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Original Research Article

# Early-life residential greenness and sleep disturbances in preschoolers across 551 cities of China

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ABSTRACT

The nexus between early-life residential greenness and sleep health in children remains underexplored. This research investigated associations of early-life greenness exposure with sleep outcomes among 101,879 preschoolers from 551 Chinese cities. Sleep status was evaluated using the Children's Sleep Habits Questionnaire (CSHQ). Greenness was estimated using satellite-derived Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) surrounding participants' home during pregnancy and post-birth period. Linear mixed-effect and random-effects logistic regression models were used to assess associations of greenness with CSHQ scores and sleep disturbance, respectively. Mediation effects of air pollution and residential distance to major roads were examined. Both prenatal and postnatal greenness exposures were significantly associated with better sleep outcomes. Specifically, an interquartile range increment in NDVI within the 250-m buffer during the entire pregnancy and from birth to investigation was associated with reductions in the total CSHQ score by 0.21 (95% confidence interval [CI]: 0.14, 0.28) and 0.22 (95% CI: 0.15, 0.29), respectively. Corresponding odds ratios for sleep disturbance were 0.96 (95% CI: 0.94, 0.98) for both periods. These associations remained consistent when considering larger buffers (500-m and 1000-m), and employing other greenness metrics like EVI and growing-season NDVI. The association between postnatal greenness exposure and sleep disturbance was partially mediated by $PM_{2.5}$, residential distance to major roads, $NO_2$, and $SO_2$. Children living in Northern China, breastfed for <6 months, or with more educated mothers showed greater benefits from greenness. Increased early-life greenness exposure appears to positively influence childhood sleep health.

## 1. Introduction

Adequate and restful sleep is crucial for the growth and developmental well-being of children. Children's sleep needs are substantially greater than those of adults, with newborns spending up to 80% of their time sleeping, and a majority of toddlers and preschoolers allocating over half of their time to sleep [1]. However, pediatric sleep disturbances are prevalent, affecting approximately 25%–40% of children at some point in their early years [2,3]. The consequences of poor sleep quality and sleep problems during early childhood are profound, influencing physical growth [4], increasing the risk of obesity [5], impairing neurobehavioral functioning [6], leading to poor academic performance [7], and potentially extending into later childhood and adulthood. Identifying risk/protective factors of childhood sleep quality is therefore essential for guiding health initiatives aimed at mitigating potentially preventable adverse health outcomes.

Green environment is increasingly recognized as a critical environmental factor influencing sleep health [8]. To effectively enhance sleep health, the establishment and enhancement of greenness is emerging as a promising environmental intervention. Greenness-related benefits on

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childhood sleep may involve multiple pathways, including but not limited to facilitating mental fatigue recovery, restoring attention, reducing stress, and fostering positive emotions, in accordance with the “biophilia hypothesis” [9].

Previous studies have linked greenness exposure to sleep-related outcomes among children [10–17]. However, most of the available evidence is concentrated in Europe and North America and predominantly involves children over the age of 6. For example, Singh et al. [11] reported a significant association between limited parent-reported exposure to green space, such as neighborhood parks, and inadequate sleep duration in children aged 6–17 years residing in America. Similarly, Dzhambov et al. [17] found that greenspace, especially home gardens, was associated with fewer sleep problems—such as difficulty falling asleep, restless sleep, and morning fatigue—among children aged 8–12 years residing in Austria and Italy. In contrast, research on this topic in rapidly urbanizing countries, such as China, remains sparse. To our knowledge, the only study in China, conducted in Guangzhou with a small cohort of 410 two-year-old toddlers, evaluated the relationship between greenness exposure and sleep quality and duration but reported no significant associations [18]. Given the limited and regionally concentrated evidence, there is a need for large-scale, nationally representative epidemiological studies in rapidly urbanizing contexts such as China. Furthermore, focusing on toddlers and preschool-aged children is particularly important, as this age group has been understudied and exhibits distinct sleep and activity patterns.

Using a nationwide cohort of over 100,000 preschoolers in China, this study quantified the associations of greenness exposure during both prenatal and postnatal periods with various aspects of early childhood sleep, including quality, symptoms of sleep disorders, and disturbances. Additionally, this study evaluated the mediation effects of environmental exposures and effect modifications by sex, maternal education level, region, breastfeeding status, and neonatal intensive care unit admission.

