Ethnic and socioeconomic inequalities in air pollution exposure: a cross-sectional analysis of nationwide individual-level data from the Netherlands

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Summary

Background Air pollution contributes to a large disease burden and some populations are disproportionately exposed. We aimed to evaluate ethnic and socioeconomic differences in exposure to air pollution in the Netherlands.

Methods We did a nationwide, cross-sectional analysis of all residents of the Netherlands on Jan 1, 2019. Sociodemographic information was centralised by Statistics Netherlands and mainly originated from the National Population Register, the tax register, and education registers. Concentrations of NO_2, $PM_{2·5}$, PM_{10}, and elemental carbon, modelled by the National Institute for Public Health and the Environment, were linked to the individual-level demographic data. We assessed differences in air pollution exposures across the 40 largest minority ethnic groups. Evaluation of how ethnicity intersected with socioeconomic position in relation to exposures was done for the ten largest ethnic groups, plus Chinese and Indian groups, in both urban and rural areas using multivariable linear regression analyses.

Findings The total study population consisted of 17 251 511 individuals. Minority ethnic groups were consistently exposed to higher levels of air pollution than the ethnic Dutch population. The magnitude of inequalities varied between the minority ethnic groups, with 3–44% higher exposures to NO_2 and 1–9% higher exposures to $PM_{2·5}$ compared with the ethnic Dutch group. Average exposures were highest for the lowest socioeconomic group. Ethnic inequalities in exposure remained after adjustment for socioeconomic position and were of similar magnitude in urban and rural areas.

Interpretation The variability in air pollution exposure across ethnic and socioeconomic subgroups in the Netherlands indicates environmental injustice at the intersection of social characteristics. The health consequences of the observed inequalities and the underlying processes driving them warrant further investigation.

Funding The Gravitation programme of the Dutch Ministry of Education, Culture, and Science, the Netherlands Organization for Scientific Research, the Netherlands Organisation for Health Research and Development, and Amsterdam University Medical Center.

Lancet Planet Health 2024; 8: e18–29

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Introduction

Air pollution emissions have major adverse consequences for human health and the natural systems on which health depends.[1] Globally, an estimated 4·9 million deaths and 147 million disability-adjusted life-years were attributable to air pollution in 2017.[2] Cardiovascular diseases, including myocardial infarction and stroke, are the leading cause of mortality and morbidity from air pollution exposure, followed by pulmonary diseases, including chronic obstructive pulmonary disease, lung cancer, and asthma.[3,4] In the EU, exposure to particulate matter $(PM)_{2·5}$ was responsible for an estimated 379 000 deaths and exposure to NO_2 was responsible for an estimated 54 000 deaths in 2018.[3]

Exposure to air pollution is not evenly distributed across socially determined population groups, as has been documented in the environmental justice literature.[5,6] Most research on this topic has been conducted in the USA and generally shows higher exposures among marginalised populations, including minority ethnic groups.[5,7] Studies in the USA have shown that disparities differ in magnitude between minority ethnic groups, underlining the importance of assessing disparities across a detailed classification of social groups.[8–10] Results from the USA cannot be extrapolated to European countries due to their distinct histories of migration, built environment development, and spatial patterns of residential segregation. Within Europe, several studies have shown that neighbourhoods with a higher percentage of immigrants are more likely to contain toxic industrial facilities.[5,6] In the Netherlands, PM_{10} and NO_2 concentrations are higher in neighbourhoods with a higher proportion of immigrants from low-income and middle-income countries (LMICs).[11] A study in England, Wales, and Ireland assessing the average air pollution concentrations

Research in context

Evidence before this study

This study was informed by systematic reviews of inequalities in exposure to air pollution and by scientific publications that report absolute concentrations of air pollution by race and ethnicity, resulting from a search of PubMed, Scopus, Web of Science, and Google Scholar on April 14, 2022. The search included the terms ("race" OR "ethnic" OR "nationality" OR "migrant") AND ("particulate matter" OR "$PM_{2·5}$" OR "PM_{10}" OR "NO_2" OR "EC" OR "BC" OR "soot") and additional synonyms of these terms per search block. Studies from high-income countries, as defined by the criteria of the World Bank, were included. After full text screening, 47 original research articles were identified, of which 42 were done in the USA, showing higher exposure to hazardous pollutants for minority ethnic groups including African American, Latin American, Asian American, and native American populations. Several studies reported on ethnic inequalities in exposure to air pollution in European countries, although they define ethnic groups in less detail than US-based studies or use aggregated data. These studies show that neighbourhoods with a higher percentage of immigrants are exposed to higher levels of air pollution and are more likely to contain toxic industrial facilities. Asian and Latin American populations live disproportionally more frequently in the most polluted areas of Barcelona and Madrid (Spain), but mixed results were found for African populations. A study in England, Wales, and Ireland found that Pakistani, Bangladeshi, Indian, African, and Caribbean populations were exposed to higher air pollution levels than the majority population. Findings on the socioeconomic gradient in exposure to air pollution in Europe are less consistent than in US-based studies, with some studies showing the highest exposures for lower socioeconomic groups and others showing the highest exposures for higher socioeconomic groups. Exposure inequalities at the intersection of social determinants were assessed by one US-based study, which found up to 45 times higher air toxicity scores for census tracts in urban areas with a higher percentage of Black residents, a higher percentage of female-headed households, and residents with a lower socioeconomic position.

