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Association of $PM_{2.5}$ With blood lipids and dyslipidaemia in a rural population of north-western china

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Background: Evidence regarding the association between particulate matter with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) and blood lipid levels is insufficient in the rural areas of developing countries. Few studies have estimated the role of $PM_{2.5}$ in blood lipid levels. We investigated the relationship between long-term exposure to $PM_{2.5}$, blood lipids, and dyslipidaemia in rural Chinese adults.

Methods: Baseline data of 15,802 participants (aged 35–74 years) in the China Northwest Cohort-Ningxia Project were used in this study. $PM_{2.5}$ levels were assessed using satellite remote sensing data in accordance with each participant's home address. Personally exposed $PM_{2.5}$ was defined as the 3-year mean concentration prior to the baseline survey. Logistic and linear models were utilised to quantify the associations of $PM_{2.5}$ with the prevalence of dyslipidaemia and with blood lipids, including total cholesterol (TC), triglyceride (TG), high-density lipoprotein cholesterol (HDL-C), and low-density lipoprotein cholesterol (LDL-C).

Results: The 3-year mean level of $PM_{2.5}$ was 35.36 ± 4.21 μg/m^3. Every 1-μg/m^3 increase in $PM_{2.5}$ was related to an increase of 0.04% (95% CI: −0.44–0.53%) in TG and decreases of 0.37% (95% CI: 0.16–0.90%) in TC, 5.76% (95% CI: 5.32–6.21%) in LDL-C, and 0.89% (95% CI: 0.72–1.05%) in HDL-C. Every 1-μg/m^3 increment in $PM_{2.5}$ was related with a 4% (95% CI:3–5%) and 18% (95% CI: 16–20%) higher risk of dyslipidaemia and hypoalphalipoproteinemia, respectively, and a decrease of 11% (95% CI:10–13%) in hyperbetalipoproteinemia. Sex, age, and BMI were adjusted for the relationships between $PM_{2.5}$, blood lipids, and dyslipidaemia.

Conclusion: Greater $PM_{2.5}$ exposure was related to harmful changes in blood lipids and dyslipidaemia. Male, elderly, and overweight individuals may be more vulnerable to the negative effects of $PM_{2.5}$.

KEYWORDS

$PM_{2.5}$, blood lipid level, dyslipidaemia, rural areas, cholesterol, north-western china

Abbreviations: SD, standard deviation.

Introduction

Dyslipidaemia refers to rising triglyceride (TG), total cholesterol (TC), and low-density lipoprotein cholesterol (LDL-C) levels, and a decrease in high-density lipoprotein cholesterol (HDL-C) levels. It is an essential but controllable risk factor for the prevalence of cardiovascular disease (CVD) outcomes (Toth, 2008; Franssen et al., 2011; Lee et al., 2012) and poses a serious threat to health in the general population. Evidence suggests that in 2012, the prevalence of hypercholesterolaemia, hypertriglyceridaemia, hypoalphalipoproteinemia, and hyperbetalipoproteinemia in China was significantly higher than 10 years earlier (Zhang M. et al., 2018). Air pollution poses a severe threat to China. The Global Burden of Disease Study showed nearly 1.1 million deaths from $PM_{2.5}$ exposure in China, in comparison with 88,400 deaths in the US (Cohen et al., 2017).

Ambient particulate matter (PM) is a serious public health problem worldwide. $PM_{2.5}$ has an aerodynamic diameter of ≤2.5 μm and is a crucial component of air pollution. Epidemiological studies have demonstrated that exposure to long-term $PM_{2.5}$ can cross the blood-brain barrier and directly enter the pulmonary alveoli and bloodstream, posing a severe health hazard (Feigin et al., 2016; Xu et al., 2016; Zhang M. et al., 2018; Xu et al., 2018).

