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Original Article

Evaluating the Effects of Long-Term Exposure to Fine Particulate Matter ($PM_{2.5}$) on Depressive Mood among Korean Older Adults Using Multilevel Analysis

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Abstract

Background: The harmful effects of particulate matter (PM) are amplified in older adults, who experience a decline in physiological function, reducing their ability to expel and detoxify inhaled PM. Moreover, older adults may be more vulnerable to fine particulate toxicity due to underlying medical conditions. We assessed the effects of long-term exposure to fine particulate matter ($PM_{2.5}$) on depressive mood (DM) in adults aged > 65 yr using community-based data.

Methods: In the 2017, Korean Community Health Survey (KCHS) data, data of $PM_{2.5}$ and community factors were constructed based on participants who responded to DM in a sample of 67,802 individuals. To evaluate the effect of $PM_{2.5}$ on DM among older adults, a multilevel regression model was constructed using individual- (KCHS) and community-level data ($PM_{2.5,}$ green area per capita, urban area, social welfare budget, health, and social business). For $PM_{2.5}$, an independent variable, quartiles were used to classify regions according to concentration.

Results: A positive correlation was found between $PM_{2.5}$ and DM of older adults. Compared to Q1, the odds ratio increased to 1.15 (95% CI 0.76-1.74) in Q2, 1.55 (95% CI 1.02-2.35) in Q3, and 1.60 (95% CI 1.16-2.20) in Q4.

Conclusion: DM may increase in older individuals living in areas with high $PM_{2.5}$. Systematic mental health management is required for older individuals residing in such areas.

Keywords: Depression; $PM_{2.5}$; Multilevel analysis; Korea community health survey; Older adults

Introduction

The population of older adults in South Korea is increasing. It is projected that by 2026, the proportion of older adults will reach 20.8%, which would result in the transition to a post-aged society (1). Older adults are expected to account for over 40% of the total world population by 2060, which would pose significant social challenges (2). Depression is common among older adults in aging societies (3). Depression is also the most prevalent mental disorder affecting over 300 million people worldwide. The number of people affected by depression increased by approximately 18% between 2005 and 2015 (4). According to the 2017 National Survey of Older Adults, 21.1%

of the older adult population in South Korea experiences depressive symptoms. Depression not only diminishes individuals' quality of life, but also increases the risk of chronic illnesses (5,6). Furthermore, depression is a powerful risk factor for suicide. About 59% of individuals who die by suicide have a history of depression (7).

Factors affecting depression include sociodemographic factors, health behaviors, and chronic diseases. Environmental factors, such as air pollution, have also been reported to have an impact on depression (2,3,8,9). Recently, uncontrolled industrialization and advancements in science and technology have worsened air pollution, especially in the form of PM, which poses a significant health risk to the population.

The harmful effects of PM can be amplified in specific vulnerable groups, including older adults, children, and individuals with underlying health conditions (10). Recent studies have raised increasing concerns about the adverse effects of $PM_{2.5}$ on psychological disorders in older adults. In the United States, $PM_{2.5}$ was significantly associated with anxiety symptoms (11), and another longitudinal analysis showed that $PM_{2.5}$ was associated with perceived stress levels in older men (12). Smaller particles can penetrate deeper into the lungs and cause damage to the alveoli (13). They can also affect the release of dopamine in the central nervous system, increasing depression and anxiety (8,11).

Studies assessing the health effects of air pollution often use time-series analysis, whereas cross-sectional studies use logistic regression. The data structure of the community health survey used in this study had a hierarchical structure, in which individuals were included in the community. Therefore, it is necessary to consider both individual- and community-level effects (14). Although some studies have used multilevel regression analysis based on community health survey data (15,16), studies using multilevel regression analysis to investigate the association between fine particulate matter ($PM_{2.5}$) and DM are lacking.

Therefore, this study aimed to determine the effects of long-term exposure to $PM_{2.5}$ on DM in older adults aged≥65 yr based on data from the 2017 Korean Community Health Survey (KCHS).

Materials and Methods

Study design

Overall, 67,802 adults aged ≥ 65 yr were selected from the KCHS 2017. To evaluate the impact of $PM_{2.5}$ on DM among the older adults, a multilevel regression model was constructed using individual- and community-level data. The individual-level data used the KCHS data, while the community-level data were built by adding environmental ($PM_{2.5}$) and e-local indicator data (Fig. 1).

