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Sociodemographic inequalities in residential nighttime light pollution in urban Bulgaria: An environmental justice analysis

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ABSTRACT

Introduction: Outdoor nighttime light (NTL) is a potential anthropogenic stressor in urban settings. While ecological studies have identified outdoor NTL exposure disparities, uncertainties remain about disparities in individual exposure levels, particularly in Europe.
Aim: To assess whether some populations are disproportionately affected by outdoor NTL at their residences in urban Bulgaria.
Methods: We analyzed 2023 data from a representative cross-sectional survey of 4,270 adults from the five largest Bulgarian cities. Respondents' annual exposures to outdoor artificial nighttime luminance were measured using satellite imagery and assigned at their places of residence. We calculated the Gini coefficient as a descriptive NTL inequality measure. Associations between respondents' NTL exposure levels and sociodemographic characteristics were assessed by estimating quantile mixed regression models. Stratified regressions were fitted by gender and for each city.
Results: We found moderate distributive NTL inequalities, as indicated by a Gini coefficient of 0.214. Regression analyses showed associations between greater NTL exposure and higher educational attainment. Respondents with incomes perceived as moderate experienced less NTL exposure at the 0.5 and 0.8 quantiles, while unemployed respondents experienced lower exposure at the 0.2 and 0.5 quantiles. We observed null associations for the elderly and non-Bulgarian ethnicities. Regardless of the quantile, greater population density was associated with higher NTL levels. Stratification by sex did not yield substantial differences in the associations. We observed notable city-specific heterogeneities in the associations, with differences in the magnitudes and directions of the associations and the NTL quantiles.
Conclusions: NTL exposures appeared to embody an environmental injustice dimension in Bulgaria. Our findings suggest that some sociodemographic populations experience higher exposure levels to NTL; however, those are not necessarily the underprivileged or marginalized. Identifying populations with high exposure levels is critical to influencing lighting policies to ease related health implications.

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1. Introduction

Environmental justice research has established that environmental hazards and amenities are frequently unequally distributed along sociodemographic gradients (Corburn, 2017; Mohai et al., 2009). Marginalized people tend to be disproportionately exposed to hazards and benefit less from amenities compared to advantaged population groups (Evans and Kantrowitz, 2002). For example, a meta-analysis has shown that lower-income earners live in places with less urban forest cover (Gerrish and Watkins, 2018). Similarly, systematic reviews have documented that the economically and socially marginalized experience disproportionately more air pollutants (Hajat et al., 2015) and transport-related noise (Trudeau et al., 2023).

Although artificial light at night has benefits (e.g., increased safety or commercial activity) (Boyce, 2019), nighttime light (NTL) (i.e., excessive artificial brightness from streetlights, billboards, or the illumination of buildings), particularly in urban areas, is also among the human-caused disturbances challenging both ecosystems (Gaston and de Miguel, 2022) and human health (Linares Arroyo et al., 2024; Zielinska-Dabkowska et al., 2023). Current estimates of NTL levels suggest that 99% of Europeans are affected (Falchi et al., 2016). Studies have associated NTL overexposure with adverse health effects, including sleep problems (Y.-X. Xu et al., 2023), overweight and obesity (Lai et al., 2020), mental disorders (Tancredi et al., 2022), and breast cancer (Wu et al., 2021). However, not everyone may be affected equally by outdoor NTL; consequently, differences in exposure levels may exist and potentially reinforce health inequalities. Given an approximately 10% annual rise in night sky brightness (Kyba et al., 2023), there is an urgent need to assess possible excessive exposure to NTL in specific populations.

NTL has received little recognition as an environmental justice issue. While a few studies have mapped area-level variations within and across countries (Falchi et al., 2019), to our knowledge, even fewer studies have analyzed sociodemographic differences in NTL exposure (Chen et al., 2022; Nadybal et al., 2020; Xiao et al., 2023a, 2023b). For example, an early area-level study in the United States substantiated that exposure to ambient light at night was considerably higher among ethnic minority neighborhoods and low-to-mid socioeconomic status neighborhoods (Nadybal et al., 2020).

Although the evidence base regarding differences in NTL exposures provides significant insights, the state-of-the-art is not well developed in three respects. First, existing studies have primarily dealt with the United States (Motairek et al., 2023; Nadybal et al., 2020; Xiao et al., 2023b), and the results can, at best, only be partially extrapolated to Europe, where urban settlements tend to be more compact. Moreover, the literature lacks studies on NTL from Eastern Europe, a region where environmental health research is still in its early stages. Second, regardless of the country, existing studies were ecological (Chen et al., 2022; Nadybal et al., 2020; Xiao et al., 2023a). It is well-established that such study design is notoriously prone to confounding due to a lack of person-level characteristics (Wakefield, 2008). Such area-level studies are also vulnerable to the modifiable areal unit problem (Openshaw, 1981), possibly rendering statistical inferences uncertain due to issues with underlying spatial scales and zoning (Tian et al., 2024). Third, while there is not as yet any consensus established regarding how to best model differences in exposure levels (Casey et al., 2023), ordinary mean regression estimates assuming that covariates are associated with the conditional distribution of the outcome (i.e., NTL) through its mean are frequently reported (Cade and Noon, 2003; Koenker and Bassett Jr, 1978); however, there are no credible grounds offered in environmental justice research for their use (Helbich et al., 2018; Tonne et al., 2018). Yet, it is reasonable to suppose that the effect sizes of people's sociodemographic characteristics depend on heterogeneous variations of the response distribution.

In response to the scarcity of European studies investigating differences in outdoor NTL exposure between population groups, along with methodological concerns of previous research, we aimed to 1) examine possible person-level sociodemographic differences in NTL at residence and 2) assess whether the associations vary across different nightlight quantiles using a representative environmental health survey among urban adults in Bulgaria, one of Europe's poorest countries (Eurostat, 2023). We generated two hypotheses. First, echoing injustice debates, we speculated that the less well-off experienced higher NTL levels. Second and unlike previous studies (Nadybal et al., 2020; Xiao et al., 2023a), we hypothesized that the strengths of the associations differed across the NTL distribution, specifically, that those in upper NTL exposure quantiles might be affected to a greater extent than those in lower quantiles. Understanding environmental NTL across sociodemographic gradients is essential for advancing the Sustainable Development Goals (United Nations, 2016), which emphasize diminishing disparities and ensuring inclusivity (Ganzleben and Kazmierczak, 2020).

