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Relationships Between PM2.5 and Maternal Anemia in Sub-Saharan African Women of Reproductive Age

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Relationships Between $PM_{2.5}$ and Hemoglobin Among Reproductive Women in Africa

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Abstract

Preliminary evidence suggests air pollution, particularly fine particulate matter 2.5 ($PM_{2.5}$) poses a significant threat to maternal health and women of reproductive age. While emerging evidence suggests a link between air pollution and maternal anemia, the specific effect of $PM_{2.5}$ exposure on hemoglobin levels among reproductive-aged women (15-49 years) remains insufficiently studied. Maternal hemoglobin decline is a known risk factor for adverse pregnancy out-comes with potentially long-term consequences. Understanding the impact of $PM_{2.5}$ exposure is crucial in regions like Sub-Saharan Africa, where both anemia rates and air pollution levels are significantly elevated. This population-based study investigates the association between ambient $PM_{2.5}$ concentrations and maternal hemoglobin levels across 43 Sub-Saharan African countries from 2000-2019. Using generalized linear regression models adjusted statistically significant negative association between $PM_{2.5}$ exposure and hemoglobin levels were observed in Central Africa, while no significant associations were found in Eastern, Western, or Southern Africa. These results suggest that $PM_{2.5}$ may be an environmental determinant of maternal anemia, with effects that vary by geography. Further research is needed in understudied regions to validate and expand on these findings.

Keywords: maternal anemia; hemoglobin; reproductive health; women of reproductive age; $PM_{2.5}$; air pollution; Sub-Saharan Africa

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Introduction

Hemoglobin (Hb) is the protein contained in red blood cells that is responsible for delivery of oxygen to the tissues, and when the hemoglobin level is low, the patient has anemia[1]. Anemia is a condition in which the red blood cell count is decreased, impairing the body's ability to meet the oxygen needs of tissues becoming a public health problem[2] where women are some of the most affected; in 2019, the World Health Organization reported around 30% of women 15-49 years of age worldwide had anemia[3]. The WHO-defined hemoglobin (Hb) cut-offs, specific to age, sex, and pregnancy status, are most widely used to diagnose anemia, with the threshold being <120 g/L for non-pregnant and <110 g/L for pregnant women of 15–49 years of age[4]. Anemia also has a high association within low-income countries, notably in Africa, where, in 2019, an estimated 106 million women were affected by anemia[5].

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Among pregnant women, maternal anemia can cause symptoms such as headaches and fatigue along with more severe cases, hemoglobin levels <6g/dL, causing a possibility of more dangerous effects secondary to decreased tissue oxygenation[6]. Pregnant and lactating women are especially susceptible to decline in hemoglobin[7], thus, it is important to analyze all risk factors that may have an impact on this. Beyond this, low maternal hemoglobin levels during pregnancy can also cause lasting effects such as fetal deaths[6,8] and an increased risk of limited cognitive development for infants after birth[9]. There are many risk factors that have been associated with the prevalence of maternal anemia and maternal hemoglobin decline such as education[10], income[11], and diet[12], however, research on the association between maternal hemoglobin and environmental factors is in its infancy.

Only a handful of studies have shown the relationship between environmental pollutants and maternal hemoglobin or anemia. One study showed that exposure levels to PM_{10}, SO_2, and CO for one and two years were significantly associated with decreased hemoglobin concentrations (all $p < 0.05$)[13]. In this study, exposure levels to PM_{10}, for instance, had an OR of 1.039 [95% CI : 1.001–1.079], highlighting the link between air pollutants and decreased hemoglobin[13]. Additionally, carbon monoxide (CO) exposure during a two-year period was closely related to anemia OR = 1.046 [95% CI: 1.004–1.091][13]. On the other hand, a study involving particulate matter 2.5 ($PM_{2.5}$) found no association with anemia prevalence during the one year exposure period[13], yet other studies have found a negative association with hemoglobin levels which may contribute to maternal hemoglobin decline[14,15]. Fine toxic pollutants such as $PM_{2.5}$, primarily from vehicle emissions and industrial activities, are more likely to travel into and deposit on the surface of the deeper parts of the lung, which can induce tissue damage[16]. Furthermore, a previous study found that $PM_{2.5}$ particles can lead to a biological response due to motor emissions that can penetrate deep into the lungs, enter the bloodstream, and induce systemic inflammation[17,18]. Addressing these environmental factors and their impact on hemoglobin is crucial for improving maternal health outcomes and developing effective public health interventions.