Evidence from $PM_{2.5}$ and oxidative stress (Miller et al., 2012) may explain the relationship with an elevated risk of CVD events (Araujo, 2011). A previous study showed that lipids associated with PM_{10} exposure contribute to the development of CVD (Chuang et al., 2010). In another study, mice exposed to $PM_{2.5}$ displayed decreased plasma HDL and increased LDL oxidation and TG (Li et al., 2013). However, the present knowledge of the relationship between $PM_{2.5}$ and lipids (Chuang et al., 2011; Jacobs et al., 2011) in human studies is relatively limited. In addition, previous studies have examined the relationship between $PM_{2.5}$, abnormal lipid metabolism, and abnormal lipid metabolism (Poursafa et al., 2014; Shanley et al., 2016; Yitshak Sade et al., 2016; Wallwork et al., 2017; McGuinn et al., 2019). A study in the United States (US) reported that $PM_{2.5}$ was associated with increased TG, TC, HDL-C, and LDL-C levels (McGuinn et al., 2019). However, Wallwork et al. demonstrated that $PM_{2.5}$ does not correspond to an increased risk of hypoalphalipoproteinemia (Wallwork et al., 2017).

However, existing research has focused on the relationship between urban regions with relatively high pollutant levels of $PM_{2.5}$ and blood lipids (Li et al., 2021). Little evidence has been reported on the relationship between $PM_{2.5}$, blood lipid levels, and dyslipidaemia in a rural Chinese area exposed to relatively low levels of air pollution. $PM_{2.5}$ is an urgent problem in rural regions of China, and the relationship between long-term $PM_{2.5}$, blood lipids, and dyslipidaemia in rural populations with low $PM_{2.5}$, is unclear.

In this study, we explored the relationships among long-term $PM_{2.5}$, blood lipids, and dyslipidaemia in rural areas with low air pollution levels using baseline data from the China Northwest Cohort-Ningxia Project study.

Materials and methods

Study population

In the present study, we included a baseline of participants in the China Northwest Natural Population Cohort: Ningxia Project conducted from 2018 to 2019 (Zhang et al., 2021). Briefly, individuals were randomly collected from rural residents living in two counties (Pingluo and Qingtongxia), including four townships in Ningxia (https://www.resdc.cn/data.aspx?DATAID=200), a landlocked province in northwestern China (Figure 1). A total of 15,802 participants, aged 35–74 years, were recruited. Written informed consent was obtained from all participants before the survey. The study was approved by the "Ningxia Medical University Ethics Committee" (approval code:2018-012).

Data collection

Baseline data, such as demographic profiles and lifestyle (alcohol consumption, smoking, intake of vegetables and fruits, intake of meat and poultry, and physical activity), were collected using standardised questionnaires. According to Chinese dietary guidelines, intake of vegetables and fruit was defined as consumption of an average of 500 g of vegetables or fruit each day, and intake of meat and poultry was defined as a mean intake of 75 g of meat or poultry each day. Body fat was estimated using the body mass index (BMI).

Blood specimens were collected from participants over 8 h after their last meal. HDL-C and LDL-C levels were analysed using a direct determination method. TC was assessed using the cholesterol oxidase method and TG was assessed using an enzymatic process.

$PM_{2.5}$ exposure measurement

The concentration of $PM_{2.5}$ was predicted according to previous studies (Van Donkelaar et al., 2019; Hammer et al., 2020). The adjusted coefficient of determination and slope for annual prediction was 0.82 and 0.90, respectively. The participants were recruited from four townships. Long-term exposure was aggregated into 3-years average air pollution exposure prior to the start of the investigation. 5-years