## 2. Methods

### 2.1. Study population and study design

This study used data from the Chinese National Cohort of Motor Development (CNCMD), which was originally conducted to investigate the neurobehavioral development and sleep status among Chinese preschoolers, along with the factors impacting these aspects. Participants were recruited from 551 county-level cities across China (Fig. S1) using a stratified cluster sampling method. Stratification was based on geographic region, age, sex, and socioeconomic status from China's 2018 to 2019 National Census. Specifically, the sampling design considered four regions (Eastern, Central, Western, and Northeastern China), two sexes (male and female), and three parental education levels (middle school or below, high school, and college or above), covering all preschool age groups. The cohort included only children attending public kindergartens, excluding those with severe visual, hearing, or intellectual impairments or other significant developmental disorders. Sampling weights were applied based on the proportion of public kindergartens in each region to enhance representativeness. Children from local kindergartens were invited to participate through the collaboration of government-supported maternity and children's health centers in each city. Parents of children, guided by class teachers, completed online questionnaires covering demographic characteristics, pregnancy history, and sleep health. More details on this cohort have been provided elsewhere [19–21].

A small number of parents ($N = 561$) either chose not to participate or failed to complete the questionnaire. We initially enrolled 166,520 singleton children aged between 3 and 7 years old from 2403 kindergartens across 551 cities in China between April 1, 2018 and December 31, 2019. We further excluded records that lacked a sleep questionnaire for their batch of surveys, as well as those with missing information on covariates such as sex and maternal age at conception, and without linkable exposure data (Fig. S2). Eventually, 101,879 preschool children met the eligibility criteria for participation in this study.

Parents of the enrolled children provided written consent for their participation in the study during the enrollment process. This study received approval from the Institutional Review Board of Shanghai First Maternity and Infant Hospital (KS18156).

### 2.2. Sleep evaluation

We applied the Children's Sleep Habits Questionnaire (CSHQ) to evaluate sleep behaviors and issues in children aged 3–7 years old. Originally developed as a cost-effective screening tool for identifying sleep disturbance in children aged between 4 and 10 years [22], the CSHQ has been validated for use in younger children under 4 years old as well [23]. The questionnaire comprises 33 parent-rated items, addressing common pediatric sleep issues across eight domains, including bedtime resistance, sleep onset delay, sleep duration, sleep anxiety, night waking, parasomnias, sleep-disordered breathing, and daytime sleepiness. Parents rated their child's sleep-related behaviors or symptoms over the past 4 weeks, using the following frequency options: “usually” (5–7 times each week), “sometimes” (2–4 times each week), or “rarely” (0–1 time each week). Subsequently, the scores for all items within each domain were aggregated to calculate a sub-score for that domain, and these eight sub-scores were then summed to create a total score for the questionnaire, reflecting overall sleep quality. A heightened CSHQ score implies a higher probability of facing sleep-related issues, with a total score above 41 suggesting the presence of pediatric sleep disturbances [22]. The CSHQ has demonstrated validity and reliability when applied to Chinese children [24].

### 2.3. Exposure assessments

We employed the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) as measures of children's exposure to residential greenness. The NDVI and EVI are satellite-derived vegetation indices that rely on the atmospherically corrected reflectance of visible and near-infrared wavelengths of the spectrum. The original data on these indices were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite, featuring a 250-m spatial resolution and a 16-day temporal resolution (https://modis.gsfc.nasa.gov/data/dataprod/mod13.php). The indices generally span from −1 to 1, where higher positive values suggest denser and healthier vegetation. Values near or below zero typically represent bare surfaces or non-vegetated features like water bodies or snow cover. Negative values corresponding to water or snow cover were omitted.

For each participant, residential addresses during pregnancy and post-birth periods were collected and geocoded. Subsequently, NDVI and EVI values were averaged over the entire pregnancy and the period from birth to investigation, aligning with the dates of last menstruation, birth, and investigation, to assess greenness exposure across the 250-m, 500-m, and 1000-m buffers. For NDVI, we also calculated the average values specifically for the growing season (April to October) during these two periods. A 250-m buffer was selected for primary analyses, considering that children typically spend a significant portion of their time in or near their residence before entering primary school [25].

We estimated $PM_{2.5}$ and $O_3$ concentrations across the entire pregnancy and post-birth periods utilizing satellite-based models with a 1 km × 1 km spatial resolution [26,27]. Additionally, average $SO_2$ and $NO_2$ levels during these exposure windows were obtained from fixed monitoring stations.