This study aims to assess regional differences in the association between PM2.5 and maternal hemoglobin levels across Africa.

Methods

This is a population-based study for Africa from 2000-2019. Data for the annual mean prevalence hemoglobin (in grams per litre) of reproductive women between the ages of 15-49 years for 43 African nations is the outcome and was obtained from the World Health Organization (WHO). Data flow is shown in Figure 1. North Africa was excluded because WHO-reported hemoglobin data for women of reproductive age were incomplete for most North African countries between 2000 to 2019. This was noted in the revised Methods section. Aside from our primary outcome, exposure data for country-specific annual mean particulate matter 2.5 ($PM_{2.5}$) from 2000-2019 was obtained from World Bank: https://www.stateofglobalair.org/data/#/air/plot.

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Primary Data Sources

• WHO Prevalence (outcome)

• Air Pollution Database ($PM_{2.5}$ - Exposure)

↓

Inclusion of 46 countries with overlapping datasets of covariates

↓

Subregional stratification

• Western Africa
• Eastern Africa
• Central Africa
• Southern Africa

↓

Analytical pipeline

• Descriptive analyses
• Regression modeling

Figure 1. Schematic of work flow.

We included covariate data on country-specific annual mean air pollution (specifically household air pollutants as percentage), cereal yield (in tonnes per hectare), gross domestic product (GDP), prevalence of reproductive women with anemia (moderate levels), low body-mass index (<18.5 kg/m^2) of whole population, and annual trend.

We modelled the region-specific associations between the annual prevalence of reproductive women hemoglobin levels and annual $PM_{2.5}$ using generalized linear model, specifically negative binomial regression using autocorrelation order 1 (i.e. AR1). This is because the outcome's variance was much greater than its mean, leading to overdispersion of data. Model coefficients were exponentiated to be interpreted as rate ratios (RR) for each 10 μg/m^3 rise in pollution levels. 95% confidence intervals were evaluated at $P<0.05$ using Student's two-sided t-tests. Microsoft Excel (V.2021) and RStudio (V.4.1.1) were used for computation, analyses and figure composition.

Results

Over the twenty-year study period from 2000 to 2019, across 43 countries within four regions of Africa, the overall average prevalence of hemoglobin among reproductive-age women was 120.8 g/L. Geographically, this prevalence was lowest over Western Africa and highest over Southern Africa (Figure 2A). Annual mean $PM_{2.5}$ levels followed a similar geographic pattern, peaking in Western Africa throughout the study period (Figure 2B). The association between average annual reproductive maternal hemoglobin (modeled on the log scale) and the set of explanatory variables was analyzed separately for each region: West, East, Central, and South. Similarly, annual mean $PM_{2.5}$ concentrations were highest in West Africa, followed by Central Africa, with Eastern and Southern Africa showing lower levels throughout 2000-2019, showcasing a possible inverse correlation between the hemoglobin levels among reproductive women in Sub-Saharan Africa and annual mean $PM_{2.5}$ concentrations (Figure 2B). Additionally, the actual mean maternal hemoglobin concentration was 116.7 g/L in Western Africa, 124.3 g/L in Eastern Africa, 117.9 g/L in Central Africa, and 125.9 g/L in Southern Africa.