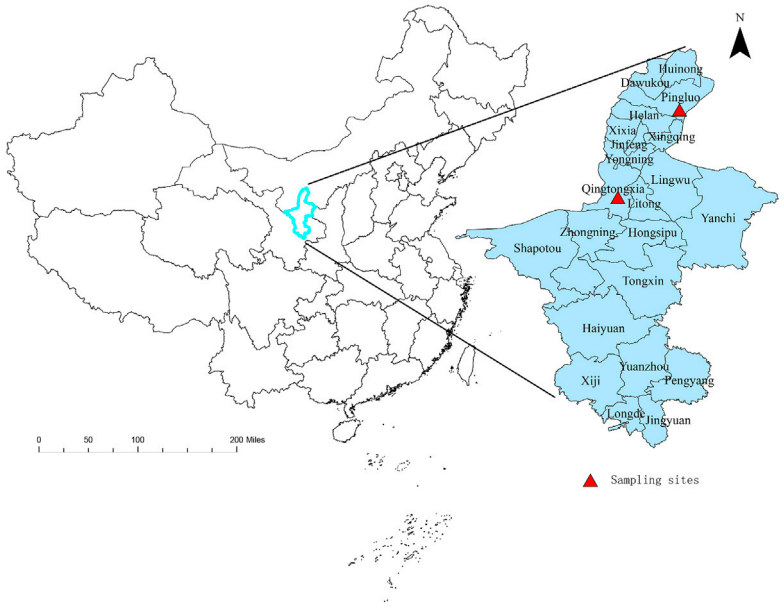

FIGURE 1
Location of sampling sites in the China Northwest Cohort-Ningxia Project Study.

average air pollution exposure was utilized in the sensitivity analysis.

Definition of dyslipidaemia

According to the Guidelines of Chinese Adult Prevention and Treatment Dyslipidaemia (2019), participants were defined as having hypercholesterolaemia with TC greater or equal to 6.22 mmol/L, hypertriglyceridaemia with TG greater or equal to 2.26 mmol/L, hypoalphalipoproteinaemia with HDL-C less than 1.04 mmol/L, and hyperbetalipoproteinaemia with LDL-C greater or equal to 4.14 mmol/L.

Statistical analysis

R4.0.3 software was utilized in this metabolic syndrome (MS), and the location of sampling sites in the China Northwest Cohort-Ningxia Project Study was described using ArcGIS 10.6 software. Multiple linear regression analyses were performed to quantify the associations between exposure to $PM_{2.5}$ and blood lipids (TC, TG, LDL-C, and HDL-C). Odds ratios (OR) with 95% confidence intervals (CI were evaluated using a binary logistic regression model to quantify associations between $PM_{2.5}$ and dyslipidaemia. Stratified analyses were employed to assess the modifying influences of sex, age, BMI, and lifestyle characteristics. Statistical significance was set at p value < 0.05.

Results

Descriptive statistics

Table 1 shows the basic characteristics of all individuals. In total, 6,334 men and 9,468 women were included in the study. The average age of individuals was 56.97 years, and the mean BMI was 24.97 kg/m^2. The mean levels of TG, TC, HDL-C, and LDL-C were 1.70, 4.86, 2.84, and 1.35 mmol/L, respectively. The prevalence of dyslipidaemia, hypercholesterolaemia, hypertriglyceridaemia, hypoalphalipoproteinemia, and hyperbetalipoproteinemia in this rural population was 31.99, 8.45, 18.66, 14.47, and 5.52%, respectively. Long-term $PM_{2.5}$ in our study was 35.36 ± 4.21 μg/m^3, ranging from 28.73 to 39.37 μg/m^3.

Association between $PM_{2.5}$ and blood lipids

Table 2 summarises the relationships between $PM_{2.5}$ and blood lipids. In the baseline model, higher $PM_{2.5}$ was related to an increase in TC and decreased TG, HDL-C, and LDL-C levels. In

TABLE 1 Characteristics of individuals in the Ningxia Rural Study.

