM2.5 exposure

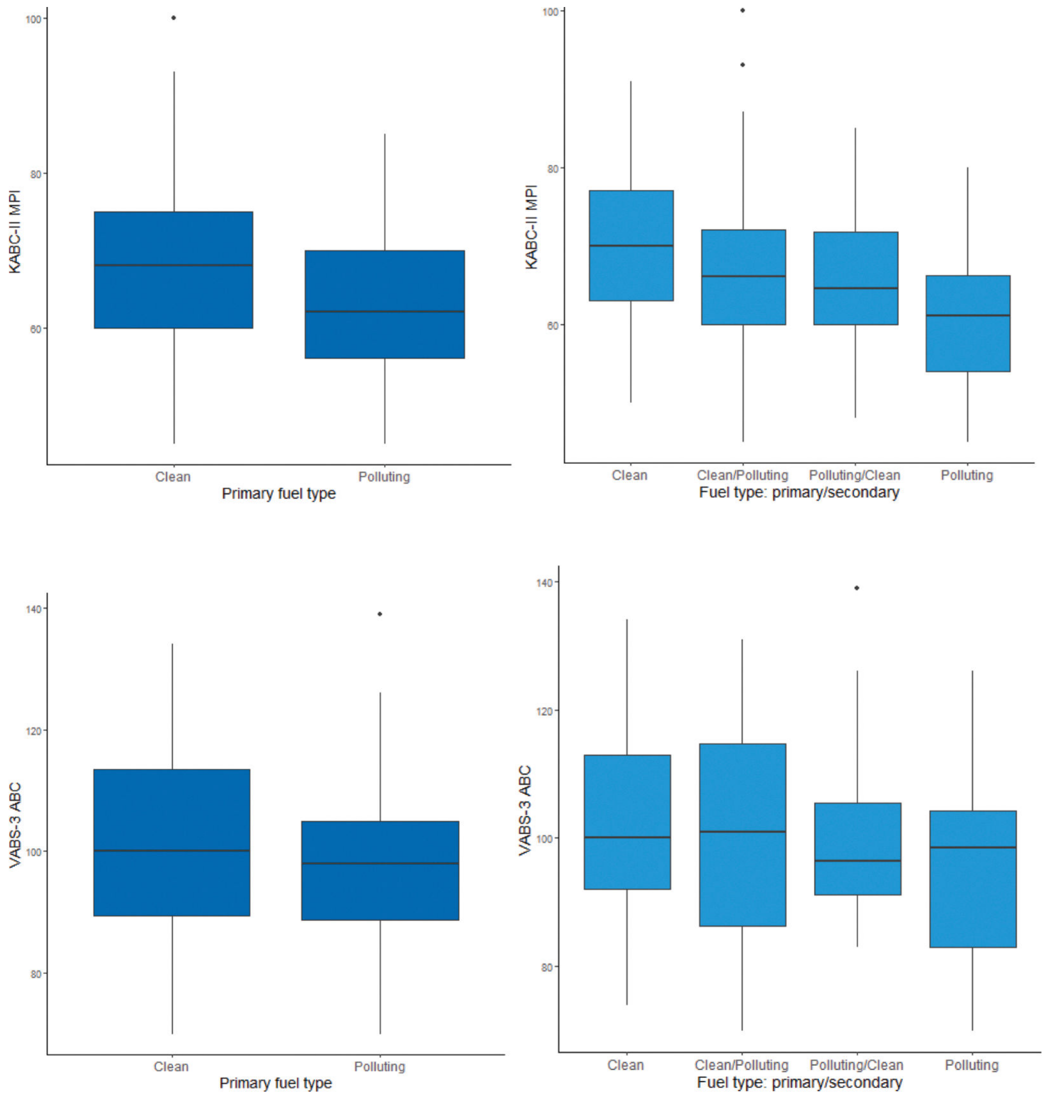
(b) KABC-II MPI in relation to indoor PM2.5 level

(c) VABS-3 ABC in relation to personal PM2.5 exposure

(d) VABS-3 ABC in relation to indoor PM2.5 level

Fig. 3.

KABC-II MPI and VABS-3 ABC developmental outcome measures in relation to indoor and personal $PM_{2.5}$ (μg/m^3) levels, with $PM_{2.5}$ displayed on a log2 scale on the X-axis.



(c) VABS-3 ABC in relation to household primary fuel type

(d) VABS-3 ABC in relation to household primary/secondary fuel type

Fig. 4.