### 2.4. Statistical analyses

We employed linear mixed-effect models and random-effects logistic regression models to explore the associations of NDVI within a 250-m buffer during pregnancy and after birth with CSHQ scores and sleep disturbance, respectively. We established three distinct model sets for our analyses. Model 1 included child's sex, age, body mass index-for-sex/age z-score, and a random intercept for kindergarten to address the correlation within kindergarten. In Model 2, we introduced additional child-related factors recognized to impact sleep health, including the occurrence of preterm birth, delivery method, birth weight, neonatal intensive care unit (NICU) admission, and breastfeeding, as well as maternal pregnancy-related characteristics, including age at conception, gravidity, and pregnancy complications. Finally, in Model 3 (i.e., the main model), we went further by adjusting for socioeconomic status (SES) factors. These factors encompassed parental education levels, maternal employment status, marital status, family structure, and provincial gross domestic product. Detailed information for covariates is provided in Supplementary Methods. All covariates in Model 3 exhibited variance inflation factor values below 2, indicating minimal signs of multicollinearity. To explore possible non-linear relationships between greenness and sleep disturbance, we applied a generalized additive mixed model, fitting greenness using cubic regression splines with 3 basis functions, while adjusting for the same covariates as the main model.

Sensitivity analyses were conducted to evaluate the robustness of our results. First, we repeated the main analyses using early-life residential NDVI values within 500-m or 1000-m buffers. Second, we divided our study area into Southern and Northern regions using the Qinling Mountains-Huai River Line as the boundary [28]. We further included regions (Southern and Northern China) as a variable in the main model to account for potential regional variations. Third, we used EVI and growing-season NDVI values within different buffers as indicators of greenness exposure and repeated the main analyses. Fourth, to account for the collinearity between prenatal and postnatal greenness exposures (Spearman correlation coefficient $r = 0.90$), we constructed linear regression models to obtain the residuals of NDVI within a 250-m buffer during pregnancy or from birth to investigation. These residuals—representing the variation in one exposure independent of the other—were then used as substitutes for the original exposures in the main models.

We further evaluated whether ambient air pollution and residential distance to major roads (a proxy for traffic-related exposures, such as noise) served as a mediator linking greenness exposure to childhood sleep health. The mediation analyses were conducted on the potential mediators showing significant associations with sleep disturbance [29]. We fitted a mediator model and an outcome model to estimate the proportion of the total association between greenness and sleep disturbance explained by each mediator [30]. The mediator and outcome models were adjusted for the same covariates as in the main model. Besides, we tested for possible effect modification by considering interaction terms and conducting stratified analyses based on child's sex, breastfeeding status, NICU admission, SES (proxies by maternal education level), and region.

All statistical analyses were performed using R (version 4.0.5), and a two-sided $P$-value < 0.05 was considered statistically significant. Results were reported as changes with 95% confidence intervals (CIs) in CSHQ scores or as odds ratios (ORs) with 95% CIs for sleep disturbance per interquartile range (IQR) increase in greenness exposure, respectively.

## 3. Results

### 3.1. Characteristics of eligible participants

Table 1 presents the characteristics of eligible children. Among the 101,879 children, the mean age (± standard deviation, SD) was 4.5 (±0.9) years, and 53.0% were boys. Approximately 11.9% of the children were born prematurely, 10.3% were admitted to the NICU, and 79.7% were exclusively breastfed for at least 6 months. The mean (±SD) of the total score of the CSHQ was 46.6 (±7.6) (Table S1). The prevalence of sleep disturbance within our study cohort was 76.2% (Table S2), aligning closely with earlier research conducted on Chinese children [31,32].

**Table 1**
Characteristics of study participants.

| Variables | Total sample ($N$ = 101,879) $N$ (%)/mean ± SD |
|---|---|
| Children characteristics | |
| Age (years) | 4.5 ± 0.9 |
| Birth weight (g) | 3325.4 ± 470.2 |
| Gestational age <37 week | 12,089 (11.9) |
| Sex | |
| Male | 53,990 (53.0) |
| Female | 47,889 (47.0) |
| BMIz | 0.5 ± 2.0 |
| Delivery mode | |
| Vaginal delivery | 53,697 (52.7) |
| Cesarean delivery | 48,182 (47.3) |
| NICU admission | |
| No | 91,385 (89.7) |
| Yes | 10,494 (10.3) |
| Exclusive breastfeeding for 6 months | |
| No | 20,635 (20.3) |
| Yes | 81,244 (79.7) |
| Parents characteristics | |
| Maternal age at conception (years) | 27.8 ± 4.2 |
| Maternal gravidity | |
| Primigravida | 46,928 (46.1) |
| Multigravida | 54,951 (53.9) |
| Pregnancy complications [a] | |
| No | 96,809 (95.0) |
| Yes | 5070 (5.0) |
| Maternal education | |
| Middle school or below | 19,615 (19.3) |
| High school | 24,111 (23.7) |
| College or above | 58,153 (57.1) |
| Maternal employment | |
| Employed (worker/businessman/administrator) | 64,642 (63.4) |
| Unemployed | 16,276 (16.0) |
| Others | 20,961 (20.6) |
| Paternal education | |
| Middle school or below | 19,404 (19.0) |
| High school | 25,844 (25.4) |
| College or above | 56,631 (55.6) |
| Marital status | |
| First marriage | 95,444 (93.7) |
| Others | 6435 (6.3) |
| Family structure [b] | |
| Nuclear household | 64,517 (63.3) |
| Lineal household | 33,470 (32.9) |
| Joint household | 3892 (3.8) |