Variables	Total (n = 15802)	Men (n = 6334)	Women (n = 9468)
Age (years), mean (SD)	56.97 (10.07)	58.83 (9.94)	55.72 (9.96)
BMI (kg/m^2), mean (SD)	24.97 (3.97)	24.96 (3.45)	24.97 (4.28)
Marital status, n (%)			
Married	14645 (92.68)	6001 (94.74)	8644 (91.30)
Unmarried/divorced/widowed	1157 (7.32)	333 (5.26)	824 (8.70)
Annual income, n (%)			
<10000 Yuan	3890 (24.62)	1587 (25.06)	2303 (24.32)
10000 Yuan ~	3815 (24.14)	1561 (24.64)	2254 (23.81)
20000 Yuan ~	3466 (21.93)	1413 (22.31)	2053 (21.68)
35000 Yuan ~	2041 (12.92)	757 (11.95)	1284 (13.56)
≥50000 Yuan	1795 (11.36)	747 (11.79)	1048 (11.07)
Unclear	795 (5.03)	269 (4.25)	526 (5.56)
Education attainment, n (%)			
Primary school or below	15198 (96.18)	5987 (94.52)	9211 (97.29)
Middle school	511 (3.23)	297 (4.69)	214 (2.26)
High school or above	93 (0.59)	50 (0.79)	43 (0.45)
Smoking status, n (%)			
Never	13420 (84.93)	4107 (64.84)	9313 (98.36)
Former	558 (3.53)	504 (7.96)	54 (0.57)
Current	1824 (11.54)	1723 (27.20)	101 (1.07)
Alcohol drinking status, n (%)			
Never	11988 (75.86)	3875 (61.18)	8113 (85.69)
Former	2803 (17.74)	1552 (24.50)	1251 (13.21)
Current	1011 (6.40)	907 (14.32)	104 (1.10)
High fat diet, n (%)	11598 (73.40)	4645 (73.33)	6953 (73.44)
Intake of adequate vegetable and fruit, n(%)	4164 (26.35)	1873 (29.57)	2291 (24.20)
Physical activity, n (%)			
Low	6129 (38.79)	2666 (42.09)	3463 (36.58)
Moderate	6236 (39.46)	2218 (35.02)	4018 (42.44)
High	3437 (21.75)	1450 (22.89)	1987 (20.99)
TC, mean (SD), mmol/L	4.86 (1.16)	4.72 (1.38)	4.96 (1.16)
TG, mean (SD), mmol/L	1.70 (1.26)	1.68 (1.21)	1.71 (1.11)
HDL-C, mean (SD), mmol/L	2.84 (0.39)	1.29 (0.41)	1.40 (0.37)
LDL-C, mean (SD), mmol/L	1.35 (1.09)	2.76 (0.92)	2.89 (1.18)
Dyslipidaemia, n (%)	5055 (31.99)	2202 (34.76)	2853 (30.13)
Hypercholesterolemia, n (%)	1336 (8.45)	390 (6.16)	946 (9.99)
Hypertriglyceridemia, n (%)	2949 (18.66)	1205 (19.02)	1744 (18.42)
Hypoalphalipoproteinemia, n(%)	2287 (14.47)	1313 (20.73)	974 (10.29)
Hyperbetalipoproteinaemia, n(%)	873 (5.52)	273 (4.31)	600 (6.34)

TABLE 2 Association between a 1-μg/m^3 increment of $PM_{2.5}$ and blood lipids.

Model	TC %Changes (95%CI)	TG %Changes (95%CI)	HDL-C %Changes (95%CI)	LDL-C %Changes (95%CI)
Baseline Model[a]	0.20 (-0.27,0.67)	−0.27 (-0.70,0.15)	−0.77 (-0.91,-0.63)	−6.27 (-6.66,-5.87)
Adjusted Model[b]	−0.37 (-0.90,0.16)	0.04 (-0.44,0.53)	−0.89 (-1.05,-0.72)	−5.76 (-6.21, -5.32)

[a]Covariates include age, sex, and body mass index.
[b]Covariates include age, sex, body mass index, marital status, education status, family income, smoking, alcohol consumption, adequate vegetable and fruit intake, high-fat diet, and physical activity.

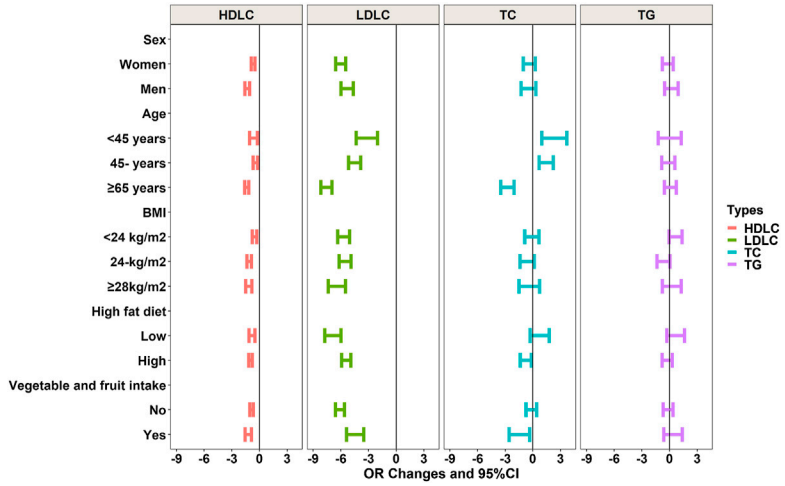

FIGURE 2
Interactions of age, sex, BMI, and lifestyle on relationships between $PM_{2.5}$ and blood lipids.