KABC-II MPI and VABS-3 ABC neurocognitive outcome measures in relation to primary and primary/secondary cooking fuel types, from exclusively clean to exclusively polluting fuels.

Table 1

Sample characteristics of children and families, $PM_{2.5}$ (μg/m^3), and neurocognitive outcomes overall and stratified by the primary fuel type (clean vs. polluting). Counts and percentages for categorical variables and median and IQR for continuous variables.

	Level	Overall	Clean	Polluting	P
n		208	135	72	
Sex of child	Female	112 (53.8)	75 (55.6)	36 (50.0)	0.537
	Male	96 (46.2)	60 (44.4)	36 (50.0)	
Age of child		7.04 [7.00, 7.33]	7.08 [7.00, 7.42]	7.00 [7.00, 7.10]	0.05
Age of mother/caregiver		36.00 [32.00, 40.00]	36.00 [32.00, 40.00]	36.00 [32.00, 40.00]	0.866
Education of mother/caregiver	None	10 (4.8)	3 (2.2)	7 (9.7)	0.005
	Primary school	49 (23.6)	25 (18.5)	24 (33.3)	
	Junior secondary school	14 (6.7)	9 (6.7)	4 (5.6)	
	Senior secondary school	105 (50.5)	73 (54.1)	32 (44.4)	
	Polytechnic	26 (12.5)	22 (16.3)	4 (5.6)	
	University	3 (1.4)	3 (2.2)	0 (0.0)	
	Not reported	1 (0.5)	0 (0.0)	1 (1.4)	
Ability to read and write	No	52 (25.0)	27 (20.0)	24 (33.3)	0.044
	Yes	155 (74.5)	108 (80.0)	47 (65.3)	
	Not reported	1 (0.5)	0 (0.0)	1 (1.4)	
Marital status of mother/caregiver	Married	188 (90.4)	123 (91.1)	64 (88.9)	0.271
	Separated	9 (4.3)	6 (4.4)	3 (4.2)	
	Divorced	2 (1.0)	0 (0.0)	2 (2.8)	
	Widowed	7 (3.4)	5 (3.7)	2 (2.8)	
	Not reported	2 (1.0)	1 (0.7)	1 (1.4)	
Number of children in family	1–2	40 (19.2)	30 (22.2)	10 (13.9)	0.127
	3–4	105 (50.5)	69 (51.1)	35 (48.6)	
	5+	61 (29.3)	34 (25.2)	27 (37.5)	
	Not reported	2 (1.0)	2 (1.5)	0 (0.0)	
Remunerated	No	191 (91.8)	121 (89.6)	69 (95.8)	0.129
employment (mother)	Yes	15 (7.2)	13 (9.6)	2 (2.8)	
	Not reported	2 (1.0)	1 (0.7)	1 (1.4)	
Remunerated	no	150 (72.1)	95 (70.4)	54 (75.0)	0.398
employment (father)	yes	40 (19.2)	29 (21.5)	11 (15.3)	
	Not reported	18 (8.7)	11 (8.1)	7 (9.7)	
Household primary and secondary	Clean	53 (25.5)	53 (39.3)	0 (0.0)	–-
	Clean/Polluting	82 (39.4)	82 (60.7)	0 (0.0)	
fuel types	Polluting/Clean	28 (13.5)	0 (0.0)	28 (38.9)	
	Polluting	44 (21.2)	0 (0.0)	44 (61.1)	
	Not reported	1 (0.5)	0 (0.0)	0 (0.0)	
Household wealth Index quintiles	1st (poorest)	48 (23.1)	19 (14.1)	29 (40.3)	<0.001