2. Materials and methods

2.1. Study area

Our study area includes the five largest cities in Bulgaria (Supplementary Fig. S1). We included the capital Sofia (≈1,249,000 inhabitants), Plovdiv (≈347,000 inhabitants), Varna (≈333,000 inhabitants), Burgas (≈203,000 inhabitants), and Ruse (≈145,000 inhabitants). Sofia is a compact city dealing with excessive lighting at various locations, such as the nearby airport and historic boulevards. Plovdiv is situated more centrally in Bulgaria and features a compact urban layout with tall residential buildings and well-lit historical landmarks. Varna and Burgas are situated on the Black Sea Coast and are seaside resorts with relatively high NLT levels. Ruse is in the northeast, where NTL is generated from extensive parking lots for heavy vehicles.

2.2. Population sample

This study encompassed a cross-sectional sample of adults from the general population of the five cities. We used stratified sampling to acquire a representative sample of each city's population and its sociodemographic characteristics while ensuring participants' residential addresses had adequate environmental variability related to traffic-related air pollution and noise (≥/<50 m of a major road), air pollution from domestic heating or cooking (≥/<100 m Euclidean distance to ≥10 households registered as using fossil fuel for heating), and green space (≥/< 300 m of a green urban area) as practice elsewhere (Dzhambov et al., 2023).

A survey company recruited participants under the research team's supervision between August and October 2023. Interviewers received training before conducting the fieldwork. Eligibility criteria for participants were that they had to be at least 18 years old, live in a private household (e.g., not in a prison or in a care home), and live at their residential address for at least a year. Fieldworkers interviewed participants at home on their demographics and physical and mental health outcomes. In total, 4,640 respondents were recruited (1,512 from Sofia, 1,012 from Plovdiv, 1,001 from Varna, 655 from Burgas, and 460 from Ruse). Response rates varied from 30.22% in Sofia to 58.40% in Plovdiv, with an overall average of 42.51%. The Ethics Committee of the Medical University of Plovdiv approved the study protocol (Protocol № 4/May 04, 2023, Opinion № P-1253/May 17, 2023).

2.3. Nighttime light exposure as the outcome

Remote sensing imagery allowed the assessment of inequalities in outdoor NTL exposure (Linares Arroyo et al., 2024; Sayyed et al., 2024). We acquired global calibrated nighttime radiance measurement data utilizing the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band instrument aboard the Suomi National Polar-orbiting Partnership satellite (Miller et al., 2012; Zhao et al., 2019). The VIIRS sensor is sensitive to low visible/near-infrared NTL levels. Gridded VIIRS images have a resolution of approximately 464 m with a lower light detection limit than first-generation NTL composites, while the VIIRS images are also not affected by saturation (Elvidge et al., 2013; Levin et al., 2020). NTL emissions vary seasonally; thus, we used average radiance composite images capturing annual NTL levels (in nW/cm^2/sr) (Kyba et al., 2015). The 2022 'VCMSLCFG' image collection in Google Earth Engine (Gorelick et al., 2017) provided the VIIRS nightlight data via the National Oceanic and Atmospheric Administration filtered to eliminate, for example, stray light and cloud cover (Román et al., 2019).

We linked the NTL data to the survey data via respondent's residential locations. The residential addresses were geocoded by the interviewers using global positioning system devices. In the case of <10 addresses, accuracy assessments revealed uncertainties in geocoding, with those address coordinates being manually adjusted based on auxiliary data, such as from the cadaster. We centered buffers on the respondents' home addresses to model their immediate and expanded spatial contexts. We used circular buffers on the respondents' home addresses to model their immediate and expanded spatial contexts. We used focal statistics to compute mean NTL levels. Guided by prior analyses (Helbich et al., 2020), we determined the average radiance level value for the 100 m, 500 m, and 800 m buffers after downsampling the original VIIRS raster layer resolution to 10 m employing bilinear interpolation. No missing values occurred after assigning the NTL levels at people's home locations. After examining the summary statistics of the NTL data, no outliers were present. Supplementary Fig. S2 summarizes the workflow.

2.4. Covariates

Survey data from 2023 provided self-reported socio-demographic information on each participant. Prior exposure inequality studies have routinely used variables similar to those in our study (Tonne et al., 2018). We reclassified age into a dummy variable representing whether the person was considered elderly (>65 years). We deemed the elderly at high risk and physiologically more vulnerable to environmental stressors (Mechanic and Tanner, 2007). A few previous studies had speculated that non-native populations experience higher levels of exposure (Mohai et al., 2009); the survey data distinguished five groups: Bulgarians, Turks, Roma, Armenians, and others. Due to the low frequencies in categories other than Bulgarian (1.7% Turks, 1.6% Roma, and 0.5% Armenians), we collapsed the ethnic groups into Bulgarian and others. Since socio-economic vulnerability is multifaceted and no uniform measure exists (Evans and Kantrowitz, 2002; Galobardes et al., 2007), we used three dimensions. The first captured perceived total monthly household incomes. The six original income categories, ranging from very difficult to very easy, were regrouped into difficult, moderate, and easy. The second captured respondents' highest educational attainment reclassified into primary education not completed/completed, secondary education completed, and higher education completed. Aggregating primary education was necessary due to the scarcity of respondents who had not completed primary education, resulting in that category being underpopulated (<0.5%). The third was a dummy variable indicating whether a respondent was employed. Finally, as NTL levels act as a proxy variable for the degree of urbanization (Zhang and Seto, 2011), we also included a population estimate within 100, 500, and 800 m buffers (divided by 1000) for 2021, as done previously (Nadybal et al., 2020). For stratified analyses, we also used the respondent's sex (male, female).

2.5. Statistical analysis

We employed summary statistics to describe the study sample. We used the Chi^2 tests to assess differences in NTL levels across socio-demographic groups. Furthermore, we assessed individual-level NTL disparities using the Gini coefficient, as provided in the *giniVarCI* R package (Muñoz et al., 2023). The Gini index ranges from 0 to 1 and was derived from the Lorenz curve illustrating the cumulative NTL distribution. A Gini value of zero signifies perfect equality; higher values indicate increasingly pronounced inequality. In our study, this signified that a smaller fraction of participants experienced a larger share of total NTL exposure (Cowell, 2011). We conducted 500 percentile bootstrap replications to obtain the Gini index's confidence intervals (CI) (Muñoz et al., 2023).