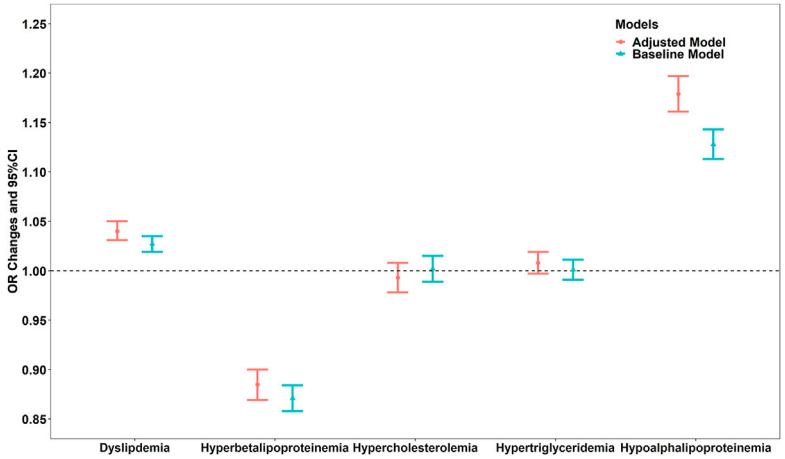

FIGURE 3
Association between a 1-μg/m^3 increment of $PM_{2.5}$ and dyslipidaemia.

the adjusted model, higher $PM_{2.5}$ was related to elevated TG levels and reduced TC, HDL-C, and LDL-C levels.

We tested the interactions among age, sex, BMI, and lifestyle characteristics (Figure 2; Supplementary Table S1). The effects of $PM_{2.5}$ were more robust in men than in women for LDL-C ($p < 0.05$). Interactions with age were associated with $PM_{2.5}$, TC, HDL-C, and LDL-C levels. The relationship between $PM_{2.5}$ and TC in individuals ≥65 years of age was significantly lower than in those aged <45 years. Furthermore, a modifying influence of BMI on the effects of $PM_{2.5}$ was present for TG, HDL-C, and LDL-C. Our study also showed that a high-fat diet could alleviate the associations between $PM_{2.5}$, TG, TC, and LDL-C. The intake of adequate vegetables and fruits adjusted the relationships between $PM_{2.5}$, TG, TC, and LDL-C.

Covariates are the same as in Table 2 above.

Association between $PM_{2.5}$ and dyslipidaemia

Figure 3 shows the relationship between $PM_{2.5}$ and dyslipidaemia. In the baseline and adjusted models, elevated $PM_{2.5}$ was related to an increased risk of dyslipidaemia and hypoalphalipoproteinemia and a reduced risk of

TABLE 3 Interactions of age, sex, and BMI on relationships between a 1-μg/m^3 increase of $PM_{2.5}$ and dyslipidaemia.