Added value of this study

To our knowledge, this study is the first in Europe to assess differences in exposure to air pollution for a detailed classification of various social groups and the first to assess inequalities at the individual-level intersection of ethnicity and socioeconomic position. We found that minority ethnic groups were consistently exposed to higher levels of air pollution than the ethnic Dutch population and that exposure also varied considerably between minority ethnic groups. Inequalities persisted after adjustment for socioeconomic position and were largest for Surinamese, Moroccan, Turkish, and former Netherlands Antillean and Aruban ethnic groups with lower socioeconomic position living in highly urbanised areas.

Implications of all the available evidence

The persistence of inequalities in exposure when stratified for socioeconomic position and urbanicity shows that higher air pollution exposure among minority ethnic groups acts both through and independently of these factors. Policies to reduce air pollution should prioritise reducing inequalities. Given our finding that inequalities in exposure were consistent across NO_2, $PM_{2·5}$, PM_{10}, and elemental carbon, emissions reductions from multiple sources are needed, including vehicular and industrial emissions. A greater understanding is needed of the role that environmental exposures have in influencing ethnic and socioeconomic health disparities.

at a local district level found higher exposures to NO_2, SO_2, $PM_{2·5}$, PM_{10}, ozone, and carbon monoxide among Pakistani, Bangladeshi, Indian, African, and Caribbean populations compared with the majority population.[12] Beyond these studies, there is a paucity of data on exposure levels for the large variety of ethnic groups in Europe. As underlying processes resulting in unequal exposures are unlikely to be equal across ethnic groups research to supplement these data are needed.

Exposure to air pollution is generally higher among groups with a lower socioeconomic position, although this association is more consistent in studies in the USA than in Europe.[7,13] Numerous studies have assessed the extent to which socioeconomic position drives exposure inequalities in air pollution between ethnicities, and some have shown that ethnic inequalities remain upon adjusting for socioeconomic position.[8,11,14] However, assessment of only the explanatory role of socioeconomic position in ethnic exposure inequalities might overlook marginalisation of populations at the intersection of these two social determinants. An intersectionality approach, wherein multiple social identities might synergistically reflect oppression and marginalisation, has been integrated into environmental justice research before.[15] Although there is no consensus or best standard yet on intersectional methods, evaluating interaction terms and exposure patterns across strata better captures the complexities of associations between social determinants than overall effect analyses.[16] US-based studies have described interactions between social determinants and applied risk stratification related to air pollution exposure.[5,17]

Comprehensive understanding of ethnic and socioeconomic disparities in exposure to air pollution in European settings, including the Netherlands, is insufficient. Most studies have assessed ethnic differences in air pollution exposure at the neighbourhood level, missing finer-scale exposure contrasts (eg, living near a major road). Assessment at the neighbourhood level could also be more prone to confounding by other area-level determinants. Furthermore, differentiation between ethnic groups has usually been done by formulating broad, heterogeneous groups. Moreover, to our knowledge, the inter-relationship between individual-level ethnicity and socioeconomic position to air pollution exposure has not been previously investigated in Europe. Before the underlying processes and health consequences of ethnic and socioeconomic inequalities in exposure to air pollution can be identified, understood, and addressed, we must evaluate to what extent these inequalities occur and inter-relate. Therefore, the first aim of our study is to identify individual-level differences in exposure to air pollution between ethnic groups in the Netherlands. The second aim of our study is to examine the inter-relationships between ethnicity and socioeconomic position to air pollution exposure.

Methods

Study design and participants

For this cross-sectional study, data on the average concentrations of air pollutants for the year 2019 were linked to sociodemographic data on all registered residents of the Netherlands. Sociodemographic information was centralised by Statistics Netherlands and mainly originated from the National Population Register, the tax register, and education registers. A detailed description of the sources and generation of the datasets from these registers can be found at Centraal Bureau voor de Statistiek. From the National Population Register, we created a cohort of all residents of the Netherlands as of Jan 1, 2019. Coverage is expected to be almost complete as registration is mandatory in the Netherlands. However, asylum seekers are slightly under-represented as registration can take up to 6 months from arrival. Average concentrations of air pollutants at all inhabited addresses in 2019 were linked to individuals in the cohort based on residential address on Jan 1, 2019. The study was conducted in compliance with privacy legislation. The medical ethical review board of the University Medical Center Utrecht deemed that ethical approval for this study was not required and provided a waiver for the Dutch Act on Medical Research Involving Human Subjects (reference number 21–655/C).