BMIz, body mass index-for-sex/age z-score; NICU, neonatal intensive care unit; SD, standard deviation.

[a] Mother who had gestational hypertension and/or gestational diabetes mellitus.

[b] Nuclear household, consisting either of a married couple or a divorced/widowed parent and their children; lineal household, consisting of grandparents, parents, and their children; or joint household, consisting of grandparents, parents, and their children, as well as married or unmarried siblings of the parents.

As shown in Table S3, the average NDVI (±SD) values within a 250-m buffer surrounding the residential addresses were 0.27 (±0.09) during the entire pregnancy and 0.28 (±0.09) from birth to investigation. The distribution of growing-season NDVI, EVI, and air pollutant levels ($PM_{2.5}$, $O_3$, $NO_2$, and $SO_2$) across the pregnancy and post-birth periods is also presented in Table S3. Low to moderate correlations were observed between NDVI parameters and other environmental exposures ($|r| = 0.11$–$0.56$) (Fig. S3).

### 3.2. Early-life greenness exposure and CSHQ scores

Table 2 presents the associations between early-life exposure to greenness and the total CSHQ score. Across three sequentially adjusted models, both maternal exposure to greenness during pregnancy and

**Table 2**
Regression coefficient (95% CI) of the total CSHQ score associated with IQR increases in NDVI within a 250-m buffer during early-life exposure windows.

| Exposure windows | Model 1[a] | | Model 2[b] | | Model 3[c] | |
|---|---|---|---|---|---|---|
| | $\beta$ coefficient | $P$ value | $\beta$ coefficient | $P$ value | $\beta$ coefficient | $P$ value |
| Entire pregnancy | −0.16 (−0.23, −0.10) | <0.001 | −0.20 (−0.27, −0.13) | <0.001 | −0.21 (−0.28, −0.14) | <0.001 |
| Birth-investigation | −0.19 (−0.25, −0.12) | <0.001 | −0.21 (−0.28, −0.14) | <0.001 | −0.22 (−0.29, −0.15) | <0.001 |

CI, confidence interval; CSHQ, Children's Sleep Habits Questionnaire; IQR, interquartile range; NDVI, normalized difference vegetation index.
[a] Adjusted for child's sex, age, body mass index-for-sex/age z-score at the time of survey, and the random contribution of kindergarten.
[b] Further adjusted for birth weight, preterm birth, delivery mode, neonatal intensive care unit admission, exclusive breastfeeding for 6 months, maternal age at conception, maternal gravidity, and medical conditions during pregnancy based on Model 1.
[c] Further adjusted for maternal and paternal education, maternal employment, marital status, family structure, and gross domestic product at the provincial level based on Model 2.

post-birth childhood greenness exposure showed significant associations with a reduction in the total CSHQ score among preschoolers, indicating a better sleep quality. Following adjustments for all covariates, the total CSHQ score decreased by 0.21 (95% CI: 0.14, 0.28) for every IQR (0.12) increase in NDVI within a 250-m buffer during the entire pregnancy and decreased by 0.22 (95% CI: 0.15, 0.29) for every IQR (0.11) increase in NDVI within a 250-m buffer after birth.

In terms of the relationships between greenness exposure and CSHQ sub-scores, we observed that NDVI within a 250-m buffer demonstrated associations with lower scores across all eight domains (Fig. S4). The largest effect estimates were found for the domain of daytime sleepiness. For each IQR increase in NDVI throughout pregnancy and after birth, the reductions in score for daytime sleepiness were 0.07 (95% CI: 0.05, 0.10) and 0.07 (95% CI: 0.04, 0.09), respectively. However, the association between NDVI throughout pregnancy and the night waking score did not reach statistical significance.