Since the absence of multicollinearity is critical to obtaining reliable regression effect estimates, we calculated variance inflation factors (VIFs) for the mixed mean regression. VIF values above five were indicative of collinearity issues among the covariates. We regressed our response variable NTL levels on sociodemographic covariates using linear quantile mixed models (Geraci and Bottai, 2014), assuming a Gaussian link function. A quantile mixed regression model allows the assessment of covariate associations for any quantile within the response distribution rather than only the mean (Cade and Noon, 2003). Since we were interested in possibly heterogeneous associations between the lower and higher NTL exposure extremes, we fitted regressions for the 0.2, 0.5, and 0.8 quantiles of the NTL distribution. The 0.5 quantile permitted comparisons with prior scholarship (Nadybal et al., 2020; Xiao et al., 2023a). Whether our hierarchical data structure (i.e., respondents were nested in cities) required a mixed model design was tested by fitting a null model with a city-specific random intercept (with no covariates) and computing intraclass correlation coefficients (ICCs) for each quantile (Bliese, 2000).

We fitted two models with differing adjustment levels in our primary analyses. The first included person-level characteristics, such as senior status, ethnicity, education, employment, and income (Model 1). Model 2 additionally adjusted for neighborhood-level population density. As a secondary analysis, Model 2 was fitted for each city separately. To assess the sensitivity of the models regarding the exposure assessment based on 500 m buffers, we 1) refitted the models with 100 m and 800 m buffers, 2) stratified the entire dataset by sex, and 3) refitted the pooled Model 2 based on the original NTL data without resampling. The coefficients for each regression quantile were reported, with confidence intervals (CIs) based on 500 bootstrap replications. The analyses were conducted in the R-4.3.2 environment (R Core Team, 2024), and the models were fitted through the *lqmm* package (Geraci, 2014).

3. Results

3.1. Sample description

Of the 4,640 participants, 365 (7.9%) had one or more relevant variables with missing data, and five had lived at their residence for less than 12 months. As a result, these 370 participants were excluded from

Table 1
Sample characteristics (N = 4,270).

	Number of people (%)
Elderly = yes (%)	1,039 (24.3)
Ethnicity = other (%)	171 (4.0)
Education (%)	
Primary education not completed/completed	210 (4.9)
Completed secondary education	2,435 (57.0)
Completed higher education	1,625 (38.1)
Unemployed = yes (%)	161 (3.8)
Perceived income situation (%)	
Difficult	935 (21.9)
Moderate	2,943 (68.9)
Easy	392 (9.2)
Sex = female (%)	2,352 (55.1)
City	
Ruse	439 (10.3)
Burgas	590 (13.8)
Plovdiv	944 (22.1)
Varna	969 (22.7)
Sofia	1,328 (31.1)

the study. The final analytical sample we used included 4,270 respondents. Table 1 summarizes the characteristics of the study population. Approximately half were female, and a quarter were older than 65. Most respondents were Bulgarians who had completed at least secondary education and perceived their income level as moderate.

3.2. Exposure distributions

Fig. 1 shows the annual NTL concentrations for each city. Unless noted otherwise, 500 m buffers overlaid on respondents' home addresses were used to assess NTL exposure. The respondents' overall mean outdoor NTL levels were 36.151 nW/cm^2/sr with a standard deviation (SD) of ±13.968 for the 500 m buffers. The exposure distribution varied substantially across the cities in our sample, with the highest mean exposure levels in Varna (43.7; SD ± 14,909) followed by Plovdiv (37.2; SD ± 11.496), Sofia (36.4; SD ± 12.851), Burgas (30.9; SD ± 10.968), and Ruse (20.3; SD ± 5.792) (Fig. 2). Supplementary Fig. S3 shows the Lorenz curve. The result indicated that the observed Lorenz curve deviated moderately from the line of an equal NTL distribution, while the Gini index was 0.214 (CI = 0.210; 0.219). Both results suggested moderate distributive NTL inequalities.

Fig. 3 shows the NTL distributions for each sociodemographic covariate. With some exceptions, including ethnicity, education, and income, the exposure distributions do not significantly deviate across individual-level characteristics. Results remained similar when additionally stratified by NTL tertile (Table 2). We observed significant differences ($p < 0.05$) based on Chi^2 tests for ethnicity, education, and income. The descriptive statistics exhibited comparable magnitudes and distributions for the 100 m and 800 m buffers (results not shown).

3.3. Pooled regression analyses

The observed VIF values were less than two, indicating no covariate multicollinearity in the mixed mean regression. The quantile-specific ICCs of the null model were moderate (0.2 quantile value: 0.081; 0.5 quantile: 0.112) while still supporting consideration of a random city-specific intercept, especially for the upper quantile (ICC = 0.203) (Bliese, 2000). Regardless of the quantile, the AIC scores decreased substantially with increasing model adjustment, suggesting that Model 2, based on 500 m buffers, achieved the best goodness-of-fit (Supplementary Table S1). Fig. 4 summarizes the primary analyses' estimated associations between NTL and sociodemographics. Supplementary Table S2 provides numeric results. Adding population density to Model 1 attenuated the effect estimates in Model 2, regardless of the quantiles. The magnitudes of the model estimate differed across quantiles and in significance.