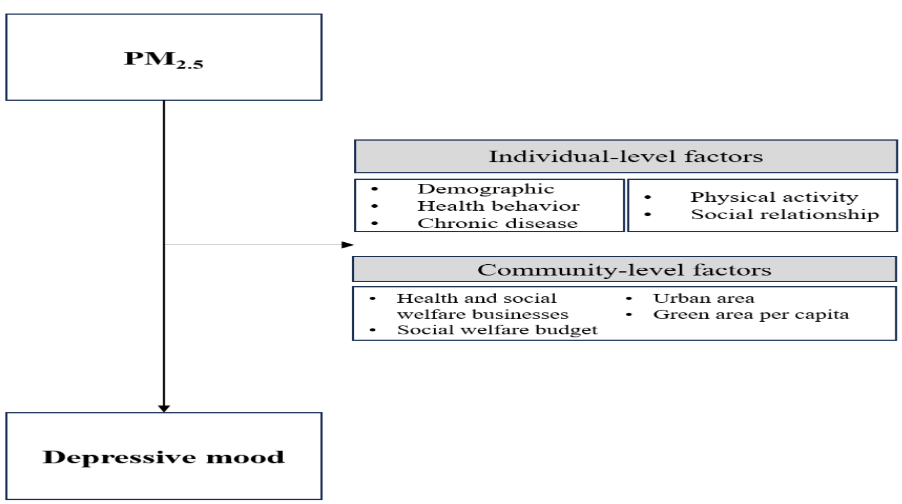

Fig. 1: Flow chart demonstrating the study findings

Study variables

Individual-level factors

This study utilized the 2017 KCHS data, conducted under the supervision of the Korea Centers for Disease Control and Prevention. The population is individuals aged 19 or older living in the community, and the sample size was calculated so that the main health indicators of each public health center had a desired sampling error of ±3% at a 95% confidence level (17). Additionally, the KCHS study was accompanied by the Korean Community Health Survey Quality Control and Evaluation (KCHS-QCE) study throughout the overall course of the survey. The purpose of KCHS-QCE is to establish a verification system for KCHS to ensure the accuracy and reliability of community health surveys (18).

The dependent variable was DM in the older adults. Participants were categorized as having experienced DM if they answered "yes" to the question "Have you ever felt sad or hopeless enough that it interfered with your daily activities for more than two consecutive weeks in the past year?"

The control variables were demographics, health behavior, and chronic diseases (8,9). Demographic factors included sex, age, level of education, marital status, living arrangements, monthly income, locality, and national basic livelihood recipient status. Health behavioral factors included smoking, alcohol consumption, physical activity (high-intensity exercise, moderate-intensity exercise, walking), body mass index (BMI), subjective health status, and sleep duration. Chronic diseases (hypertension, diabetes, dyslipidemia, arthritis) were categorized on the basis of whether they were diagnosed by a physician. In addition, we considered social relationship factors (trust between neighbors, social network) that may influence the relationship between $PM_{2.5}$ and DM (19).

Community-level factors

The independent variable was $PM_{2.5}$, and we used the annual average concentration from the Ministry of Environment's Annual Report of Ambient Air Quality in Korea, 2017. The average annual concentration was calculated using the 1-hour average data from 91 measuring stations distributed throughout the country (20). We used quartiles to convert the annual average $PM_{2.5}$ concentration into a categorical variable and divided it into four groups according to $PM_{2.5}$ level: 1st quartile (0-22.9), 2nd quartile (23.0-24.9), 3rd quartile (25.0-25.9) and 4th quartile (26.0-36.9)

The community-level control variables used were the e-local indicators provided by the Statistics Korea, and included: health and social welfare businesses, social welfare budget, urban area, and green area per capita. Control variables at the community-level were also used by converting continuous variables into quartiles (21).

Ethical considerations

The raw data were requested from the KCHS homepage (http: //chs.cdc.go.kr/), and were obtained with all private information remaining anonymous.