	Level	Overall	Clean	Polluting	P
	2nd	48 (23.1)	27 (20.0)	21 (29.2)	
	3rd	31 (14.9)	18 (13.3)	12 (16.7)	
	4th	34 (16.3)	27 (20.0)	7 (9.7)	
	5th (wealthiest)	47 (22.6)	44 (32.6)	3 (4.2)	
Indoor PM2.5 overall	43.82 [31.72, 64.56]	40.35 [30.02, 61.13]	49.91 [34.48, 70.32]	0.032	
Indoor PM2.5 baseline	42.20 [29.49, 76.96]	38.80 [27.43, 73.45]	46.93 [33.12, 79.31]	0.123	
Indoor PM2.5 follow-up	38.89 [29.86, 59.06]	38.15 [27.60, 55.52]	40.90 [31.92, 65.07]	0.096	
Personal PM2.5 overall	53.12 [34.40, 79.60]	47.89 [31.27, 65.86]	64.05 [48.41, 83.67]	<0.001	
Personal PM2.5 baseline	49.92 [33.82, 89.07]	45.95 [29.46, 80.87]	61.13 [41.67, 103.55]	0.004	
Personal PM2.5 follow-up	50.93 [34.58, 81.10]	44.23 [31.70, 69.59]	67.94 [44.69, 101.96]	0.001	
KABC-II MPI	65.50 [59.00, 72.25]	68.00 [60.00, 75.00]	62.00 [56.00, 70.00]	0.001	
VABS-3 ABC	100.00 [89.00, 110.00]	100.00 [89.50, 113.50]	98.00 [88.75, 105.00]	0.093	
SDQ	18.00 [15.00, 21.00]	18.00 [14.00, 21.00]	18.00 [15.75, 21.25]	0.232	

Table 2

Indoor and personal $PM_{2.5}$ ($\mu g/m^3$) levels in relation to primary fuel type (Model 1) and primary and secondary fuel types (Model 2), unadjusted and adjusted for demographic factors: simple/multiple regression models.

Personal PM2.5			**Model 1**		**Model 2**	
	Geometric Mean (GM)		**Fold-change (FC)**		**Fold-change (FC)**	
	GM (95 % CI)	**P**	**FC (95 % CI)**	**P-val**	**FC (95 % CI)**	**P**
Primary fuel type						
Ref. Clean	**47.16 (43.1, 51.6)**					
Polluting	**64.99 (57.48, 73.48)**	**<0.001**	**1.26 (1.06, 1.49)**	**0.008**		
Primary/secondary fuel type						
Ref. Clean/Clean	44.7 (38.73, 51.60)					
Clean/Polluting	48.84 (43.49, 54.85)	0.348			1.05 (0.88, 1.27)	0.57
Polluting/Clean	**64.31 (52.79, 78.35)**	**0.004**			1.28 (1.0, 1.65)	0.056
Polluting/Polluting	**65.42 (55.89, 76.58)**	**0.001**			**1.32 (1.04, 1.67)**	**0.023**
Child’s Age			**0.97 (0.9, 0.99)**	**0.047**	0.97 (0.95, 1.00)	0.051
Child’s Sex						
Ref. Female	**48.81 (44.07, 54.06)**					
Male	**57.66 (51.68, 64.33)**	**0.029**	**1.19 (1.03, 1.37)**	**0.02**	**1.19 (1.03, 1.38)**	**0.02**
Mother/Caregiver’s Age			1.0 (0.98, 1.01)	0.65	1.0 (0.98, 1.01)	0.67
Mother’s Education			**0.93 (0.86, 0.99)**	**0.038**	**0.93 (0.86, 1.0)**	**0.046**
Household Wealth Index			1.0 (0.94, 1.05)	0.89	1.0 (0.94, 1.06)	0.95
Indoor PM2.5						
Primary fuel type						
Ref. Clean	44.91 (41.02, 49.17)					
Polluting	51.97 (45.93, 58.81)	0.063	1.08 (0.91, 1.28)	0.36		
Primary/secondary fuel type						
Ref. Clean/Clean	45.93 (39.72, 53.11)					
Clean/Polluting	44.27 (39.44, 49.70)	0.698			0.93 (0.77, 1.12)	0.44
Polluting/Clean	**58.83 (48.26, 71.70)**	**0.05**			1.15 (0.89, 1.48)	0.3
Polluting/Polluting	48.03 (41.02, 56.25)	0.683			0.95 (0.75, 1.21)	0.67

Personal PM2.5			Model 1		Model 2	
	Geometric Mean (GM)		Fold-change (FC)		Fold-change (FC)	
	GM (95 % CI)	P	FC (95 % CI)	P-val	FC (95 % CI)	P
Child's Age			**0.98 (0.96, 1.01)**	**0.26**	**0.98 (0.96, 1.00)**	**0.21**
Child's Sex						
Ref. Female	**44.29 (40.08, 48.94)**					
Male	**51.44 (46.20, 57.27)**	**0.046**	**1.19 (1.03, 1.38)**	**0.022**	**1.17 (1.01, 1.36)**	**0.038**
Mother/Caregiver's Age			0.99 (0.98, 1.0)	0.21	0.99 (0.98, 1.00)	0.17
Mother's Education			**0.91 (0.85, 0.98)**	**0.012**	**0.91 (0.85, 0.98)**	**0.012**
Household Wealth Index			1.02 (0.96, 1.08)	0.55	1.0 (0.95, 1.07)	0.77

Abbreviations: CI, confidence interval; GM, geometric mean; FC, fold change; P, p-value.