### 3.3. Early-life greenness exposure and sleep disturbance

Fig. 1 illustrates the relationship between early-life greenness exposure and the risk of sleep disturbance in children. Higher greenness

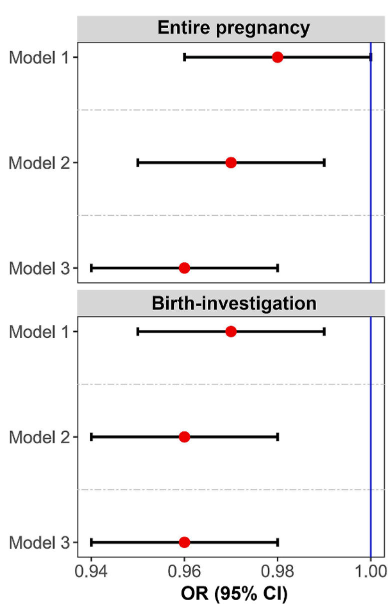


**Fig. 1.** OR (95% CI) for sleep disturbance associated with IQR increases in NDVI within a 250-m buffer during early-life exposure windows. Model 1 adjusted for child's sex, age, body mass index-for-sex/age z-score at the time of survey, and the random contribution of kindergarten; Model 2 further adjusted for birth weight, preterm birth, delivery mode, neonatal intensive care unit admission, exclusive breastfeeding for 6 months, maternal age at conception, maternal gravidity, and medical conditions during pregnancy based on Model 1; Model 3 further adjusted for maternal and paternal education, maternal employment, marital status, family structure, and gross domestic product at the provincial level based on Model 2.

levels were associated with a reduced risk of sleep disturbance. For instance, within the 250-m buffer, each IQR increase in NDVI during both pregnancy and the postnatal period was associated with an adjusted OR of 0.96 (95% CI: 0.94, 0.98) for sleep disturbance.

As shown in Fig. S5, the exposure-response curves between greenness and the odds of sleep disturbance demonstrated a monotonic decrease at relatively low NDVI levels, followed by a plateau at higher NDVI values (approximately 0.4).

### 3.4. Sensitivity analyses

The associations with total CSHQ score and risk of sleep disturbance remained consistent when using varying radial buffers to assess NDVI exposure (Table S4), most likely due to strong correlations among various metrics ($r$ = 0.93–0.99) (Fig. S3). The associations between greenness and sleep outcomes remained robust after further adjustment for region (Table S5).

The effect estimates for two other metrics (i.e., NDVI during the growing season and EVI) were consistent with those obtained using NDVI (Table S4). For example, within the 250-m buffer, each IQR increase in growing-season NDVI during both pregnancy and the postnatal period was associated with an adjusted OR of 0.95 (95% CI: 0.93, 0.97) for sleep disturbance. For EVI, the adjusted ORs were 0.96 (95% CI: 0.94, 0.98) and 0.95 (95% CI: 0.93, 0.97) during these respective periods.

When the residuals of NDVI within a 250-m buffer during pregnancy or from birth to the time of investigation were used as substitutes for the original exposures, the association between postnatal greenness exposure and sleep outcomes remained robust. However, the associations for prenatal greenness exposure were attenuated towards the null (Table S6).

### 3.5. Mediation analyses

We observed that postnatal exposures to $PM_{2.5}$, $NO_2$, and $SO_2$ were significantly associated with increased odds of sleep disturbance, and greater residential distance from major roads was associated with lower odds of sleep disturbance (Table S7). The mediation analyses showed that $PM_{2.5}$, residential distance to major roads, $NO_2$, and $SO_2$ mediated 30.2% (13.2%, 67.0%), 18.8% (4.3%, 56.0%), 7.9% (2.3%, 18.0%), and 4.3% (1.2%, 11.0%) of the association with average NDVI within the 250-m buffer from birth to investigation, respectively (Table 3).

**Table 3**
Estimated proportion of associations between post-birth greenness exposure and sleep disturbance mediated by air pollutants and residential distance to major roads.

| Mediators | Sleep disturbance | |
|---|---|---|
| | Proportion mediated (95% CI) | $P$ value |
| $PM_{2.5}$ | 30.2% (13.2%, 67.0%) | <0.001 |
| $NO_2$ | 7.9% (2.3%, 18.0%) | 0.002 |
| $SO_2$ | 4.3% (1.2%, 11.0%) | 0.014 |
| Residential distance to major roads | 18.8% (4.3%, 56.0%) | 0.008 |