Statistical analysis

Rao-Scott Chi-Squared test was used to identify general characteristics at the individual (demographics, health behavior, and chronic diseases) and community (green area per capita, urban area, social welfare budget, health and social welfare businesses) level factors, and significant differences between variables according to DM status and regional distribution of $PM_{2.5}$. A multilevel logistic regression analysis was performed using the PROC GLIMMIX Procedure to determine the effect of $PM_{2.5}$ on DM in the older adults, and significance was set at $P<0.05$. All statistical analyses were performed using SAS ver. 9.4 (SAS Institute Inc., Cary, NC, USA).

Results

Overall, 67,802 participants aged ≥65 yr were included in this study, of whom 93.1% belonged to the non-DM group and 6.9% to the DM group. Demographic characteristics of the DM group showed the highest proportion of the following: females (9.6%), 75-79 yr age group (7.9%), no formal education (10.8%), 'no spouse' in marital status (10.5%), 'alone' in living arrangement (11.2%), 'less than 1 million' in monthly income (10.5%), 'rural' in region (8.2%), 'yes' in national basic livelihood recipient status (17.9%), 'no' in trust between neighbors (10.2), 'less than once a month' in social network relatives (relatives:10.2%, neighbors:9.5%, friends:9.7%). All variables showed significant differences (Table 1).

Table 1: Characteristics of study participants

Variable		*DM*		*P-value*
		Yes	No	
Sex				
	Male	1,342(5.6)	26,630(94.4)	<0.001
	Female	3,338(9.6)	36,492(90.4)	
Age (yr)				
	65-69	1,206(6.9)	17,835(93.1)	<0.001
	70-74	1,224(7.9)	16,106(92.1)	
	75-79	1,188(8.7)	15,254(91.3)	
	80-84	747(8.3)	9,426(91.7)	
	≥85	315(8.3)	4,501(91.7)	
Level of education				
	No formal education	1,909(10.8)	19,894(89.2)	<0.001
	Elementary school	1,521(8.3)	21,220(91.7)	
	Middle school	560(6.8)	9,006(93.2)	
	High school	514(6.0)	9,025(94.0)	
	College or higher	164(4.8)	3,900(95.2)	
Marital status				
	Spouse	2,355(6.4)	40,316(93.6)	<0.001
	No spouse	2,321(10.5)	22,764(89.5)	
Living arrangement				
	Alone	1,661(11.2)	15,831(88.8)	<0.001
	With spouse	1,809(5.9)	31,940(94.1)	
	With family or others	1,210(8.5)	15,344(91.5)	
Monthly income (1,000,000 KW)				
	< 1	2,903(10.5)	31,431(89.5)	<0.001
	1-2	862(6.4)	14,527(93.6)	
	2-3	459(6.8)	7,696(93.2)	
	≥ 3	423(5.3)	9,019(94.7)	
Locality				
	Urban	2,576(6.9)	39,004(93.1)	<0.001
	Rural	2,104(8.2)	24,118(91.8)	
National basic livelihood recipient status				
	Yes	606(17.9)	3,397(82.1)	<0.001
	No	4,072(7.2)	59,705(92.8)	
Trust between neighbors				
	Yes	3,239(6.8)	50,431(93.2)	<0.001
	No	1,242(10.2)	10,757(89.8)	
Social network, relatives				
	2-4 times a week	1,981(6.8)	30,659(93.2)	<0.001
	2-4 times a month	1,243(7.2)	18,064(92.8)	
	Less than once a month	1,452(10.2)	14,375(89.8)	
Social network, neighbors				
	2-4 times a week	2,816(6.9)	44,582(93.1)	<0.001
	2-4 times a month	605(7.6)	6,748(92.4)	
	Less than once a month	1,243(9.5)	11,668(90.5)	
Social network, friends				
	2-4 times a week	1,526(6.8)	25,338(93.2)	<0.001
	2-4 times a month	697(5.9)	11,113(94.1)	
	Less than once a month	2,437(9.7)	26.489(90.3)	

KW, Korean won
Values are presented as number (%).
Rao-Scott chi-squared test.

Health behaviors and chronic conditions of the DM group showed the highest proportion of the following: smokers (8.3%), non-drinkers (10.1%), 0 d of high-intensity exercise (8.0%), 0 d of moderate-intensity exercise (8.3%), 0 d of walking (10.3%), underweight (10.0%), poor subjective health (12.0%), and less than 6 h of sleep duration (11.6%). All variables showed significant differences except smoking status (Table 2).