[*] Fold change in $PM_{2.5}$ level is calculated from simple/multiple regression models.

[**] Per unit increase in education levels from primary school, junior secondary school, senior secondary school, polytechnic, to university.

Table 3

Children's developmental assessment scores in relation to personal $PM_{2.5}$ ($\mu g/m^3$) exposures (Model 1) and indoor $PM_{2.5}$ levels (Model 2) unadjusted and adjusted for demographic factors: simple/multiple regression models.

	Unadjusted		Model 1		Model 2	
Variables	**Effect (95 % CI)**	**P**	**Effect (95 % CI)**	**P-val**	**Effect (95 % CI)**	**P**
KABC-II (Standardized)						
Personal PM2.5 (2-fold change)	**−4.43 (−6.04, −2.81)**	**<0.001**	**−3.04 (−4.62, −1.46)**	**<0.001**		
Indoor PM2.5 (2-fold change)	**−2.70 (−4.41, −0.99)**	**0.002**			−1.57 (−3.17, 0.04)	0.057
Child's Age	0.39 (−0.16, 0.94)	0.16	0.12 (−0.32, 0.56)	0.6	0.19 (−0.25, 0.63)	0.41
Child's Sex (Ref. Female)	−1.84 (−4.56, 0.87)	0.19	−1.69 (−4.14, 0.75)	0.18	−1.97 (−4.44, 0.51)	0.12
Mother's Age	0.04 (−0.20, 0.27)	0.76	0.12 (−0.09, 0.34)	0.25	0.13 (−0.08, 0.35)	0.23
Mother/Caregiver's Education *	**3.21 (2.12, 4.30)**	**<0.001**	**2.24 (1.05, 3.44)**	**<0.001**	**2.37 (1.16, 3.59)**	**<0.001**
Household Wealth Index	**2.48 (1.63, 3.33)**	**<0.001**	**1.35 (0.44. 2.26)**	**0.004**	**1.58 (0.66, 2.50)**	**0.001**
VABS-3						
Personal PM2.5 (2-fold change)	**−2.79 (−5.30, −0.29)**	**0.03**	−2.18 (−4.79, 0.43)	0.1		
Indoor PM2.5 (2-fold change)	**−2.63 (−5.20, −0.06)**	**0.046**			−1.73 (−4.34, 0.88)	0.2
Child's Age	−0.52 (−1.23, 0.18)	0.15	−0.68 (−1.40, 0.04)	0.064	−0.65 (−1.37, 0.06)	0.074
Child's Sex (Ref. Female)	−2.63 (−6.64, 1.38)	0.201	− 2.46 (−6.50, 1.57)	0.23	−2.80 (−6.82, 1.23)	0.18
Mother's Age	0.13 (−0.22, 0.48)	0.46	0.24 (−0.11, 0.59)	0.18	0.22 (−0.13, 0.57)	0.22
Mother/Caregiver's Education *	**2.60 (0.90, 4.29)**	**0.003**	**2.70 (0.73, 4.67)**	**0.008**	**2.91 (0.94, 4.88)**	**0.004**
Household Wealth Index	0.77 (−0.58, 2.12)	0.26	−0.05 (−1.55, 0.04)	0.23	−0.05 (−1.55, 1.23)	0.77
SDQ						
Personal PM2.5 (2-fold change)	0.38 (−0.41, 2.22)	0.35	0.27 (−0.56, 1.54) **	0.52		
Indoor PM2.5 (2-fold change)	0.13 (−0.66, 0.77)	0.75			−0.01 (−0.84, −0.03) **	0.99

Abbreviations: CI, confidence interval; P, p-value; KABC-II: Kaufman Assessment Battery for Children; VABS: Vineland Adaptive Behavior Scales; SDQ: Strengths & Difficulties Questionnaire.

* Per unit increase in education levels from primary school, junior secondary school, senior secondary school, polytechnic, to university.

** Adjusting for child's age, sex, mother's age, mother/caregiver's education, and household wealth index in multiple linear regressions.