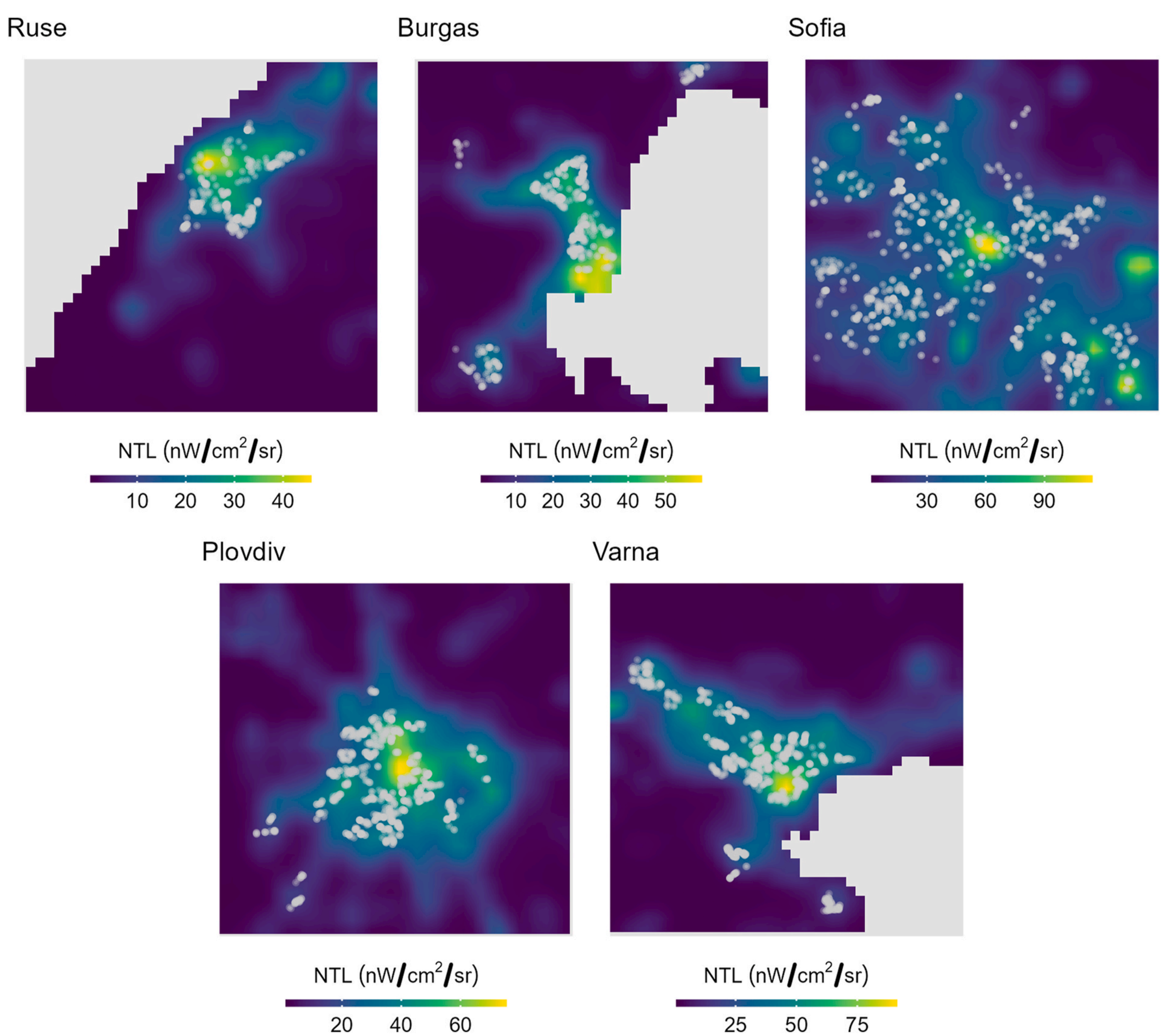

Fig. 1. Annual nighttime light concentrations across the five largest Bulgarian cities based on VIIRS data. Cells colored in light gray indicate waterbodies and/or where outside the study areas. The gray points refer to the respondents' address locations.

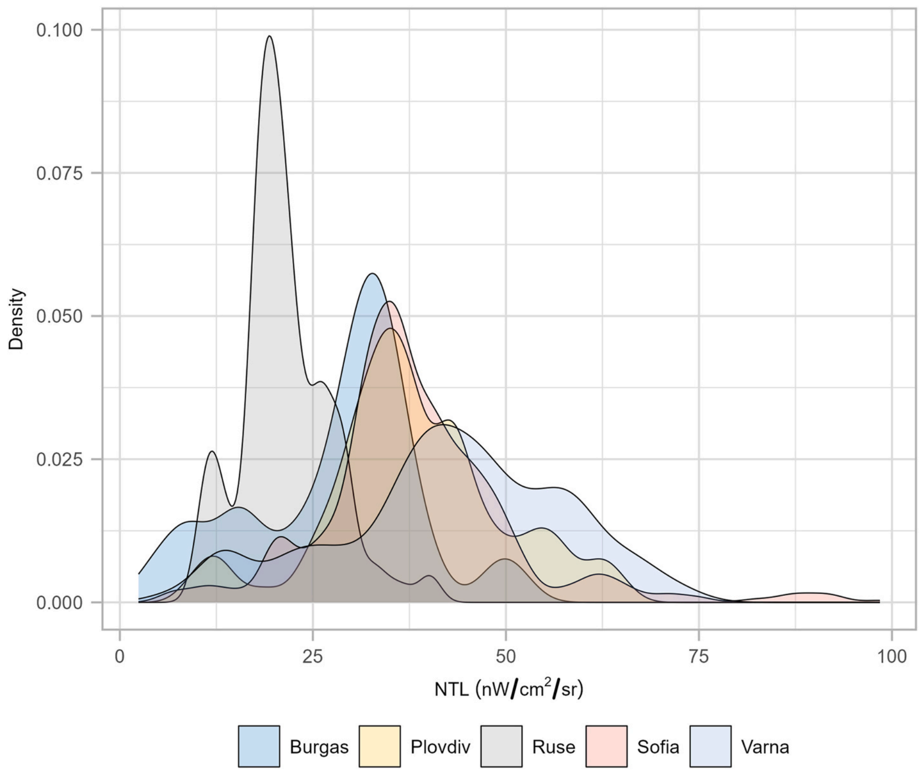

Fig. 2. City-specific nighttime light exposure distribution.