Table 2: Health behavior and chronic diseases of study participants

Variable		*DM*		*P-value*
		Yes	No	
Smoking				
	Yes	417(8.3)	5,574(91.7)	0.364
	No	4,263(7.8)	57,548(92.2)	
Alcohol consumption				
	Yes	1,568(6.2)	26,697(93.8)	<0.001
	No	1,348(10.1)	14,267(89.4)	
High intensity exercise (days)				
	0	4,115(8.0)	55,373(92.0)	0.015
	1-2	166(6.0)	2,357(94.0)	
	≥3	395(7.4)	5,366(92.6)	
Moderate intensity exercise (days)				
	0	3,610(8.3)	45,500(91.7)	<0.001
	1-2	283(7.5)	4,175(92.5)	
	≥3	783(6.1)	13,420(93.9)	
Walking (days)				
	0	1,747(10.3)	19,863(89.7)	<0.001
	1-2	443(9.4)	4,937(90.6)	
	≥3	2,488(6.8)	38,297(93.2)	
BMI (kg/m²)				
	Healthy weight (18.5-24.9)	2,803(7.6)	39,564(92.4)	<0.001
	Underweight (<18.5)	834(10.0)	9,416(90.0)	
	Obese (25.0-30.0)	901(7.5)	12,786(92.5)	
	Severely obese (≥30.0)	142(9.5)	1,356(90.5)	
Subjective health status				
	Good	364(3.1)	12,494(96.9)	<0.001
	Average	986(5.0)	23,156(95.0)	
	Poor	3,330(12.0)	27,468(87.0)	
Sleep duration (h)				
	6-8	2,574(6.2)	44,409(93.8)	<0.001
	<6	1,779(11.6)	15,179(88.4)	
	>8	327(10.7)	3,534(89.3)	
Hypertension				
	Yes	2,722(8.3)	34,496(91.7)	0.002
	No	1,953(7.3)	28,605(92.7)	
Diabetes				
	Yes	1,180(8.7)	13,416(91.3)	0.001
	No	3,495(7.6)	49,679(92.4)	
Hyperlipidemia				
	Yes	1,499(9.4)	15,778(90.6)	<0.001
	No	3,148(7.2)	47,117(92.8)	
Arthritis				
	Yes	2,307(11.1)	21,630(88.9)	<0.001
	No	2,369(6.3)	41,461(93.7)	

BMI, body mass index; Values are presented as number (%); Rao-Scott chi-squared test

For community-level factors, the rate of experiencing DM increased as $PM_{2.5}$ increased from Q1 to Q4 in the DM group. Green area per capita was highest in Q2 and lowest in Q3, and urban area was highest in Q2 and lowest in Q1. Social welfare budgets were the highest in Q3 and lowest in Q1, and health and social welfare businesses showed an increase in DM from Q1 to Q4. All community level variables were statistically significant (Table 3).

Table 3: Community-level variables of study participants

Variable		*DM*			*P-value*
		M±SD	Yes	No	
$PM_{2.5}$					
	Q1	20.5±1.4	885(5.5)	15,431(94.5)	<0.001
	Q2	23.5±0.5	887(6.5)	13,977(93.5)	
	Q3	25.0±0.0	1,008(8.4)	12,745(91.6)	
	Q4	27.7±1.9	1,900(9.0)	20,969(91.0)	
Green area per capita (㎡)					
	Q1	39.2±27.8	984(8.2)	11,231(91.8)	<0.001
	Q2	236.4±90.0	983(8.9)	11,251(91.1)	
	Q3	530.4±120.1	1,202(6.6)	18,889(93.4)	
	Q4	1249.9±597.2	1,511(6.7)	21,751(93.3)	
Urban area (㎡)					
	Q1	14488276.4±5607055.8	1,291(6.5)	20,698(93.5)	<0.001
	Q2	34996113.0±6472813.8	1,381(8.3)	16,900(91.7)	
	Q3	75322883.4±21718459.6	1,092(8.2)	13,687(91.8)	
	Q4	236445585.0±107577057.0	916(8.0)	11,837(92.0)	
Social welfare budget (%)					
	Q1	17.4±1.9	1,464 (6.1)	23,575(93.9)	<0.001
	Q2	23.7±2.4	1,333(7.6)	17,648(92.4)	
	Q3	34.8±4.0	972(8.6)	10,534(91.4)	
	Q4	53.5±5.1	911(7.8)	11,365(92.2)	
Health and social welfare businesses (%)					
	Q1	2.7±0.5	1,068(6.6)	15,291(93.4)	<0.001
	Q2	3.4±0.1	1,020(7.8)	14,038(92.2)	
	Q3	3.8±0.1	1,230(8.2)	16,091(91.8)	
	Q4	4.6±0.4	1,362(8.3)	17,702(91.7)	