### 3.6. Stratified analyses

Table 4 presents the results of stratified and interaction term model analyses for the associations of NDVI with sleep disturbance. We observed statistically significant interactions of greenness with maternal education in the association between greenness and sleep disturbance ($P_{interaction}$ = 0.02–0.05), and the effect estimates tended to be stronger for children of mothers with higher educational attainment. For example, each IQR increase in NDVI from birth to investigation was associated with a 5% reduction in sleep disturbance risk (OR = 0.95, 95% CI: 0.92, 0.97) among children of mothers with a college education or higher, compared to a 3% reduction (OR = 0.97, 95% CI: 0.94, 0.99) among children whose mothers had a high school education or lower. Additionally, our analysis revealed significant interactions between greenness and region ($P_{interaction}$ = 0.002–0.005). The effect estimates of increased greenness on sleep disturbance were greater in Northern China compared to Southern China. During pregnancy, the adjusted ORs were 0.95 (95% CI: 0.92, 0.98) in Northern China versus 0.97 (95% CI: 0.95, 0.99) in Southern China. Similarly, for the period from birth to investigation, the ORs were 0.94 (95% CI: 0.91, 0.97) in Northern China versus 0.97 (95% CI: 0.94, 0.99) in Southern China. The magnitude of association was relatively larger among children who received exclusive breastfeeding for a duration of less than 6 months (from birth to investigation: OR = 0.93, 95% CI: 0.89, 0.98) compared with those who received exclusive breastfeeding for more than 6 months (from birth to investigation: OR = 0.96, 95% CI: 0.94, 0.98). Analyses of interaction terms between exposures and other modifying variables (i.e., child's sex and NICU admission), as well as stratified analyses, revealed no significant between-group differences in estimated associations.

## 4. Discussion

Within this extensive nationwide cohort comprising 101,879 preschoolers in China, we observed that both prenatal and postnatal exposure to greenness exhibited associations with better sleep quality and a reduced risk of sleep disturbance. The positive association for postnatal greenness exposure was partially mediated by reductions in environmental exposures. Notably, children with higher maternal education levels, those living in Northern China, or those with exclusive breastfeeding durations of <6 months showed more pronounced beneficial effects from greenness compared to their counterparts.

The body of research investigating the impacts of greenness on children's sleep outcomes is relatively limited, posing challenges for drawing direct comparisons with existing literature. To our knowledge, only one study has been conducted in China. Unlike our findings, this study reported no significant association between residential surrounding greenness during the initial 1000 days of life and sleep quality issues, based on a sample of 410 children from Guangzhou city [18]. However, our findings may align to some extent with two American nationwide studies that reported increased odds of insufficient sleep in children without access to nearby parks [11,13]. Our study provides robust evidence from China regarding the positive association between greenness and children's sleep, using objective measurements of greenness and a comprehensive standardized sleep questionnaire with multiple indicators.

The exposure–response relationship curves for greenness and sleep disturbance showed a primarily linear trend at relatively low NDVI levels. Notably, over 75% of participants were exposed to NDVI at or below 0.33, indicating that increasing green environments could provide significant benefits for the majority of the population. Additionally, the exposure-response curves exhibited a plateau at higher NDVI values (approximately 0.4), indicating a threshold effect, beyond which further increases in greenness may not lead to additional improvements in sleep outcomes. Similar findings from a Chinese study indicated that overall health benefits peaked at an NDVI value of 0.4 [33]. The observed threshold effect might be attributed to multiple factors. First, large green spaces may only be partially utilized, as inaccessibility and safety concerns—particularly in areas with inadequate security—can significantly limit their use, thereby diminishing potential health benefits [34,35]. Second, excessive vegetation density may impede visibility and induce a sense of enclosure, potentially diminishing the restorative and relaxing benefits typically associated with green spaces [36]. Third, the type and quality of green spaces may also play a role. Higher proportions of green space may reflect agricultural land or undeveloped natural areas, which often lack essential facilities and are of lower usability and quality, thus weakening their health-promoting potential [33,35].

While the exact mechanisms by which natural environments influence sleep are not fully understood, several possible pathways could be at play. First, living close to greener areas may enhance physical activities and social interactions for children, which may positively impact brain development and promote sleep health [9,37,38]. Second, green spaces can impact feelings and emotions by activating the parasympathetic nervous system, which helps alleviate stress and autonomic arousal, thereby promoting better sleep regulation in children [9]. Third, greenness may act as a mitigating factor against environmental risks like air pollution and noise [39], which are known to affect children's sleep [20,40]. Previous studies have suggested that greenness can absorb gaseous pollutants such as $NO_2$ and $SO_2$, trap particulate matter on plant surfaces, and reduce noise pollution by absorbing and scattering sound waves or acting as a physical barrier [41–43]. Our mediation analyses further support this hypothesis, showing that the link between postnatal greenness exposure and sleep disturbance was partially mediated by reductions in typical ambient air pollutants (e.g., $PM_{2.5}$, $SO_2$, and $NO_2$) and traffic-related exposures (e.g., noise or air pollution).