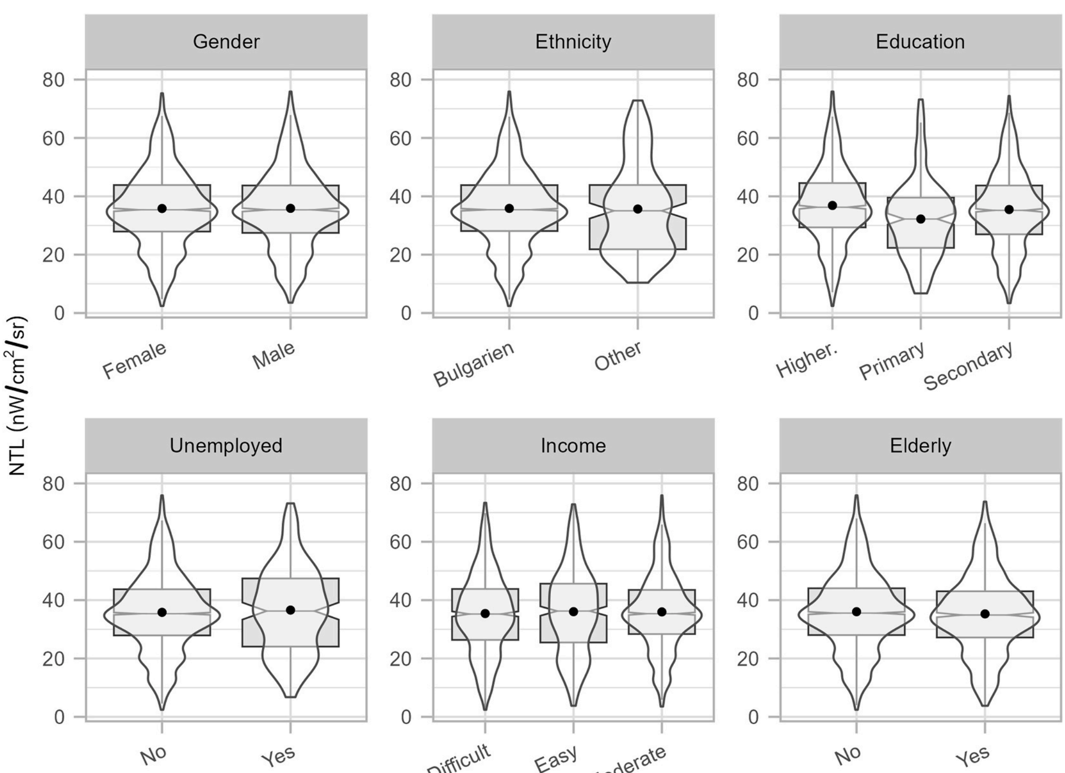

Fig. 3. Nighttime light exposures for the 500 m buffer stratified by the covariates. The dots represent means. Not shown in the boxplots are observations beyond the end of the whiskers.

Respondents who had, at minimum, completed secondary school education had greater NTL exposure than those with lower educational attainment at the 0.5 and 0.8 quantiles; the association was null for the 0.2 quantile. Those who had completed higher education showed more pronounced effect sizes. Independent of the quantile, the association between NTL exposure and the elderly was negative and insignificant.

Table 2
Nighttime light exposure for the 500 m buffer stratified across tertiles and covariates.

	Low NTL (1st tertile) [2.42,31.26)	Moderate NTL (2nd tertile) [31.26,40.64)	High NTL (3rd tertile) [40.64,98.43]	*p*-value
Ethnicity				0.012
Bulgarian	1,351 (94.9%)	1,382 (97.1%)	1,366 (95.9%)	
Other	72 (5.1%)	41 (2.9%)	58 (4.1%)	
Education				<0.001
Primary educ. not completed/compl	97 (6.8%)	67 (4.7%)	46 (3.2%)	
Completed secondary educ.	843 (59.2%)	801 (56.3%)	791 (55.5%)	
Completed higher educ.	483 (33.9%)	555 (39.0%)	587 (41.2%)	
Unemployed				0.387
No	1,370 (96.3%)	1,376 (96.7%)	1,363 (95.7%)	
Yes	53 (3.7%)	47 (3.3%)	61 (4.3%)	
Income				<0.001
Difficult	342 (24.0%)	269 (18.9%)	324 (22.8%)	
Moderate	943 (66.3%)	1,055 (74.1%)	945 (66.4%)	
Easy	138 (9.7%)	99 (7.0%)	155 (10.9%)	
Elderly				0.397
no	1,059 (74.4%)	1,088 (76.5%)	1,084 (76.1%)	
yes	364 (25.6%)	335 (23.5%)	340 (23.9%)	
Sex				0.582
Male	624 (43.9%)	651 (45.7%)	643 (45.2%)	
Female	799 (56.1%)	772 (54.3%)	781 (54.8%)	

Note: Chi^2 tests assessed differences across tertiles for categorical variables.

Likewise, there was an insignificant association between NTL exposure and non-Bulgarian populations. We observed null associations across all quantiles between NTL exposure and those who perceived their income as easy. Unlike those who perceived their income as difficult, those with moderate self-perceived income difficulties had lower NTL exposure levels at the 0.5 and 0.8 quantiles. Unemployment was inversely associated with NTL exposure levels for the 0.2 and 0.5 quantiles and insignificant at the 0.8 quantile. Population density was robustly associated with higher NTL exposure across all quantiles, with a slightly stronger effect size for the 0.8 quantile.

3.4. City-specific regression analyses

Our secondary analyses showed notable differences when fitting city-specific models (Fig. 5; for numeric results, see Supplementary Table S3). We observed heterogeneous associations with perceived income situations. While high-income respondents in Ruse and Varna faced lower NTL exposure across the quantile than those facing income difficulties, the reverse appeared in Plovdiv, and the associations were primarily null elsewhere. The tendency observed in the pooled data (Fig. 4), where respondents with higher educational attainment faced higher levels of NTL exposure, was also evident in Ruse, Plovdiv, and Varna for the median and upper quantile. The elderly were less exposed to NTL than other adults in Ruse, a result that was not apparent elsewhere. In Plovdiv and Varna, we observed that non-Bulgarians had greater NTL exposure than Bulgarians across the three quantiles, while in the remaining cities, the associations were null. In contrast to the pooled model, employment status did not reach statistical significance. Population density was positively associated with NTL levels, irrespective of quantile and city, though the magnitude of the effect size differed.