$PM_{2.5}$, particulate matter 2.5 micrometers or less in diameter
Values are presented as number (%).
Rao-Scott chi-squared test.

The associations between $PM_{2.5}$ and DM risk factors varied markedly. We found a statistically significant increase in the odds ratio (OR) [1.60 (95% confidence interval [CI], 1.16-2.20)] in Q4 in terms of $PM_{2.5}$. At the community level, we identified a significant decrease in the OR from Q1 to Q4 for health and social welfare businesses, with no clear trend for other variables (green area per capita, urban area, social welfare budget).

The OR of DM was higher in women (OR,1.45; 95% CI, 1.44-1.47) and it gradually decreased with increasing age. In terms of education, the OR of DM was highest among individuals with elementary school level education (OR, 1.03; 95% CI, 1.02-1.04). 'No spouse' status (OR,1.08; 95% CI, 1.07-1.10) was associated with a higher OR of DM; and for living arrangement, 'with spouse' (OR, 0.66; 95% CI, 0.61-0.72) was associated with a lower OR of DM. Also, '≥3 million' monthly income (OR, 0.68; 95% CI, 0.67-0.69) was associated with the lowest OR DM. Residing in urban (OR, 1.28; 95% CI, 1.27-1.30) rather than rural areas, and national basic livelihood recipiency (OR, 1.60; 95% CI, 1.58-1.61) were associated with a higher OR of DM.

The OR of DM increased with 'yes' of smoking

(OR, 1.35; 95% CI, 1.33-1.37), 'underweight' of BMI (OR, 1.15; 95% CI, 1.13-1.16), 'poor' of subjective health status (OR, 3.30; 95% CI, 3.26-3.34), and 'less than 6 h' of sleep duration (OR, 1.48; 95% CI, 1.47-1.49). For physical activity, more days of high-intensity exercise (OR, 1.49; 95% CI, 1.47-1.51) increased the risk of depression. However, more days of moderate-intensity exercise (OR, 0.93; 95% CI, 0.92-0.94) and walking (OR, 0.81; 95% CI, 0.81-0.82) decreased the OR of DM.

Hyperlipidemia (OR, 1.14; 95% CI, 1.13-1.15), and arthritis (OR, 1.26; 95% CI, 1.25-1.27) were associated with higher OR of DM.

The OR of DM increased when there was 'no' trust between neighbors (OR, 1.10; 95% CI, 1.09-1.11). Moreover, it was also found that the OR of DM increased as the number of interactions with others in the social network (relatives, neighbors, and friends) decreased (Table 4).