Characteristic	Dyslipidaemia OR (95%CI)	$P_{interaction}$	Hypercholesterolemia OR (95%CI)	$P_{interaction}$	Hypertriglyceridemia OR (95%CI)	$P_{interaction}$	Hypoalphalipoproteinemia OR (95%CI)	$P_{interaction}$	Hyperbetalipoproteinemia OR (95%CI)	$P_{interaction}$
Sex										
Male	1.07 (1.06, 1.09)		1.01 (0.98,1.03)		1.01 (0.99,1.03)		1.19 (1.17,1.22)		0.92 (0.89,0.95)	
Female	1.02 (1.01,1.04)	<0.001	0.99 (0.97,1.00)	0.117	1.01 (0.99,1.02)	0.378	1.17 (1.14,1.19)	<0.001	0.87 (0.85,0.89)	<0.001
age										
<45 years	1.04 (1.01,1.07)		1.04 (0.99,1.10)		1.00 (0.97,1.03)		1.15 (1.10,1.19)		0.953 (0.892,1.018)	
45- years	1.04 (1.03,1.06)	<0.001	1.03 (1.01,1.05)	0.013	1.01 (0.99,1.02)	0.330	1.142 (1.11,1.17)	<0.001	0.922 (0.90,0.95)	<0.001
≥65 years	1.04 (1.03,1.05)	<0.001	0.96 (0.94,0.97)	<0.001	1.01 (0.99,1.02)	0.288	1.2118 (1.19,1.24)	<0.001	0.86 (0.83,0.87)	<0.001
BMI										
<24 kg/m^2	1.06 (1.04,1.07)		1.00 (0.98,1.02)		1.03 (1.01,1.05)		1.18 (1.15,1.21)		0.89 (0.87,0.92)	
24-kg/m^2	1.02 (1.01,1.04)	<0.001	0.98 (0.96,1.00)	0.072	0.99 (0.98,1.01)	0.208	1.18 (1.15,1.21)	<0.001	0.87 (0.85,0.90)	<0.001
≥28 kg/m^2	1.05 (1.03,1.07)	<0.001	1.00 (0.98,1.03)	0.795	1.01 (0.99,1.03)	0.408	1.19 (1.16,1.23)	<0.001	0.89 (0.86,0.92)	<0.001
High-fat diet										
No	1.06 (1.04,1.08)		1.01 (0.98,1.04)		1.02 (1.00,1.04)	0.108	1.15 (1.12,1.19)		0.83 (0.80,0.86)	
Yes	1.04 (1.02,1.05)	<0.001	0.99 (0.97,1.00)	0.134	1.01 (0.99,1.02)	0.370	1.19 (1.17,1.21)	<0.001	0.90 (0.88,0.92)	<0.001
Intake of adequate vegetable and fruit										
No	1.04 (1.03,1.05)		1.00 (0.98,1.02)		1.01 (1.00,1.02)		1.17 (1.15,1.19)		0.87 (0.85,0.88)	
Yes	1.03 (1.01,1.05)	0.003	0.96 (0.93,0.99)	0.021	1.00 (0.98,1.03)	0.820	1.20 (1.16,1.24)	<0.001	0.94 (0.91,0.97)	<0.001

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hyperbetalipoproteinemia (see Figure 3; Supplementary Table S2). In the adjusted model, the OR (95% CI) for dyslipidaemia, hypoalphalipoproteinemia, and hyperbetalipoproteinemia were 1.040 (1.031–1.050), 1.179 (1.161–1.197), and 0.885 (0.869–0.900), respectively.

Table 3 shows the results of the interaction analyses between $PM_{2.5}$, dyslipidaemia, age, sex, BMI, and lifestyle factors. Men are more vulnerable to $PM_{2.5}$. For instance, the impact of $PM_{2.5}$ on dyslipidaemia in women (OR:1.02, 95% CI:1.01–1.04) was stronger than that in men (OR:1.07, 95% CI:1.06–1.09). The influence of $PM_{2.5}$ on dyslipidaemia, hypercholesterolaemia, hypoalphalipoproteinemia, and hyperbetalipoproteinemia was significant according to age. In addition, the intake of vegetables and fruit adjusted the relationships of $PM_{2.5}$, dyslipidaemia, hypertriglyceridaemia, hypoalphalipoproteinemia, and hyperbetalipoproteinemia.

Covariates are the same as in Table 2 above.

Sensitivity analyses

Compared with the results of previous studies, the relationships of $PM_{2.5}$, blood lipids, and dyslipidaemia were consistent in sensitivity analyses (see Supplementary Table S3, 4), and 1-year and 5-years $PM_{2.5}$ exposure was utilized.

Discussion

This study in a rural population of China provides new evidence regarding the harmful effects of long-term $PM_{2.5}$ exposure on blood lipids and dyslipidaemia, which has implications for preventing CVD. Greater long-term $PM_{2.5}$ was related to increased TC and decreased HDL-C and LDL-C levels. Greater $PM_{2.5}$ was also related to an elevated risk of dyslipidaemia and hypoalphalipoproteinemia, as well as a reduced risk of hyperbetalipoproteinemia. Our study implies that males, the elderly, and overweight individuals may be more susceptible to the harmful effects of $PM_{2.5}$.