**Table 4**
Stratified and interaction term model analyses for the associations of NDVI within a 250-m buffer with sleep disturbance.

| Subgroups | Odds ratios (ORs) for sleep disturbance (95% CI) | | |
|---|---|---|---|
| | Stratified model | | $P_{interaction}$ |
| Child's sex | Male (*N* = 53,990) | Female (*N* = 47,889) | NDVI × sex (*N* = 101,879) |
| Entire pregnancy | 0.95 (0.93, 0.98) | 0.96 (0.93, 0.99) | 0.95 |
| Birth-investigation | 0.96 (0.93, 0.98) | 0.95 (0.92, 0.98) | 0.63 |
| Maternal education | High school or below (*N* = 43,726) | College or above (*N* = 58,153) | NDVI × education (*N* = 101,879) |
| Entire pregnancy | 0.97 (0.94, 1.00) | 0.94 (0.92, 0.97) | 0.02 |
| Birth-investigation | 0.97 (0.94, 0.99) | 0.95 (0.92, 0.97) | 0.05 |
| Exclusive breastfeeding | Yes (*N* = 81,244) | No (*N* = 20,635) | NDVI × breastfeeding (*N* = 101,879) |
| Entire pregnancy | / | / | / |
| Birth-investigation | 0.96 (0.94, 0.98) | 0.93 (0.89, 0.98) | 0.13 |
| Geographic region | Southern China (*N* = 71,291) | Northern China (*N* = 30,588) | NDVI × region (*N* = 101,879) |
| Entire pregnancy | 0.97 (0.95, 0.99) | 0.95 (0.92, 0.98) | 0.005 |
| Birth-investigation | 0.97 (0.94, 0.99) | 0.94 (0.91, 0.97) | 0.002 |
| NICU admission | Yes (N = 10,494) | No (N = 91,385) | NDVI × NICU admission (*N* = 101,879) |
| Entire pregnancy | / | / | / |
| Birth-investigation | 0.95 (0.89, 1.01) | 0.96 (0.93, 0.98) | 0.97 |

Our findings also suggested that prenatal exposure to greenness might improve sleep health among preschool-aged children. However, since most individuals did not relocate between the prenatal and postnatal periods, it is difficult to fully disentangle the effects of greenness exposure across these timeframes due to potential collinearity. Although the association with prenatal greenness exposure was no longer significant after accounting for postnatal exposure through residualization, several plausible mechanisms may still support a role for prenatal greenness in shaping early sleep health. The nervous system begins establishing signaling networks related to sleep regulation during the early stages of life, starting even before birth, gradually forming a stable sleep-wake circadian rhythm [44]. Exposure to green environments during pregnancy might encourage pregnant women to engage in more outdoor activities [45], and effectively promote maternal well-being [46] and sleep quality [8], potentially aiding the development of a normal fetal sleep-wake rhythm. Furthermore, prenatal exposure to greenness has been linked to a reduced risk of adverse birth outcomes, such as preterm birth [47], which may subsequently lower the probability of sleep issues in children as they grow [48]. Despite these insights, further research is needed to fully elucidate these mechanisms.

Interestingly, our study revealed a more pronounced protective effect of greenness on sleep health among children of mothers with higher education levels. This observation challenges the prevailing equigenic effect hypothesis of green space, which suggests that exposure to greenness may help reduce health disparities by offering greater benefits to socioeconomically disadvantaged populations with less access to nature and green spaces [9]. Contrary to this hypothesis, our study found that children with mothers of lower educational levels resided in areas with higher average NDVI values within a 250-m buffer, suggesting better access to greenness compared to their higher-educated counterparts (0.29 vs. 0.26). Furthermore, a cohort study in Massachusetts revealed that a greater proportion of grass was linked to less efficient sleep among children from lower SES neighborhoods, while a higher total percentage of greenness was linked to better sleep duration among those in higher SES neighborhoods [12]. This indicates that vegetation types may vary the health effects of greenness in children from different socioeconomic backgrounds. One plausible explanation for our finding could be that higher-education individuals in China might have greater access to higher-quality green spaces, such as well-maintained parks. These individuals might also possess more knowledge or resources to effectively utilize these spaces for health benefits. Notably, our study did not measure specific vegetation types or the quality aspects of greenness. Therefore, further research is necessary to explore these potential mechanisms and understand the nuances of how green space quality and type might influence health outcomes in different socioeconomic groups.