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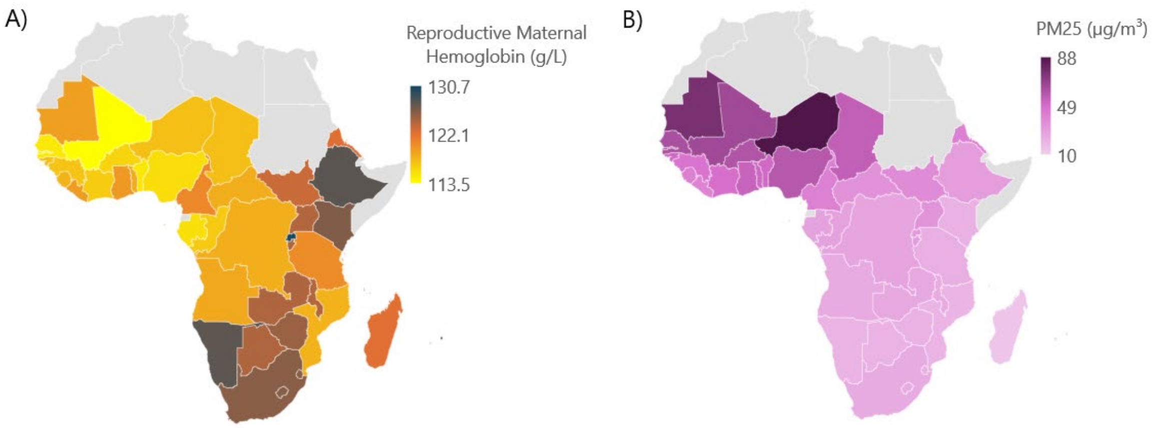

Figure 2. A) Annual country-specific reproductive maternal women (15-49 years) hemoglobin prevalence; B) annual mean $PM_{2.5}$ from 2000-2019.

Our models suggest that for each annual 10 μg/m³ rise in $PM_{2.5}$ the RR for reproductive maternal hemoglobin found was no association for Western, Eastern, and Southern Africa, yet only Central Africa had the significant results [RR 0.999 (P=0.035)].

The model for the West region indicated that $PM_{2.5}$ was not a statistically significant predictor of maternal hemoglobin (RR=1.000, P=0.70). In the East region, $PM_{2.5}$ also lacked a significant association (RR=1.000, P=0.91). This region, however, identified several significant predictors, including a positive association with agricultural cereal yield per hectare (RR=1.001, P=0.0002) and the GDP (constant with 2015 US dollar) was also found to be significant predictor (P=0.015).

Finally, the South region model did not show a significant association for $PM_{2.5}$, yet we did find a significant positive predictor for indoor house air pollution (P=0.02) and a rising trend in anemia prevalence annually (P=0.017).

The main findings (noted from Table 1) suggests that countries of Central African regions had a negative association between prevalence of maternal reproductive women and $PM_{2.5}$ from 2000-2019.

Table 1. Regional-specific association models for annual reproductive maternal hemoglobin and $PM_{2.5}$ from 2000-2019.

Region	Adjusted RR (P-value)*
West	1.000 (P=0.70)
East	1.000 (P=0.91)
Central	0.999 (P=0.035)
South	1.000 (P=0.24)

* adjust for household pollution, cereal yield, GDP, prevalence reproductive women anemia (moderate levels), underweight BMI, and trend.

Discussion

The results of our study found that only Central Africa is statistically significant in the effect of $PM_{2.5}$ on maternal hemoglobin levels, whereas other regions were insignificant, hence suggesting regional differences in Africa. In a past study that analyzed the pregnancy conditions of Chinese women [20-45 years, n=7932] delivering between 2015-2018, it was found that an increase in $PM_{2.5}$ concentration for all pregnant women (mean: 69.56 μg/m³, standard deviation: 15.24 μg/m³) by one interquartile range increase (19.37 μg/m³) was associated with a decrease in hemoglobin levels in multiparous women (mean age: 32.77±3.75 years, n=2609), but not for primiparous women (mean age: 28.78±3.25 years, n=5323)[14]. Exposure to $PM_{2.5}$ was associated with decreased hemoglobin in the third trimester of multiparous women, but not detrimental to the degree of being associated with anemia[14].