3.5. Sensitivity analyses

Our sensitivity tests confirmed that overall results were robust against changes in the neighborhood specification from the 500 m buffer to the 100 or 800 m buffers (Supplementary Figs. S4 and S5). After stratification by sex, the estimates replicated the results of the pooled model in our primary analyses (Supplementary Figs. S6 and S7). Refitting Model 2 using the NTL data with the original resolution resulted in minor changes (Supplementary Table S4). For example, compared to the main model (Fig. 4), unemployment in the 0.2 quantile turned borderline significant. In the 0.5 quantile, the elderly turned from weakly to significantly associated. The results for the 0.8 quantile remained unchanged. Changing the buffer sizes to 100 and 800 m in the city-specific models did not lead to significant differences in the estimated associations (Supplementary Figs. S8 and S9).

4. Discussion

Artificial NTL is a growing public urban health issue (Zielinska--Dabkowska et al., 2023). As with other environmental threats (Gerrish and Watkins, 2018; Hajat et al., 2015; Trudeau et al., 2023), specific populations may be disproportionately burdened and vulnerable to nighttime light exposure. In our multi-city study of 4,270 adults in urban Bulgaria, we examined disparities in NTL exposure at the individual level.

4.1. Principle findings and interpretation given the available evidence

Our individual-level results were not directly comparable to results from other studies as the existing evidence on disparities in NTL exposure was ecological (Motairek et al., 2023; Nadybal et al., 2020; Xiao et al., 2023a). Our descriptive results revealed that NTL levels vary substantially geographically, with the highest levels of NTL occurring in the coastal city of Varna, where the tourism season remained active throughout the first half of the survey, and the lowest in Ruse. A previous small-area study in the United States also reported that urban and coastal areas face pronounced NTL (Xiao et al., 2023a).

Our regressions revealed partial disparities along the sociodemographic gradient, with some aligning with our hypotheses and others not. We observed greater NTL exposure levels among people with higher educational attainment compared to those with completed/uncompleted primary education, while those who perceived their income situations as moderate experienced less NTL exposure than those facing difficult income situations. It is not feasible to compare these education-related findings with others because we are unaware of any other NTL study that used education as a proxy for socioeconomic status. In Bulgaria, it is not necessarily the case that those with high educational attainment belong to the high-income group (Bratoeva-Manoleva, 2017) and often reside in densely populated mixed-use neighborhoods or high-rise residential complexes in intermediate and peripheral areas. By contrast, our results on income differ from those of earlier work. For example, another census tract-based study in the continental United States found that mid-household income tracts faced higher NTL exposure (Nadybal et al., 2020), while low and high-income tracts were

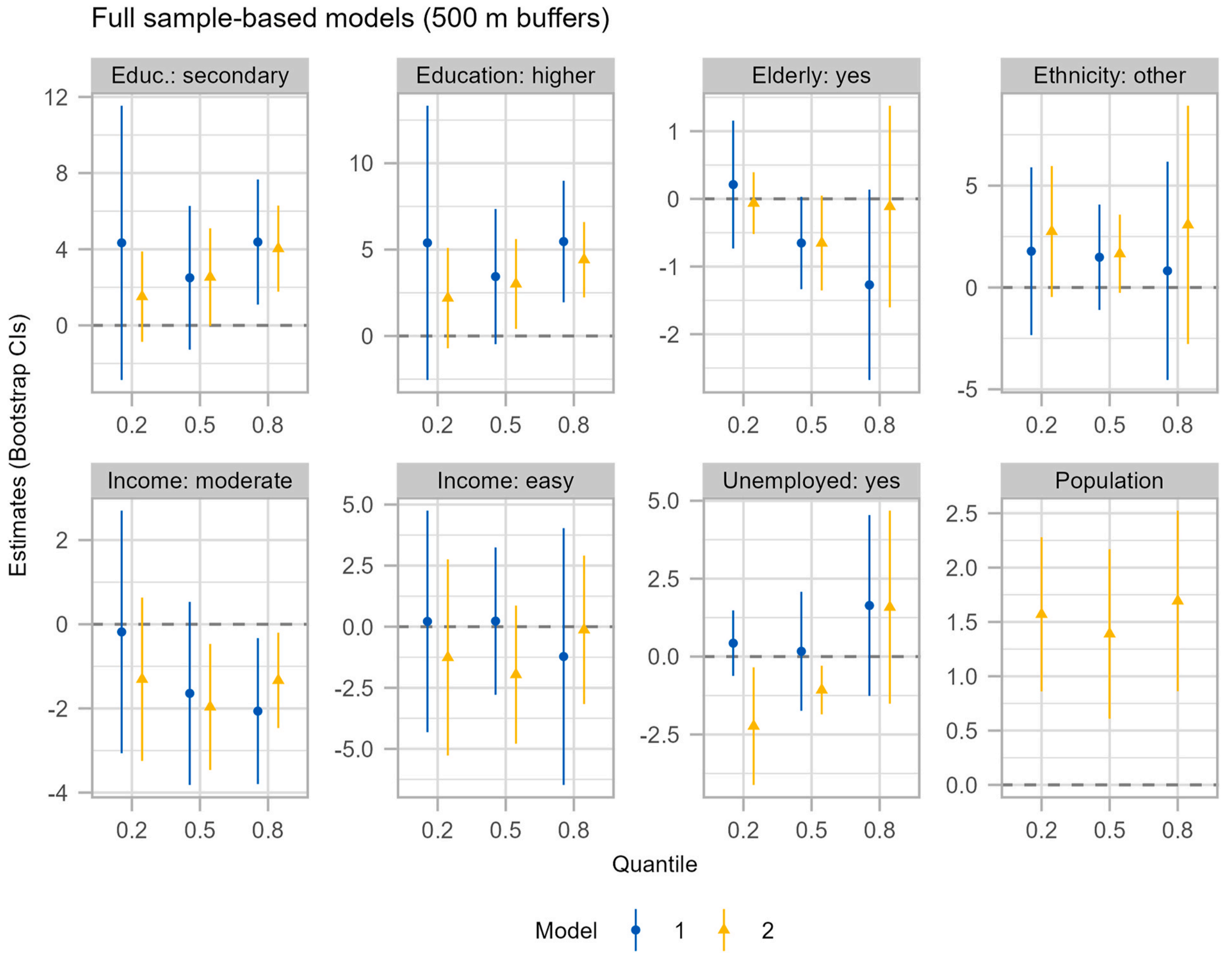

Fig. 4. Associations between nighttime light at the place of residence and sociodemographics for the 0.2, 0.5, and 0.8 quantiles. Point estimates and the CIs obtained through 500 bootstrap replications are reported. Effects were estimated using linear mixed quantile regressions. We adjusted for sociodemographics in Model 1 and further adjusted for population density in Model 2. The reference categories were as follows: a) primary education not completed/completed, b) no elderly person, c) Bulgarian, d) difficult self-perceived income situation, and e) employed. The values '0.2', '0.5', and '0.8' refer to the 0.2, 0.5, and 0.8 regression quantile estimates.