Table 4: Effects of $PM_{2.5}$ on DM in older adults using multilevel analysis

		OR	*95% CI*
Independent variable	$PM_{2.5}$ (/Q1)		
	Q2	1.15	0.76-1.74
	Q3	1.55	1.02-2.35
	Q4	1.60	1.16-2.20
Community-level	Green area per capita (/Q1)		
	Q2	1.14	1.12-1.17
	Q3	0.99	0.96-1.02
	Q4	1.33	1.29-1.37
	Urban area (/Q1)		
	Q2	0.93	0.92-0.94
	Q3	1.39	1.37-1.42
	Q4	1.14	1.11-1.17
	Social welfare budget (/Q1)		
	Q2	1.27	1.24-1.29
	Q3	1.45	1.43-1.47
	Q4	1.23	1.21-1.25
	Health and social welfare businesses (/Q1)		
	Q2	1.12	1.10-1.15
	Q3	0.97	0.94-0.99
	Q4	0.88	0.85-0.91
Individual-level	Sex (/Male)		
	Female	1.45	1.44-1.47
	Age (/65-69 yr)		
	70-74	1.02	1.01-1.03
	75-79	0.93	0.92-0.94
	80-84	0.82	0.81-0.83
	>85	0.67	0.66-0.68
	Level of education (/No formal education)		
	Elementary school	1.03	1.02-1.04
	Middle school	0.95	0.93-0.96
	High school	0.99	0.98-1.01
	College or higher	1.02	1.00-1.04
	Marital status (/Spouse)		
	No spouse	1.08	1.07-1.10
	Living arrangement (/Alone)		
	With Spouse	0.66	0.61-0.72
	With family or others	0.91	0.90-0.93
	Monthly income (/<1 million)		
	1-2 million	0.76	0.76-0.77
	2-3 million	0.84	0.83-0.85
	≥3 million	0.68	0.67-0.69
	Locality (/Rural)		
	Urban	1.28	1.27-1.30
	National basic livelihood recipient status (/No)		
	Yes	1.60	1.58-1.61
	Smoking (/No)		

Table 4: Continued…

Yes	1.35	1.33-1.37
Alcohol consumption (/No)		
Yes	0.78	0.78-0.79
High intensity exercise (/0 day)		
1-2	1.02	1.00-1.04
≥3	1.49	1.47-1.51
Moderate intensity exercise (/0 day)		
1-2	1.25	1.23-1.26
≥3	0.93	0.92-0.94
Walking (/0 day)		
1-2	1.03	1.02-1.05
≥3	0.81	0.81-0.82
BMI (/Healthy weight)		
Under weight	1.15	1.13-1.16
Obese	0.93	0.92-0.93
Severely obese	1.03	1.01-1.06
Subjective health status (/Good)		
Average	1.43	1.41-1.45
Poor	3.30	3.26-3.34
Sleep duration (h) (/6-8)		
>6	1.48	1.47-1.49
>8	1.45	1.43-1.47
Hypertension (/No)		
Yes	0.93	0.93-0.94
Diabetes (/No)		
Yes	0.93	0.93-0.94
Hyperlipidemia (/No)		
Yes	1.14	1.13-1.15
Arthritis (/No)		
Yes	1.26	1.25-1.27
Trust between neighbors (/Yes)		
No	1.10	1.09-1.11
Social network, relatives (/2-4 times a week)		
2-4 times a month	1.12	1.11-1.13
Less than once a month	1.34	1.33-1.35
Social network, neighbors (/2-4 times a week)		
2-4 times a month	1.11	1.09-1.12
Less than once a month	1.24	1.22-1.25
Social network, friends (/2-4 times a week)		
2-4 times a month	0.84	0.83-0.85
Less than once a month	1.11	1.10-1.12

PM2.5, particulate matter 2.5 micrometers or less in diameter (Q1:0-22.9 ㎍/㎥, Q2:23.0-24.9 ㎍/㎥, Q3: 25.0-25.9 ㎍/㎥, Q4:26.0-36.9 ㎍/㎥); CI, confidence interval; OR, Odds ratio; BMI, body mass index; Values are presented as OR (95% CI)

Discussion

We used multilevel logistic regression to determine the impact of long-term exposure to $PM_{2.5}$ on DM in older adults, which allowed us to account for both the individual- and community-levels. First, we found a positive association between $PM_{2.5}$ and DM in older adults. We also found that the risk of DM increased toward the highest $PM_{2.5}$ area (Q4). An increasing number of studies have reported on the association between PM and mental disorders (8,9,19). In particular, our findings are supported by the finding that the risk of DM increases as $PM_{2.5}$ concentration increases in older adults (22,23). In the case of older individuals, the physiological functions of the body are reduced, and when PM is inhaled, its ability to discharge the PM outside the body and remove toxicity is reduced (24). In addition, since majority of the older individuals already have underlying diseases, they may be more vulnerable to PM toxicity due to low resistance (25).

PM affects depression through three main mechanisms. First, it migrates to the brain tissue through the olfactory bulb and causes an inflammatory response (26). Second, it invades the nasal epithelial cells in the nasal cavity, causing inflammation and damage to the brain tissue. Third, PM not removed by mucous cells can reach the alveoli, cause inflammation, and secrete cytokines to promote inflammation, thereby affecting the nervous system in older adults (27). In addition, smaller is the size of the PM, the easier it is for it to reach inside the body. Therefore, the risk of $PM_{2.5}$ can be greater than that of PM_{10} (28).