Procedures

Total exposure to air pollution cannot be represented by a single air pollutant due to different sources and dispersion patterns. We therefore selected NO_2, $PM_{2\cdot5}$, PM_{10}, and elemental carbon as air pollutants to be evaluated, given their importance from a regulatory and health perspective.[18,19] The average concentrations of these air pollutants for the year 2019 were modelled and mapped on a grid with a resolution of 25 m by the National Institute for Public Health and the Environment. The maps were constructed from 1 km resolution nationwide background concentration maps combined with local traffic information. In short, the nationwide background concentration maps were based on dispersion models including information on industrial, vehicular, and household emissions in the Netherlands and abroad, meteorological information, and chemical information.[20] Two models (one for roads within cities and one for highways in more open terrain) based on local vehicular traffic data, originating from the Dutch Nationaal Samenwerkingsprogramma Luchtkwaliteit[21–23] were combined with the national background maps. Next, air pollution concentrations were calculated at 9 million datapoints in the Netherlands, which were then interpolated to a raster map with a 25 m resolution using ordinary Kriging. The Geoscience and Health Cohort Consortium linked the air pollution concentration to address locations and exported these to tabular format.[24] Model prediction patterns and absolute concentrations generally agreed well with measurements for NO_2 and $PM_{2\cdot5}$;[20,22] however, quality quantification is hard to interpret as measurements have been used in calibrating the models. The models for elemental carbon were more recently developed and are less well calibrated, resulting in potential misclassification of the absolute concentrations.[23] As misclassification is expected to be similar between social groups, comparisons of relative differences between groups will be interpretable.

To align with previous Dutch publications, we differentiated between ethnic groups according to the Statistics Netherlands' definition for migration background, which is based on country of birth of the person and their parents.[25] If the person was born abroad but both parents in the Netherlands, ethnicity was classified as Dutch. If the person and both parents were born in the Netherlands, the person's ethnicity was classified as Dutch. If the person and one or both parents was born abroad (ie, first-generation immigrant), ethnicity was based on the person's country of birth. If the person was born in the Netherlands and one of the parents was born abroad (ie, second-generation immigrant), ethnicity was based on the country of birth of the parent born abroad. If the person was born in the Netherlands and both parents were born abroad (ie, second-generation immigrant), ethnicity was based on the mother's country of birth.

For **sources and generation of datasets** see www.cbs.nl/microdata

The primary outcome was differences in exposure to air pollution between ethnic groups in the Netherlands. For the primary analyses, a combination of standardised disposable household income and taxable assets was used as an indicator of individual-level socioeconomic position. These data are available from the national tax register and are nearly complete. The main taxable assets are houses, shares, and savings. Debts are deducted from these. Income was determined as gross household income minus income transfers, such as alimony, income insurance premiums, health insurance premiums, and taxes. Income was standardised by household composition by dividing the value by an equivalence factor derived by Statistics Netherlands: $E=(Pv+[0\cdot8\times Pk])^{0\cdot5}$ where Pv is the number of adults and Pk the number of children in