We observed that the beneficial effect of greenness on children's sleep appeared to be more pronounced in Northern China compared to Southern China. This regional variation may reflect differences in baseline greenness levels and other contextual factors. In Southern China, where greenness is generally more abundant (mean NDVI: 0.31 for the period from birth to investigation), we hypothesize that a saturation effect may limit additional health benefits from further increases in greenness. Conversely, in Northern China, where greenness levels are relatively lower (mean NDVI: 0.23), increased exposure to green spaces might provide more substantial improvements in children's living environments, potentially leading to greater health benefits. Additionally, differences in air pollution levels, patterns of green space utilization, and other environmental factors between the two regions may also contribute to this variation.

Moreover, our results also suggested that children who received exclusive breastfeeding for less than 6 months experienced more pronounced benefits from exposure to greenness, potentially reducing sleep disturbance risk. Breastfeeding plays a vital role in supporting immune system maturation and fostering proper immunological responses [49]. Consequently, children who received limited or no breastfeeding might possess comparatively less robust immune systems, potentially making them more vulnerable to a range of health issues. In such scenarios, contact with green surroundings could potentially serve as a means to enhance and fine-tune their immunomodulatory capabilities [37]. This interaction might not only contribute to reinforcing their immune responses but also enhance their overall well-being during early childhood, indicating the multifaceted benefits of green spaces in child health development.

This study has several strengths. First, as far as we are aware, it stands as the inaugural nationwide investigation in China—a rapidly urbanizing country—delving into the relationship between greenness exposure and sleep health in preschool-aged children. Second, we provided important insights into the potential pathways linking greenness and children's sleep by examining the mediation effects of typical ambient air pollutants and traffic-related exposures on these associations. Third, we have comprehensively incorporated and controlled for an extensive array of potential confounding factors, encompassing prenatal, antenatal, and postnatal characteristics, along with child and family attributes, adding robustness to our findings.

The limitations should also be noted. First, though CSHQ is a well-validated questionnaire, the use of parent-reported CSHQ could introduce recall bias or inaccuracies in assessing children's sleep quality. Future research should incorporate objective measurements, such as actigraphy, to offer more accurate assessments. Second, while objective greenness measures were used, they do not differentiate specific vegetation types and reflect the quality of green space. Third, crucial factors like physical, visual, and auditory access to greenness were not accounted for in our study. Additionally, we did not control for additional potential confounders like bedroom light use and second-hand smoking exposure. Lastly, although exposure assessments were conducted separately for prenatal and postnatal addresses, the majority of our participants (over 80%) did not relocate during the study period. Consequently, prenatal and postnatal greenness exposures were highly correlated, which complicates the ability to disentangle their independent effects on sleep outcomes.

Our findings might provide a feasible intervention to alleviate the burden of sleep problems in children. In addition to traditional intervention measures, such as reducing air pollution or limiting noise, integrating public health strategies with urban planning to enhance green infrastructure and optimize its utilization could significantly benefit the sleep health of most children. First, efforts should be directed toward increasing green space coverage in areas with limited greenness. Second, health-oriented activities should be regularly organized to ensure that children and their caregivers are equipped with the knowledge and resources needed to make effective use of green spaces for health benefits. Third, in regions where greenery is already abundant, it is important to optimize its design by improving connectivity, ensuring the provision of essential infrastructure, and enhancing safety to promote accessibility and usability. Furthermore, our findings based on subgroup analyses may offer valuable insights for future green space planning, emphasizing the importance of considering regional and demographic disparities to maximize the public health benefits of greenness. For example, priority should be given to populations with lower SES to promote equitable access and health outcomes.

In conclusion, this nationwide study provides compelling evidence of the positive associations between early-life exposure to greenness and sleep health among preschool-aged children in China.

## CRediT authorship contribution statement

**Yang Shen:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Yan Zhao:** Writing – review & editing, Investigation. **Xia Meng:** Writing – review & editing, Methodology. **Kexin Yu:** Methodology. **Gareth J. Williams:** Writing – review & editing. **Wenchong Du:** Writing – review & editing. **Jing Cai:** Writing – review & editing, Methodology, Conceptualization. **Haidong Kan:** Writing – review

& editing, Supervision, Conceptualization. **Jing Hua:** Writing – review & editing, Investigation, Data curation, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eehl.2025.100165.

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