associated with less NTL, suggesting a non-linear effect. Detrimental exposures, including NTL, in more deprived US areas are possibly a legacy of historic redlining (Lee et al., 2022; Motairek et al., 2023). Opposed to our hypothesis, the unemployed experienced lower NTL levels at low to moderate exposure magnitudes. Although not universally the case, we speculate that more affluent populations experience greater NTL exposure, have more financial means, opt to live in prestigious central (and historical) neighborhoods, and thus benefit from enhanced accessibility to workplaces, cultural amenities, and commercial services, while having the financial means to minimize indoor exposure to NTL. Significantly lower levels of NTL annoyance reported by high-income earners, as supported in our post hoc analysis by a significant Chi^2 test ($p < 0.001$), support this speculation. By contrast, unemployed people often have lower socioeconomic status and reside in remote, less appealing neighborhoods, frequently accommodating other land use activities requiring less nighttime illumination.

We observed null NTL differences between the elderly versus the non-elderly and between those of non-Bulgarian ethnicity versus Bulgarians. The finding that minorities experience similar levels of exposure to NTL is in contradistinction to the two available US studies (Nadybal et al., 2020; Xiao et al., 2023a). For example, census tracts with higher proportions of non-native residents (e.g., Black, Hispanic, and Asian populations) had higher NTL exposure levels (Nadybal et al., 2020). Note that, due to a low frequency of non-Bulgarians in our complete sample (3.8%), we aggregated those ethnic groups for statistical reasons, possibly hiding such associations at the expense of minority groups. Despite data aggregation across ethnic groups, the statistical power to detect between-group differences remained low. Regarding urbanicity, the positive association between population density and NTL was congruent with our expectations, mirroring previous scholarship (Nadybal et al., 2020) and attributable to an increased level of economic activities, which often go hand-in-hand with higher radiance levels in high-density areas (Zhang and Seto, 2011).

Synthesizing the available within-city results suggested that they mostly confirmed what had been reported by similar analyses. Congruent with others (Peris and Arguelles, 2023), the results show more complex and differentiated patterns of sociodemographic inequalities when looking at the cities individually rather than analyzing the cities in aggregate. Moreover, as was the case elsewhere (Helbich et al., 2018; Tonne et al., 2018), for some sociodemographics (e.g., education and income), we noticed varying associations in magnitudes across low, mid, and high NTL exposure quantiles. These were only partially captured by applying regressions to the mean as typically applied in environmental justice scholarship (Casey et al., 2023). These results suggest that localized strategies to combat NTL disparities are vital to achieving equal and sustainable cities.

These observed NTL exposure disparities may disproportionately affect overexposed and vulnerable sociodemographic groups, potentially increasing health disparities. While still a matter of debate, NTL exposure has been linked to circadian rhythms becoming desynchronized from diurnal environmental changes, partially caused by suppression of melatonin production. Tentatively, this desynchronization of