	Total cohort (n=17 251 511)	Dutch (n=13 175 068)	Turkish (n=409 372)	Moroccan (n=401 871)	Indonesian (n=358 196)	Surinamese (n=353 425)	German (n=350 703)	Polish (n=184 692)	Antillean and Aruban* (n=160 960)	Belgian (n=119 457)	Syrian (n=97 997)	Chinese (n=77 363)	Indian (n=48 563)
Sex													
Male	8 564 692 (49·6%)	6 557 285 (49·8%)	210 736 (51·5%)	204 379 (50·9%)	173 317 (48·4%)	167 411 (47·4%)	161 925 (46·2%)	88 276 (47·8%)	80 519 (50·0%)	57 064 (47·8%)	54 619 (55·7%)	36 279 (46·9%)	27 467 (56·6%)
Female	8 686 806 (50·4%)	6 617 783 (50·2%)	198 636 (48·5%)	197 492 (49·1%)	184 879 (51·6%)	186 014 (52·6%)	188 778 (53·8%)	96 416 (52·2%)	80 441 (50·0%)	62 393 (52·2%)	43 378 (44·3%)	41 084 (53·1%)	21 096 (43·4%)
Missing	13 (<0·1%)	0	0	0	0	0	0	0	0	0	0	0	0
Age													
0–25 years	4 844 020 (28·1%)	3 532 210 (26·8%)	142 927 (34·9%)	170 553 (42·4%)	26 390 (7·4%)	96 328 (27·3%)	63 300 (18·0%)	55 858 (30·2%)	62 572 (38·9%)	33 099 (27·7%)	50 566 (51·6%)	26 903 (34·8%)	15 500 (31·9%)
25–60 years	7 982 522 (46·3%)	5 861 195 (44·5%)	231 461 (56·5%)	195 108 (48·5%)	199 698 (55·8%)	197 090 (55·8%)	128 204 (36·6%)	117 854 (63·8%)	80 703 (50·1%)	50 375 (42·2%)	44 300 (45·2%)	44 077 (57·0%)	30 801 (63·4%)
>60 years	4 424 956 (25·6%)	3 781 663 (28·7%)	34 984 (8·5%)	36 210 (9·0%)	132 108 (36·9%)	60 007 (17·0%)	159 199 (45·4%)	10 980 (5·9%)	17 685 (11·0%)	35 983 (30·1%)	3131 (3·2%)	6383 (8·3%)	2262 (4·7%)
Missing	13 (<0·1%)	0	0	0	0	0	0	0	0	0	0	0	0
Socioeconomic position† determined by standardised disposable household income and assets													
Low	4 840 715 (28·1%)	2 922 147 (22·2%)	205 956 (50·3%)	255 644 (63·6%)	96 870 (27·0%)	146 698 (41·5%)	120 896 (34·5%)	87 521 (47·4%)	89 497 (55·6%)	34 637 (29·0%)	91 646 (93·5%)	37 883 (49·0%)	19 678 (40·5%)
Middle	6 020 457 (34·9%)	4 786 563 (36·3%)	145 963 (35·7%)	110 736 (27·6%)	121 967 (34·1%)	125 694 (35·6%)	116 449 (33·2%)	73 299 (39·7%)	45 894 (28·5%)	38 531 (32·3%)	4647 (4·7%)	18 408 (23·8%)	14 894 (30·7%)
High	6 389 371 (37·0%)	5 465 960 (41·5%)	57 415 (14·0%)	35 450 (8·8%)	139 341 (38·9%)	81 008 (22·9%)	113 339 (32·3%)	23 826 (12·9%)	25 531 (15·9%)	46 277 (38·7%)	1688 (1·7%)	21 060 (27·2%)	13 984 (28·8%)
Missing	968 (<0·1%)	398 (<0·1%)	38 (<0·1%)	41 (<0·1%)	18 (<0·1%)	25 (<0·1%)	19 (<0·1%)	46 (<0·1%)	38 (<0·1%)	12 (<0·1%)	16 (<0·1%)	12 (<0·1%)	7 (<0·1%)
Education level													
Low	3 987 024 (23·1%)	2 785 945 (31·6%)	152 721 (45·9%)	169 668 (49·6%)	37 040 (16·7%)	83 995 (29·6%)	56 232 (31·3%)	62 431 (55·4%)	50 603 (35·8%)	26 705 (37·3%)	51 700 (74·1%)	21 911 (44·0%)	11 737 (50·7%)
Middle	3 588 188 (20·8%)	2 743 776 (31·1%)	111 007 (33·4%)	108 054 (31·6%)	70 426 (31·7%)	108 056 (38·1%)	55 331 (30·8%)	30 772 (27·3%)	49 803 (35·3%)	19 605 (27·4%)	11 409 (16·3%)	7283 (14·6%)	2962 (12·8%)
High	4 152 519 (24·1%)	3 279 055 (37·2%)	68 935 (20·7%)	64 386 (18·8%)	114 478 (51·6%)	91 735 (32·3%)	68 148 (37·9%)	19 554 (17·3%)	40 801 (28·9%)	25 338 (35·4%)	6678 (9·6%)	20 614 (41·4%)	8437 (36·5%)
Missing	5 523 780 (32·0%)	4 366 292 (33·1%)	76 709 (18·7%)	59 763 (14·9%)	136 252 (38·0%)	69 639 (19·7%)	170 992 (48·8%)	71 935 (38·9%)	19 753 (12·3%)	47 809 (40·0%)	28 210 (28·8%)	27 555 (35·6%)	25 427 (52·4%)
Job seeker													
Yes	1 483 525 (8·6%)	881 804 (6·7%)	66 371 (16·2%)	71 569 (17·8%)	37 893 (10·6%)	63 140 (17·9%)	24 143 (6·9%)	26 899 (14·6%)	31 006 (19·3%)	8395 (7·0%)	45 740 (46·7%)	4708 (6·1%)	2096 (4·3%)
No	15 767 986 (91·4%)	12 293 264 (93·3%)	343 001 (83·8%)	330 302 (82·2%)	320 303 (89·4%)	290 285 (82·1%)	326 560 (93·1%)	157 793 (85·4%)	129 954 (80·7%)	111 062 (93·0%)	52 257 (53·3%)	72 655 (93·9%)	46 467 (95·7%)
Missing	0	0	0	0	0	0	0	0	0	0	0	0	

(Table 1 continues on next page)

	Total cohort (n=17 251 511)	Dutch (n=13 175 068)	Turkish (n=409 372)	Moroccan (n=401 871)	Indonesian (n=358 196)	Surinamese (n=353 425)	German (n=350 703)	Polish (n=184 692)	Antillean and Aruban* (n=160 960)	Belgian (n=119 457)	Syrian (n=97 997)	Chinese (n=77 363)	Indian (n=48 563)
(Continued from previous page)													
Urbanicity (address density per km²)													
<2000	11 389 626 (66·0%)	9 531 959 (72·3%)	143 915 (35·2%)	126 828 (31·6%)	205 098 (57·3%)	127 805 (36·2%)	227 214 (64·8%)	109 481 (59·3%)	62 707 (39·0%)	82 444 (69·0%)	59 966 (61·2%)	33 532 (43·3%)	14 346 (29·5%)
≥2000	5 861 614 (34·0%)	3 642 871 (27·7%)	265 450 (64·8%)	275 035 (68·4%)	153 097 (42·7%)	225 617 (63·8%)	123 488 (35·2%)	75 211 (40·7%)	98 252 (61·0%)	37 011 (31·0%)	38 031 (38·8%)	43 831 (56·7%)	34 217 (70·5%)
Missing	271 (<0·1%)	238 (<0·1%)	7 (<0·1%)	8 (<0·1%)	1 (<0·1%)	3 (<0·1%)	1 (<0·1%)	0	1 (<0·1%)	2 (<0·1%)	0	0	0
Neighbourhood average income in euros (÷1000)													
Median (IQR)	30·9 (27·1–35·0)	31·6 (28·0–35·4)	25·6 (23·2–29·5)	26·2 (23·5–30·1)	31·0 (27·0–35·5)	27·5 (24·1–32·8)	29·9 (26·4–34·2)	28·9 (25·1–32·9)	27·0 (23·5–31·6)	30·7 (27·5–34·8)	27·7 (24·2–31·3)	28·7 (24·4–34·2)	30·6 (25·7–35·4)
Missing	433 099 (2·5%)	383 673 (2·9%)	1446 (0·4%)	1511 (0·4%)	5747 (1·6%)	2551 (0·7%)	7418 (2·1%)	3233 (1·8%)	1574 (1·0%)	3280 (2·7%)	1110 (1·1%)	768 (1·0%)	390 (0·8%)