The link between $PM_{2.5}$ exposure and decreased maternal hemoglobin levels is believed to be driven by inflammation as a biological response[14]. $PM_{2.5}$ particles can deeply penetrate the lungs through motor emissions, enter the bloodstream, and trigger systemic inflammation, leading to oxidative stress and vascular dysfunction[17,18]. Pregnant and lactating women are especially vulnerable to hemoglobin decline, which has severe consequences for maternal health, and infant development, including impacts on cognitive function[7]. Additionally, a previous study also shows that decreased hemoglobin levels are linked to cardiovascular disease in pregnant women, which further worsens the effect of $PM_{2.5}$[19,20]. These factors underscore the importance of addressing $PM_{2.5}$ in strategies aimed at improving hemoglobin levels, particularly among maternal women in regions with poor air quality, such as Africa.

Several epidemiologic studies have confirmed that $PM_{2.5}$ harms pregnant women and leads to more severe impacts on hemoglobin levels[13]. It is confirmed based on availability of data that a mother with low hemoglobin was at risk of delivering a newborn with stunted growth[21]. Additionally, in Africa, a lack of dietary and malnutrition variety during pregnancy doubles the odds of developing maternal anemia, which in turn leads to low child birth weight and therefore low hemoglobin levels[22].

The association between $PM_{2.5}$ and maternal hemoglobin levels observed in this study is limited by confounding factors, such as exposure to other air pollutants like PM_1, PM_{10}, and NO_2, which have also been linked to decreased hemoglobin levels[12]. Since these pollutants are formed from emissions such as those from motor vehicles, it is difficult to isolate $PM_{2.5}$ from other pollutants that may also affect hemoglobin levels[16]. Moreover, socioeconomic status is another confounding factor that can influence both exposure to air pollution and access to healthcare, which further affects the relationship between $PM_{2.5}$ and hemoglobin levels[23]. The lack of nutrition education and iron rich food has been associated with decreased hemoglobin levels, which we were not able to control for[24]. This study does not fully reflect the true prevalence or severity of low maternal hemoglobin, and interventions may be less effective due to African areas with limited healthcare access[25].

Nevertheless, this study adds value to the literature that focuses on a specific region (i.e. Africa) - discussing the association between $PM_{2.5}$ and maternal hemoglobin[11]. This study highlights the regional variance and indicates that $PM_{2.5}$ is negatively associated with hemoglobin levels in maternal women. The study further helps to confirm our hypothesis that $PM_{2.5}$ increases the likelihood of maternal anemia. This is a concern since rising levels of $PM_{2.5}$ are exacerbated with further climate changes leading to clinical implications or reduced hemoglobin levels[26].

Conclusions

Our findings demonstrate that $PM_{2.5}$ exposure poses a region-specific risk factor for maternal hemoglobin decline and highlighted regional effects of $PM_{2.5}$ on maternal hemoglobin. This advances the current understanding of the relationship between environmental pollutants, particularly $PM_{2.5}$, to maternal hemoglobin levels, with a focus on regional dynamics throughout Sub-Saharan Africa. Our results underscore the need for a targeted, regionally informed strategy to mitigate the impact of $PM_{2.5}$ pollution on maternal health, broadened the scope to other low-income regions to determine whether this hypothesis holds true globally and addressing $PM_{2.5}$ exposure should be prioritized as a key element of maternal health strategies, particularly in regions burdened by environmental degradation and limited health infrastructure. If left unaddressed, the burden of reduced hemoglobin levels in women of reproductive age will likely persist and potentially worsen, exacerbating maternal mortality rates and perpetuating cycles of poor health in vulnerable communities. Without timely and region-specific interventions, these disparities may pose significant challenges to future public health efforts and policy implementation.

Additionally, the study can be used to collaborate with specific African regions' governments to create considerable and lasting regulations. These regulations may decrease the prevalence of anemia

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among maternal women, reducing the chances of maternal health complications that arise in response to exposure from $PM_{2.5}$.

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Institutional Review Board Statement: Ethical review and approval were **Not applicable** for this study due to due to the use of publicly available, anonymized data that does not involve direct interaction with human participants.

Data Availability Statement: Publicly available datasets were analyzed in this study. These data are available from the World Health Organization (WHO) and can be accessed at https://www.who.int/data. Access to specific datasets may require registration or approval from the WHO.

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