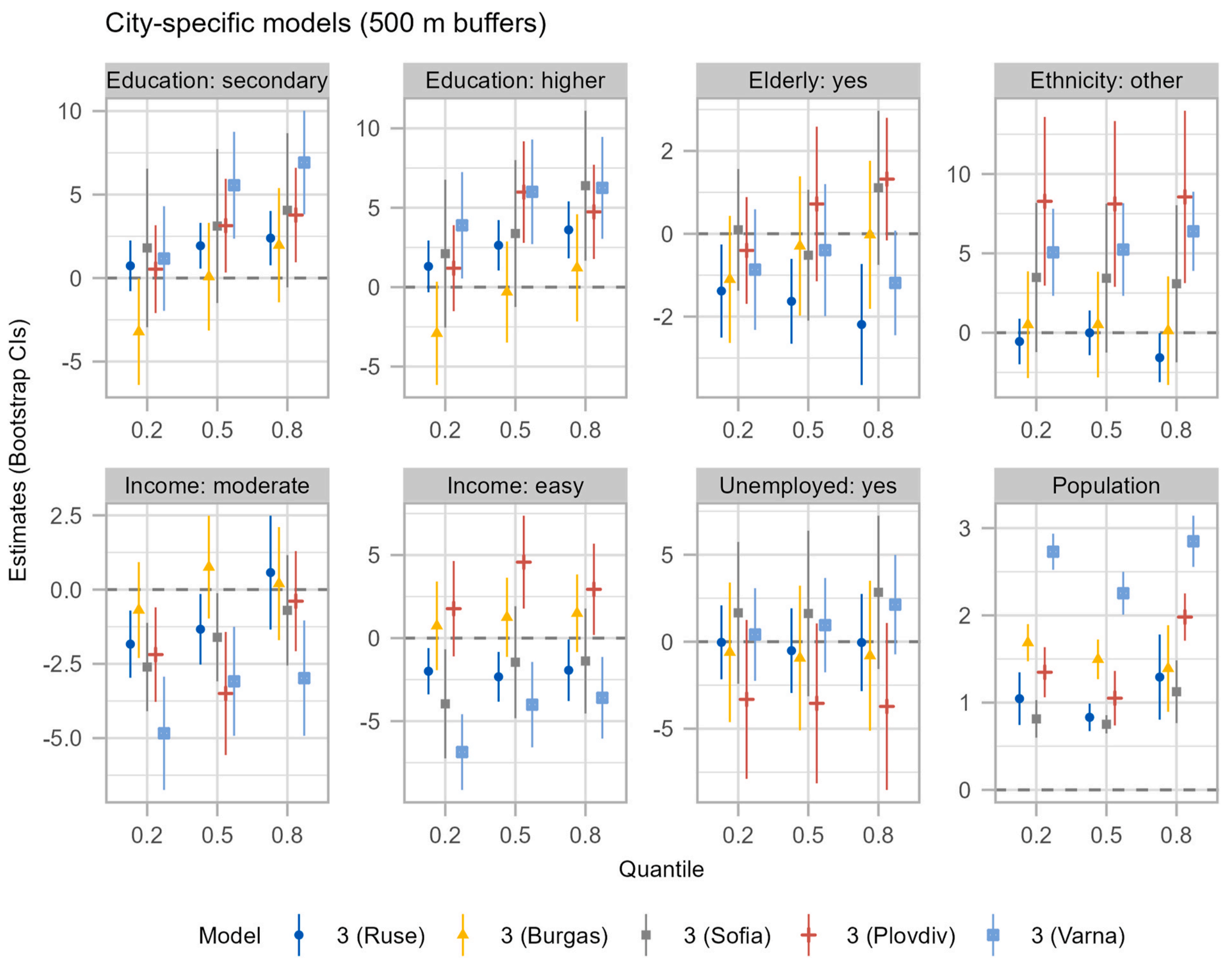

Fig. 5. City-specific associations between nighttime light at the place of residence and sociodemographics for the 0.2, 0.5, and 0.8 quantiles. Point estimates and the CIs obtained through 500 bootstrap replications are reported. Effects were estimated using linear quantile regressions. Fig. 3 provides the reference categories. Cities are ranked by increasing mean nightlight levels. The values '0.2', '0.5', and '0.8' refer to the 0.2, 0.5, and 0.8 regression quantile estimates.

circadian rhythms is related to poorer health outcomes (Tähkämö et al., 2019). For example, a meta-analysis has shown a 12% higher risk for breast cancer for the most versus the least exposed to NTL in outdoor environments and a 13% higher risk in indoor environments (Lai et al., 2021). Similarly, increased nightlight exposure has been related to a 22% higher prevalence of sleep issues (Y.-X. Xu et al., 2023), a 21% higher risk of cardiometabolic disease (Y. Xu et al., 2023), and increased mental disorder risks (Tancredi et al., 2022).

4.2. Strengths and limitations

This study possesses multiple strengths. In contrast to prior environmental injustice research (Hayward and Helbich, 2024), our study is one of the few that analyzed disparities in outdoor NTL exposure; to our knowledge, it is the first dealing with NTL exposure at the individual level and offers more nuanced results than the ecological studies conducted previously (Xiao et al., 2023a). Regardless of the study design, while previous scholarship centered on North America (Nadybal et al., 2020; Xiao et al., 2023a), we relied on Eastern Europe, where NTL tends to be lower but is rising (Falchi et al., 2019). Our analysis benefited from using the first representative health survey data of the five largest Bulgarian cities. Another notable advancement is our exposure assessment. We obtained actual residential addresses, enabling us to use home-based exposure assessments instead of assigning NTL exposures based on administrative units previously known to have conceptual deficits. A methodological strength of our analysis was that we transcended the rigidity of regressions to use the mean (Geraci and Bottai, 2014). Our quantile regressions offered a more detailed depiction of how peoples' sociodemographics relate to NTL.

Some caveats must be acknowledged, as with all studies, along with recommendations for future research. First and foremost, NTL estimates were assessed through moderate-resolution satellite imagery (Levin et al., 2020; Zhao et al., 2019), potentially overlooking small-scale variations in NTL (e.g., emitted from localized sources such as streetlights) and underestimated visual NTL (Harding et al., 2024). As the geographic coverage of new satellites increases (e.g., Jilin-1 with its ~1 m resolution), such high-resolution instruments will become feasible alternatives (Xu et al., 2022). Currently, however, VIIRS imagery is widely accessible, allowing the reproduction of studies in various contexts and strengthening the knowledge base concerning disparities in NTL (Sayyed et al., 2024). Future studies may also downscale the moderate-resolution VIIRS data based on auxiliary land use data. Second, for privacy-related reasons, we only had data available on perceived income situations, likely an imperfect measure of people's socioeconomic conditions (Galobardes et al., 2007). Third, similar to ours, environmental justice studies usually assess exposures one at a time. While unfavorable exposures typically co-occur (Hankey and Marshall, 2017), scholarship considering synergistic and competing effects is warranted to capture possible multi-environmental jeopardy (Doiron et al., 2020). Fourth, some socio-demographics that were found elsewhere to be related to NTL were insignificant in our case. We would like to emphasize that this may be due to power issues because some covariate classes had few observations. Finally, our study was cross-sectional and not meant to provide insights into causalities. Future studies are encouraged to adopt longitudinal designs to attain a more causal understanding and time trends of disparities in NTL exposure to alleviate this limitation (Xiao et al., 2023b).

5. Conclusions

NTL generated by human activities is a growing health concern. However, as our study of urban Bulgaria suggested, this burden is, at least in part, unevenly distributed across urban populations, possibly widening health inequalities. In addition to geographic variations across the cities we studied, we found that some sociodemographic populations experienced disproportionate NTL exposures. The stratified models for each city elucidated more complex patterns and heterogeneous associations. To tackle the root causes of these NTL disparities and to realize healthy and equitable societies, it appears critical to foster nuanced policy measures that transcend generic, uniform NTL mitigation strategies centering on local circumstances. Further individual-level analyses of other cities, similar to our pioneering study, are warranted to build a more solid evidence base, ideally anchored by longitudinal data.

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Declaration of generative AI in scientific writing

No generative AI and AI-assisted technologies were used during the preparation of this work.

Data sharing

Nighttime light data used in this study can be made available to researchers directed to the corresponding author. The survey data used for this publication are available based on a data transfer agreement upon a reasonable request to Angel M. Dzhambov.

CRediT authorship contribution statement

Marco Helbich: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Angel Burov:** Writing – review & editing, Data curation. **Donka Dimitrova:** Writing – review & editing, Data curation. **Iana Markevych:** Writing – review & editing, Data curation. **Mark J. Nieuwenhuijsen:** Writing – review & editing, Data curation. **Angel M. Dzhambov:** Writing – review & editing, Project administration, Funding acquisition, Data curation.

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.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.119803.

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