Data are n (%) unless otherwise specified. The 12 main ethnic groups represent the ten largest ethnic groups plus Indian and Chinese groups. The total cohort also includes the smaller ethnic groups (9% of the total). *Former Netherlands Antillean and Aruban. †Socioeconomic position defined by standardised disposable household income and assets.

Table 1: Population characteristics

the household. This adjustment results in a lower standardised disposable household income for larger households, an approach widely used in research into socioeconomic inequality.[26] Income and assets were equally weighted, divided into percentiles, and summed into tertiles indicating a low, middle, or high socioeconomic position.

As a sensitivity analysis, to capture multiple domains of socioeconomic position, we constructed a composite socioeconomic position index by scoring and summing income and assets (low=0, middle=1, high=2), highest level of attained education (low=0, middle=1, high=2) and job-seeker registration (yes=0, no=2) into one variable. Level of education was divided into lower (primary school and lower levels of secondary school), middle (higher levels of secondary school), or higher (college and university) levels. Registration as a job seeker is obligatory in the Netherlands to receive unemployment benefits. We did not use this composite socioeconomic position index in the primary analysis due to the high proportion of missing values for education (32·0%), especially for older inhabitants and for people who completed education abroad. We excluded individuals younger than 25 years from the sensitivity analysis because they are frequently still studying, which would make level of attained education a less reliable indicator of socioeconomic position. Neighbourhood average standardised household income, categorised into tertiles, was used as an indicator of neighbourhood-level socioeconomic position. The socioeconomic position index scores were divided into three categories representing low, middle, and high socioeconomic position.

Age (in years) and gender (approximated by sex as registered at birth) were obtained from the National Population Register. Neighbourhoods in the Netherlands are defined as a homogeneously bounded part of a municipality from a building or socioeconomic perspective.[27] Urbanicity was defined by the neighbourhoods' address density. The neighbourhood's address density was the average address density around residential address in the neighbourhood. The address density around residential address was calculated as the number of addresses in a 1 km² circular buffer around the residential address. We divided urbanicity into two categories indicating that the residential address was situated in a rural to moderately urbanised neighbourhood (<2000 addresses per km²) or a highly urbanised neighbourhood (>2000 addresses per km²). We selected this cutoff to capture highly urbanised areas and still maintain sufficient numbers per ethnic and socioeconomic category.

Statistical analysis

We calculated mean (SD) exposures for the 40 largest ethnic groups in the Netherlands (representing 98% of the total population). Using independent sample *t* tests

	NO_2 (μg/m³)	NO_2 percentage difference compared with Dutch individuals	$PM_{2.5}$ (μg/m³)	$PM_{2.5}$ percentage difference compared with Dutch individuals	PM_{10} (μg/m³)	PM_{10} percentage difference compared with Dutch individuals
Total cohort (n=17 251 511)	17·5 (4·3)	..	10·1 (1·1)	..	17·6 (1·5)	..
Dutch (n=13 175 068)	16·9 (4·1)	..	10·0 (1·1)	..	17·4 (1·5)	..
Turkish (n=409 372)	20·4 (4·0)	20·1%	10·6 (0·8)	5·7%	18·3 (1·2)	5·3%
Moroccan (n=401 871)	20·8 (3·9)	22·8%	10·7 (0·8)	6·6%	18·5 (1·1)	6·3%
Indonesian (n=358 196)	18·4 (4·1)	8·4%	10·2 (1·0)	2·3%	17·8 (1·3)	2·2%
Surinamese (n=353 425)	20·6 (4·3)	21·4%	10·4 (0·9)	4·1%	18·3 (1·2)	4·8%
German (n=350 703)	17·4 (4·1)	2·8%	10·1 (1·0)	1·1%	17·5 (1·4)	0·2%
Polish (n=184 692)	18·6 (4·2)	9·7%	10·3 (1·0)	3·0%	17·9 (1·4)	2·9%
Antillean and Aruban* (n=160 960)	20·0 (4·6)	18·3%	10·3 (1·0)	3·4%	18·1 (1·4)	3·7%
Belgian (n=119 457)	17·9 (3·7)	5·4%	10·2 (1·0)	1·6%	17·5 (1·3)	0·7%
Syrian (n=97 997)	17·6 (4·0)	3·6%	10·1 (1·0)	1·3%	17·6 (1·4)	0·9%
Chinese (n=77 363)	19·9 (4·5)	17·7%	10·4 (1·0)	4·2%	18·1 (1·3)	4·1%
Indian (n=48 563)	20·8 (3·9)	22·8%	10·5 (0·9)	5·2%	18·4 (1·2)	5·5%

Data are mean (SD) unless otherwise specified. The 12 selected ethnic groups represent the ten largest ethnic groups plus Indian and Chinese groups. The total cohort also includes the smaller ethnic groups (9% of the total). PM=particulate matter. p values were calculated for each ethnicity against each pollutant, with ethnic Dutch as the reference group, using independent sample *t* tests and were not tested for the total cohort. All derived p values were $<2 \cdot 2 \times 10^{-16}$. *Former Netherlands Antillean and Aruban.