$PM_{2.5}$ showed adverse effects on blood lipids and dyslipidaemia. The positive effects of $PM_{2.5}$ on TC level were similar. Our results are comparable to those reported by Zhang (Zhang, 2021). In an urban population of North China, the authors found that per 1-μg/m^3 increase in $PM_{2.5}$ corresponding to a 0.065% (95% CI:0.003–0.128%], 0.056% (95% CI: 0.033–0.079%), and 0.063% (95% CI:0.035–0.091%) increase in TG, TC, and LDL-C, respectively, and a 0.091% (95% CI: 0.068–0.113%) decrease in HDL-C. Our study findings showed that every 1-μg/m^3 increment of $PM_{2.5}$ was related to an increase in TG and non-significant decreases in TC, LDL-C, and HDL-C. This change implies that urban populations may be less susceptible to $PM_{2.5}$ than rural populations.

Several studies have evaluated the effects of $PM_{2.5}$. For instance, a study in Europe showed that $PM_{2.5}$ was related to increased TC and LDL-C (Sorensen et al., 2015). However, our findings regarding TC and TG levels are inconsistent with those reported in previous studies. Some studies have shown no relationship between $PM_{2.5}$, HDL-C, and the prevalence of hypoalphalipoproteinemia (Wallwork, 2017). However, other studies have shown that higher $PM_{2.5}$ exposure is associated with increased TC and LDL-C levels and reduced TG and HDL-C, with a higher risk of hypercholesterolaemia, hyperbetalipoproteinemia, and hypoalphalipoproteinemia (Mao, 2020). Laura et al. reported consistently elevated associations between long-term $PM_{2.5}$ and HDL-C (McGuinn et al., 2019). However, our study demonstrated that an increase in $PM_{2.5}$ was related to a decrease in LDL-C and HDL-C levels. Recent research has shown that statins, one of the most widely used lipid-lowering drugs, significantly reduce levels of LDL-C than TG (Awad et al., 2017). $PM_{2.5}$ and LDL-C could be associated with lipid-lowering drugs, even though we did not collect the exact drugs. Rats exposed to $PM_{2.5}$ develop atherosclerosis, which is correlated with cholesterol levels, oxidative stress, and inflammation. Atorvastatin significantly reduced the levels of LDL-C induced by $PM_{2.5}$ in rats (Yao and Lv, 2017). A previous study also found that serum HDL-C was reduced in the ApoE−/− mice after exposure to diesel exhaust particles (Qu et al., 2022).

There are several possible explanations for these discrepancies. First, different levels, compositions, and sources of air pollution may have diverse effects (Valavanidis et al., 2008). For example, large disparities in air pollution concentrations exist in diverse areas of China. Second, differences in the distribution of risk factors among populations may also account for these differences, including the way of life and health status (Cao et al., 2011). The participants of this study were from rural areas. The intake of meat, eggs, dairy, fish, and shellfish in rural populations is lower than that in urban populations (Guo et al., 2017). Additionally, lipid-lowering medications may influence the blood lipid levels (Awad et al., 2017).

The mechanism of lipid metabolism and the potential adverse effects of air pollution exposure remain unclear. Several potential pathways may be supported by existing evidence. Previous studies have suggested that long-term exposure to air pollution could induce oxidative stress and inflammation, interfere with lipid metabolism, and alter dyslipidaemia (Araujo and Nel, 2009; Xu et al., 2011; Shanley et al., 2016). Some evidence has demonstrated that air pollution can induce changes in DNA methylation of genes associated with lipid metabolism (Mendez et al., 2013; Bind et al., 2014; Chen et al., 2016). Differences in hazard factor distributions among participants may also illustrate these differences, including health status (Cao et al., 2011). As noted above, the dietary intake of

dairy, meat, and other foods is lower in rural residents than in their urban counterparts (Guo et al., 2017).