Second, for community-level variables, the risk of DM decreased as the proportion of health and welfare services increased. Health and social welfare businesses refer to the percentage of these out of all businesses (21). The higher is the ratio of health and social welfare businesses, the more hospitals and welfare facilities are concentrated, the easier it is to access medical facilities, and the higher is the quality of medical and welfare services. Therefore, there is a tendency to control one's health and frequently engage in health behaviors. In contrast, the older adults in areas with poor health and welfare facilities tended to have a high number of chronic diseases, less healthy behavior, and generally reported a high level of DM, confirming results similar to those of a previous study (29). In other community-level variables, a heightened risk of DM was observed in areas with elevated $PM_{2.5}$ levels. Notably, the per capita green area represents the total green space within the region, thus necessitating consideration when interpreting these results.

Third, in terms of the social relationship factors, the risk of DM increased when there was no trust between neighbors. Relationships with neighbors have been reported to have a direct depression-protective effect and act as buffer stressors (30). In addition, individuals in a social community receive emotional and social help from the people around them, and the risk of DM can be reduced. Relationships that continuously interact socially (like family, friends, neighbors) are called social networks (31). In this study, the risk of DM increased as the number of interactions with social networks decreased. For older adults, social networks gradually decrease, social isolation and loneliness increases, and the level of DM may increase (32).

Fourth, in the case of individual-level variables, the risk of depression was high in female (2,3,9,22,33,34), no spouse (33,34), urban (34), national basic livelihood recipiency (22), smoking (22), poor subjective health (33,34), sleep disorder (33). Additionally, in factors of physical activity, the risk of DM decreased with an increase in the number of days of moderate-intensity exercise and walking. Appropriate physical activity affects the secretion of serotonin and brain substances such as endorphins, which reduce negative thoughts, can help improve mental health, and alleviate DM (35). Contrastingly, in the case of high-intensity exercise, the risk of DM increased with the number of days. Both low- and high-intensity physical activity reduces depression (35). Depression decreases with an increase in leisure physical activity (35). However, the physical activity items used in this study included leisure and occupational activities, so the mental impact of high-intensity occupational activities may have had some effect. Therefore, it is difficult to conclude whether high-intensity exercise increases depression. Furthermore, the risk of DM decreased with increasing age. However, as previous studies have shown contrasting trends, further research is needed to elucidate age-specific effects among older adults (36).

This study had some limitations. First, for $PM_{2.5}$ data collection in 2017, the measurement stations were concentrated in the metropolitan areas and large cities. Thus, areas without measurement networks were replaced by values located at the nearest straight-line distance on the map (37). Thus, there is a possibility that the $PM_{2.5}$ concentration to which an individual is actually exposed may differ slightly. Therefore, it is necessary to install a measurement network in all administrative districts in the future. Second, DM refers to a state in which it persists for a certain period, and caution is needed when interpreting depression and DM (38). Third, the study classified regions according to the long-term exposure level of $PM_{2.5}$ in 2017 and confirmed the effect on regional DM. Therefore, it is difficult to explain the causal relationship between $PM_{2.5}$ and DM.

The strength of this study is that DM was selected as the dependent variable. Moreover, a group with vulnerable mental health was selected, and the influence of $PM_{2.5}$ was identified to confirm meaningful results. In addition, the effect of $PM_{2.5}$ on DM was analyzed at multiple levels. Furthermore, the effects of $PM_{2.5}$ on the DM of older individuals were comprehensively evaluated considering various factors.

Conclusion

DM might increase among older adults living in areas with high levels of $PM_{2.5}$. Therefore, it is necessary to establish systematic mental health care and activate social networks for older adults living in regions with a high risk of $PM_{2.5}$ exposure. Furthermore, further research is needed to explore the factors influencing the relationship between DM in older adults in areas with elevated $PM_{2.5}$ levels, which will provide a more accurate understanding of the impact of $PM_{2.5}$ on the mental health of older adults in South Korea.

Journalism Ethics considerations

Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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Conflict of interest

The author declares that there is no conflict of interest.

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