***Table 2:* Annual average air pollution concentrations (mean [SD]) at the residential address for the 12 main ethnic groups**

	NO_2 (μg/m³)	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)
Socioeconomic position			
Low (n=4 840 715)	18·3 (4·5)	10·2 (1·1)	17·7 (1·5)
Medium (n=6 020 457)	17·2 (4·2)	10·0 (1·1)	17·4 (1·5)
High (n=6 389 371)	17·3 (4·1)	10·1 (1·1)	17·6 (1·4)
p value	$p<2 \cdot 2 \times 10^{-16}$	$p<2 \cdot 2 \times 10^{-16}$	$p<2 \cdot 2 \times 10^{-16}$

Data are mean (SD) unless otherwise specified. Air pollution concentrations are for the residential addresses of individuals. Socioeconomic groups are based on standardised disposable household income and assets. p values were assessed by one-way ANOVA testing the mean difference between socioeconomic groups.

***Table 3:* Annual average air pollution concentrations for the three socioeconomic groups**

with Bonferroni correction for multiple comparisons, we tested mean exposure differences between each minority ethnic group and the ethnic Dutch population and calculated percentage differences. For all other analyses, we assessed the ten largest ethnic groups, plus Indian and Chinese groups—12 ethnic groups in total—to maintain sufficient numbers to stratify across multiple determinants. Indian and Chinese groups were included because they make up a large portion of the world's migrant population.[28] We calculated mean (SD) air pollution exposures for the three socioeconomic groups and tested the mean differences using a one-way ANOVA. To assess the inter-relationship of socioeconomic position and ethnicity to air pollution exposure, we did multivariable linear regression analyses and calculated estimated marginal mean exposure concentrations for each air pollutant. We stratified the regression analyses by urbanicity (rural to moderately urbanised or highly urbanised) to evaluate whether exposure inequalities persist within urban and rural areas and to compare exposure patterns between urban and rural areas. Ethnicity, socioeconomic position based on income and assets, gender, and age were independent variables in the models. Estimated marginal means were standardised by gender and age. We tested the interaction between socioeconomic position and ethnicity and stratified the estimated marginal means by socioeconomic position.

To evaluate if exposure patterns were consistent using the multidimensional socioeconomic position index, we did a complete case analysis including individuals older than 25 years, comparing models with income and assets as indicators of socioeconomic position versus the multidimensional socioeconomic position index. As secondary analyses, we compared exposure disparities across three age groups (<25 years, 25–60 years, >60 years) and upon exclusion of second-generation immigrants. We also added a random intercept for neighbourhood to the models to evaluate the extent to which exposure inequalities reflect high pollution in neighbourhoods wherein minority ethnic and lower socioeconomic groups cluster. Next, we added neighbourhood socioeconomic position as a fixed effect to these models with a random intercept to evaluate its contribution. For all regression analyses, we evaluated diagnostics and found that the residuals were normally distributed and that there was negligible multicollinearity or heteroscedasticity. R version 4.1.3 was used for all analyses.