Sex and age may adjust for the toxic effects of $PM_{2.5}$ on blood lipid. This result is consistent with the findings (Shanley et al., 2016). Men have robust relationships between exposure to PM_{10} and TG and TC. Additionally, women living in urban areas have been found to be more susceptible to $PM_{2.5}$ exposure than men (Yang et al., 2018). However, our study findings implied that sex did not affect the relationships between $PM_{2.5}$, TC, and TG, which is consistent with the results of a previous study (Sorensen et al., 2015). Differences in the biological and lifestyle characteristics between men and women may be responsible for this difference. First, smoking and drinking may influence the effects of $PM_{2.5}$. In China, the rates of smoking and drinking are lower in women than in men, which can lead to a higher risk of dyslipidaemia. Moreover, most individuals in the present study were peasants. Male peasants in rural regions spend considerable time outdoors and are more heavily exposed to $PM_{2.5}$. Some studies have also suggested that long-term air pollution can activate oestrogen disruptors and play a vital role in the production of oxidative stress (Chen et al., 2013; Bell et al., 2017).

A previous study reported a greater susceptibility to $PM_{2.5}$ among older people (Yang et al., 2018). However, several studies have shown no modifying effects of age on the relationship between $PM_{2.5}$ and blood lipid (Sorensen et al., 2015; Shanley et al., 2016). Changes in body components associated with aging can induce numerous metabolic complications, resulting in pro-inflammatory conditions and interference with lipid metabolism (Liu and Li, 2015). This difference may be attributed to the utilisation of health services. Older people have low local health service utilisation, which may result in a greater toxic impact of air pollutants (Zhang X. et al., 2018).

Long-term dietary habits are strongly associated with air pollution, blood lipid levels, and dyslipidaemia. Unhealthy eating habits, including the consumption of more added sugar and fats, increase the prevalence of dyslipidaemia. In this study, we analysed the interactions of nutritional habits in the relationship between $PM_{2.5}$, blood lipids, and dyslipidaemia. Surprisingly, a high-fat diet was found to alleviate the relationship between $PM_{2.5}$, TC, HDL-C, and LDL-C in the current study. A similar study was conducted in a previous report (Lin et al., 2017), in which a high-fat diet was inversely related to high TC. The intake of vegetables and fruits was also shown to have a modifying effect. Studies have shown that consuming fruits and vegetables could mitigate the toxic health effects of outdoor air pollution owing to the high levels of carotenoids, vitamin C, and flavonoids, given the role of antioxidants in response to oxidative stress (Bowler and Crapo, 2002). Differences in food supplies, food choices, and dietary customs among different populations influence the intake of vegetables and fruits, which is linked to inadequate intake of antioxidants in rural areas (Jia et al., 2018).

Our study had several limitations. First, the major limitation is the cross-sectional design, which hinders us from drawing firm conclusions regarding causality. The results should be validated using a longitudinal method with repeated measurements. Second, the effects of other air pollutants should be considered, some of which may be highly correlated with our measures of interest (Chen et al., 2012). Third, although permanent rural residents were collected as individuals and we excluded those who had migrated to the study area within the 3 years prior to the investigation, the exact locations of some participants during the past 3 years were unknown. Additionally, we lacked information on individual levels that might affect exposure to $PM_{2.5}$, such as indoor exposure to pollutants, which might have induced exposure misclassification errors and underestimation of the associations.

Conclusion

In conclusion, this study demonstrated that long-term exposure to $PM_{2.5}$ was related to altered lipid levels and a higher risk of hypoalphalipoproteinemia and lower risk of hyperbetalipoproteinemia in rural regions of northwestern China. In particular, men and the elderly may be more susceptible to the toxic effects of air pollutants. More well-designed studies in the future are needed to confirm our findings because there are several limitations to this study.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving human participants were reviewed and approved by the study was Ethics Review Board of Ningxia Medical University (Ethics ID 2018-012). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

KW conceptualized the study and contributed to the acquisition of data, analysis, interpretation of data, and manuscript drafting. YZ analyzes, interprets data, and provides critical feedback on the manuscript. QW contributed to the interpretation of data. YZ contributed to the interpretation of data and provided critical feedback on the manuscript. YuZ contributed to manuscript and supervised the project.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.955279/full#supplementary-material

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