Table 4

Children's developmental assessment scores in relation to in relation to primary fuel type (Model 1) as well as to primary and secondary fuel types (Model 2), unadjusted and adjusted for demographic factors: simple/multiple regression models.

			Model 1		Model 2	
	Means (95 % CI)	**P**	**Effect (95 % CI)**	**P**	**Effect (95 % CI)**	**P**
KABC-II (Standardized)						
Primary fuel type						
Clean (Ref.)	**68.01 (66.37, 69.65)**					
Polluting	**62.92 (60.67, 65.16)**	**<0.001**	−1.06 (−3.93, 1.82)	0.47		
Primary/secondary fuel type						
Clean/Clean (Ref.)	69.79 (67.22, 72.37)					
Clean/Polluting	66.85 (64.78, 68.92)	0.081			−1.42 (−4.55,1.71)	0.37
Polluting/Clean	66.36 (62.81, 69.90)	0.124			0.66 (−3.64, 4.97)	0.76
Polluting/Polluting	**60.73 (57.90, 63.55)**	**<0.001**			**−4.07 (−8.12, −0.02)**	**0.049**
Child's Age			0.24 (−0.21, 0.68)	0.3	0.20 (−0.25, 0.64)	0.39
Child's Sex						
Female (Ref.)	67.08 (65.24, 68.93)					
Male	65.24 (63.25, 67.23)	0.18	−2.41 (−4.89, 0.08)	0.059	**−2.77 (−5.27, −0.27)**	**0.03**
Mother/Caregiver's Age			0.14 (−0.08, 0.36)	0.21	0.12 (−0.09, 0.34)	0.26
Mother/Caregiver's Education *			**2.54 (1.32, 3.76)**	**<0.001**	**2.55 (1.32, 3.77)**	**<0.001**
Household Wealth Index			**1.39 (0.41, 2.36)**	**0.006**	**1.18 (0.19, 2.16)**	**0.02**
VABS-3						
Primary fuel type						
Clean (Ref.)	101.9 (99.42, 104.4)					
Polluting	98.01 (94.62, 101.4)	0.072	−2.76 (−7.38, 1.86)	0.24		
Primary/secondary fuel type						
Clean/Clean (Ref.)	103.19 (99.23, 107.2)					
Clean/Polluting	101.06 (97.88, 104.2)	0.412			−1.36 (−6.41, 3.69)	0.6
Polluting/Clean	99.61 (94.16, 105.1)	0.298			−1.37 (−8.30, 5.57)	0.7
Polluting/Polluting	**97.0 (92.65, 101.3)**	**0.039**			−5.45 (−11.98, 1.09)	0.1
Child's Age			−0.65 (−1.37, 1.86)	0.076	−0.69 (−1.41, 0.03)	0.063

			Model 1		Model 2	
	Means (95 % CI)	P	Effect (95 % CI)	P	Effect (95 % CI)	P
Child's Sex						
Female (Ref.)	101.72 (99.00, 104.4)					
Male	99.09 (96.15, 102.0)	0.2	−3.10 (−7.08, 0.89)	0.13	−3.41 (−7.44, 0.62)	0.099
Mother's Age			0.22 (−0.13, 0.57)	0.57	0.21 (−0.14, 0.56)	0.25
Mother/Caregiver's Education *			**2.98 (1.03, 4.94)**	**0.003**	**2.98 (1.01, 4.96)**	**0.003**
Household Wealth Index			−0.38 (−1.94, 1.19)	0.64	−0.56 (−2.15, 1.03)	0.49
SDQ						
Primary fuel type						
Clean (Ref.)						
Polluting			0.85 (−0.61, 3.08) **	0.26		
Primary/secondary fuel type						
Clean/Clean (Ref.)						
Clean/Polluting					1.27 (−0.33, 4.33) **	0.12
Polluting/Clean					1.81 (−0.38, 5.00) **	0.11
Polluting/Polluting					1.61 (−0.45, 4.61) **	0.13

Abbreviations: CI, confidence interval; P, p-value; KABC-II: Kaufman Assessment Battery for Children; VABS: Vineland Adaptive Behavior Scales; SDQ: Strengths & Difficulties Questionnaire.

* Per unit increase in education levels from primary school, junior secondary school, senior secondary school, polytechnic, to university.

** Adjusting for child's age, sex, mother's age, mother/caregiver's education, and household wealth index in multiple linear regressions.