Role of the funding source

The funders of this study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

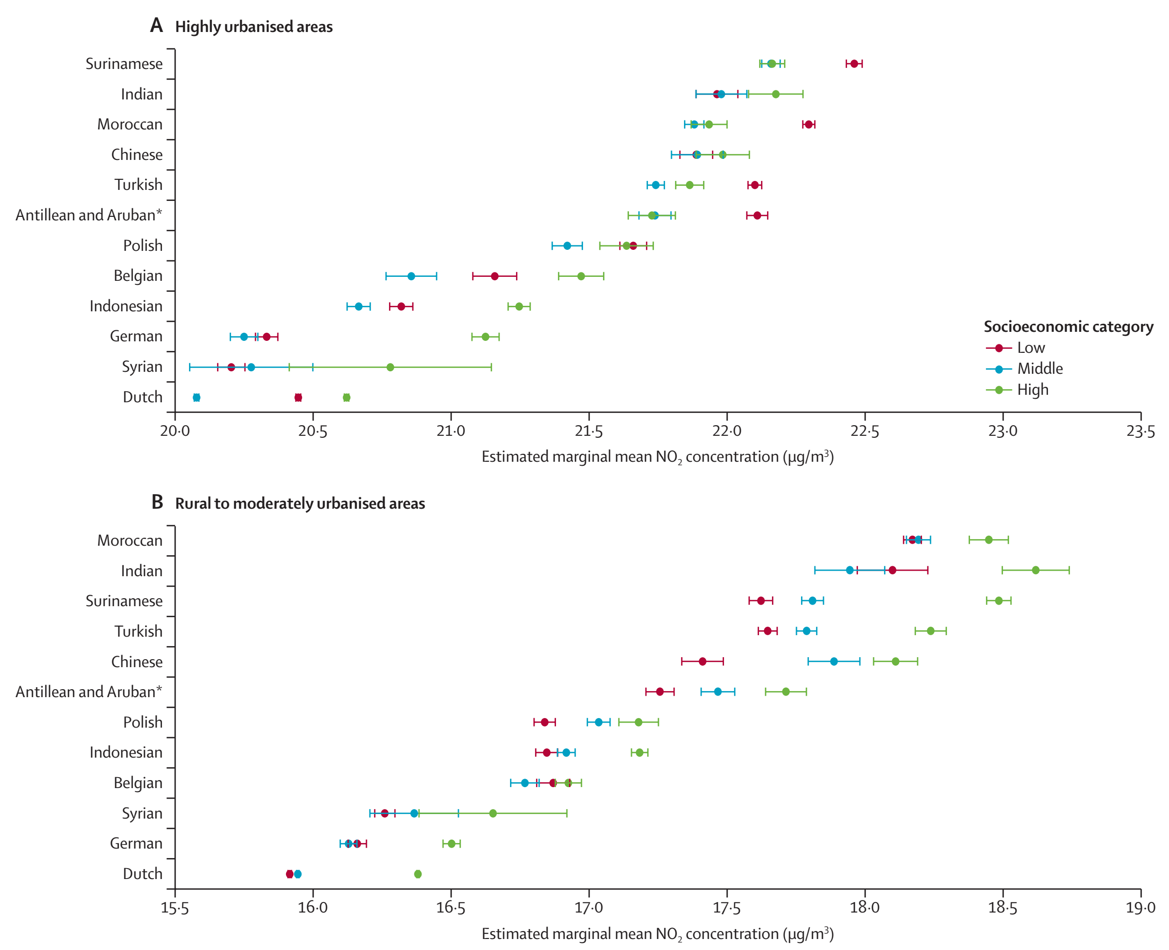

Figure 1: **Estimated marginal mean NO_2 exposure by socioeconomic and ethnic group**
Marginal means are adjusted for age and gender. Error bars show 99% CI. On the y-axis, ethnic groups are ordered from highest to lowest exposure. The range of the x-axis differs between A and B. NO_2=nitrogen dioxide. µg=micrograms. *Former Netherlands Antillean and Aruban.

Results

Our search yielded 9 239 996 inhabited addresses. Average concentrations of air pollutants at all inhabited addresses were linked to individuals in the cohort based on residential address on Jan 1, 2019. Linkage was successful for 9 165 337 (99·2%) of the 9 239 996 addresses; unsuccessful linkages were due to inconsistencies in addresses. 17 251 511 inhabitants were registered at these addresses, with 11 389 626 in rural to moderately urbanised neighbourhoods and 5 861 615 in highly urbanised neighbourhoods; 271 individuals had missing data. Of the 17 251 511 included individuals, 4 076 443 (23·6%) were of non-Dutch ethnicity (table 1; appendix p 2). Population characteristics varied widely between the ethnic groups. Socioeconomic position and education levels were lower for most minority ethnic groups compared with the ethnic Dutch group. Indian, Chinese, and Dutch ethnic groups were least often registered as job seekers (table 1). A higher proportion of minority ethnicities (31·0–70·5%) lived in highly urbanised areas compared with the ethnic Dutch group (27·7%). For the primary analysis, there were 15 737 667 (91·2%) individuals in the 12 selected ethnic groups.

Pollutant exposures per ethnic and socioeconomic position group were approximately normally distributed (appendix pp 8–9). For the total population, the mean concentration in µg/m³ was 17·7 (SD 4·3) for NO_2, 10·1 (1·1) for $PM_{2·5}$, 17·6 (1·5) for PM_{10}, and 0·6 (0·1) for elemental carbon (table 2; appendix p 5). Minority ethnic groups were consistently and significantly exposed to higher concentrations of air pollution as compared with the ethnic Dutch group, with mean concentrations being 2·8–22·8% higher for NO_2, 1·1–6·6% higher for $PM_{2·5}$, and 0·7–5·5% higher for PM_{10} among the main ethnic groups (table 2). Cape Verdeans were exposed to the highest concentrations of these pollutants (appendix p 5). Exposure to elemental carbon was also unequally distributed (appendix pp 5–7). For all pollutants, exposures were highest for the group with the lowest socioeconomic position and lowest for the group with

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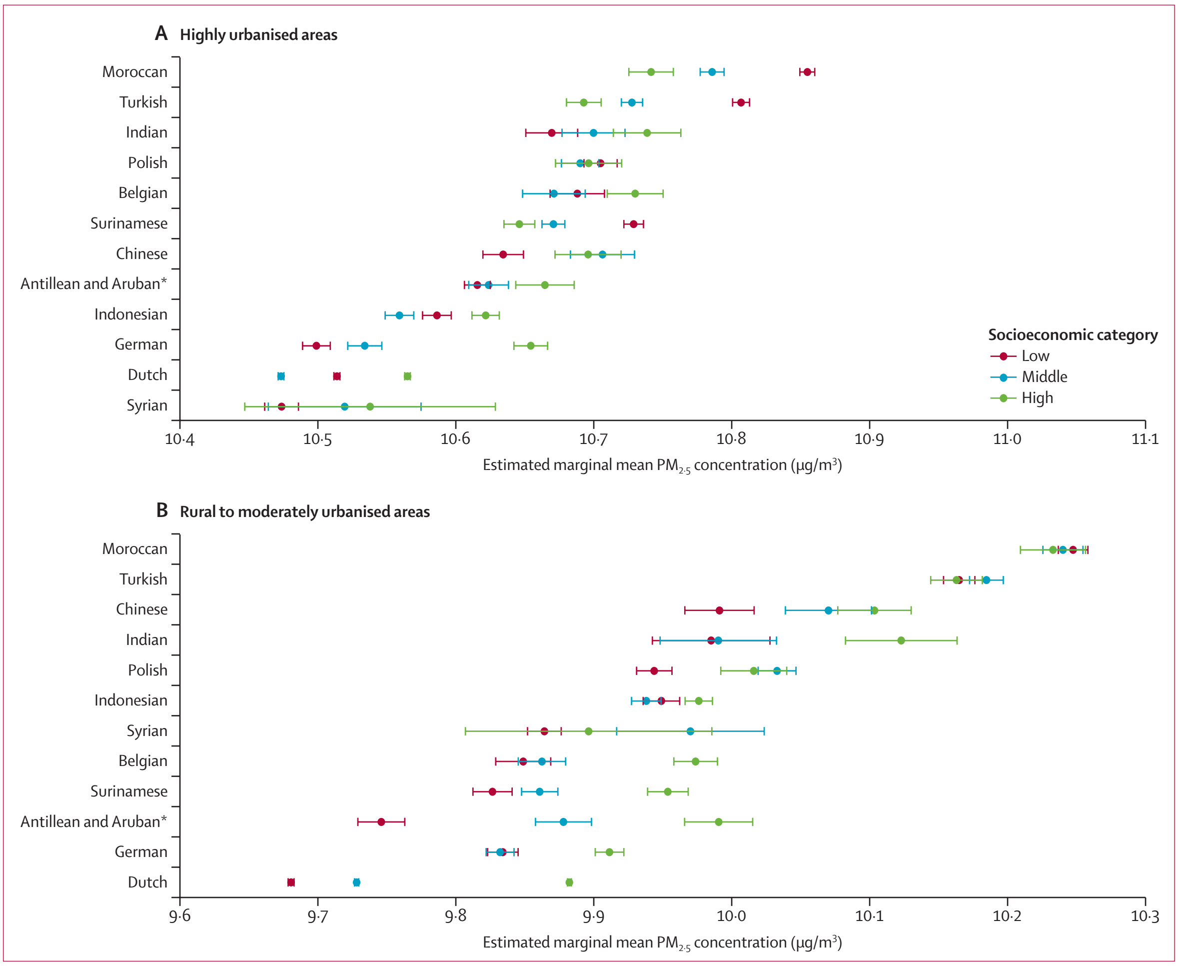

Figure 2: **Estimated marginal mean $PM_{2·5}$ exposure by socioeconomic and ethnic group**
Data are for (A) highly urbanised areas and (B) rural to moderately urbanised areas. Marginal means are adjusted for age and gender. Error bars show 99% CI. On the y axis, ethnic groups are ordered from highest to lowest exposure. The range of the x axis differs between A and B. PM=particulate matter. μg=micrograms. *Former Netherlands Antillean and Aruban.

the middle socioeconomic position (table 3). Differences between the three socioeconomic position groups were about 1% for $PM_{2·5}$ and PM_{10}, and 5% for NO_2 and elemental carbon, which is considerably smaller than the differences between ethnic groups.

Across all air pollutants, ethnic inequalities in exposure persisted when socioeconomic position and urbanicity were taken into account, (figures 1–3; appendix p 10). We found a significant interaction between ethnicity and socioeconomic position in relation to air pollution exposures (interaction $p<2·2\times10^{-16}$ for all four pollutants), indicating that differences in exposures between ethnic groups were affected by socioeconomic position. The ranking of ethnic groups based on inequalities in exposure was similar for all pollutants and urbanicity levels, with the exception of Belgians, who were exposed to high levels of elemental carbon (appendix p 14) compared with the other pollutants. The inequalities in exposure were largest for Turkish, Moroccan, Surinamese, and Indian ethnic groups with low socioeconomic position living in highly urbanised areas (445 218 individuals, 2·6% of total population), with Turkish representing the first, Moroccan the second, Surinamese the third, and Indian the seventh most populous minority ethnic groups. These subgroups were exposed to up to 9·9% higher estimated mean NO_2 concentrations than the ethnic Dutch group with low socioeconomic position living in highly urbanised areas and 11·9% higher than the ethnic Dutch group with middle socioeconomic position living in highly urbanised areas (figure 1A, B).

After stratification, the socioeconomic position groups with the highest estimated marginal mean exposure differed by ethnicity and urbanity level. Among the highest exposed ethnic groups, the group with low socioeconomic position had the highest exposure. By contrast, the exposures for Dutch, Indonesian, German, Belgian, Indian, and former Netherlands Antillean and Aruban groups were highest (up to 4·3% higher) for the groups with high

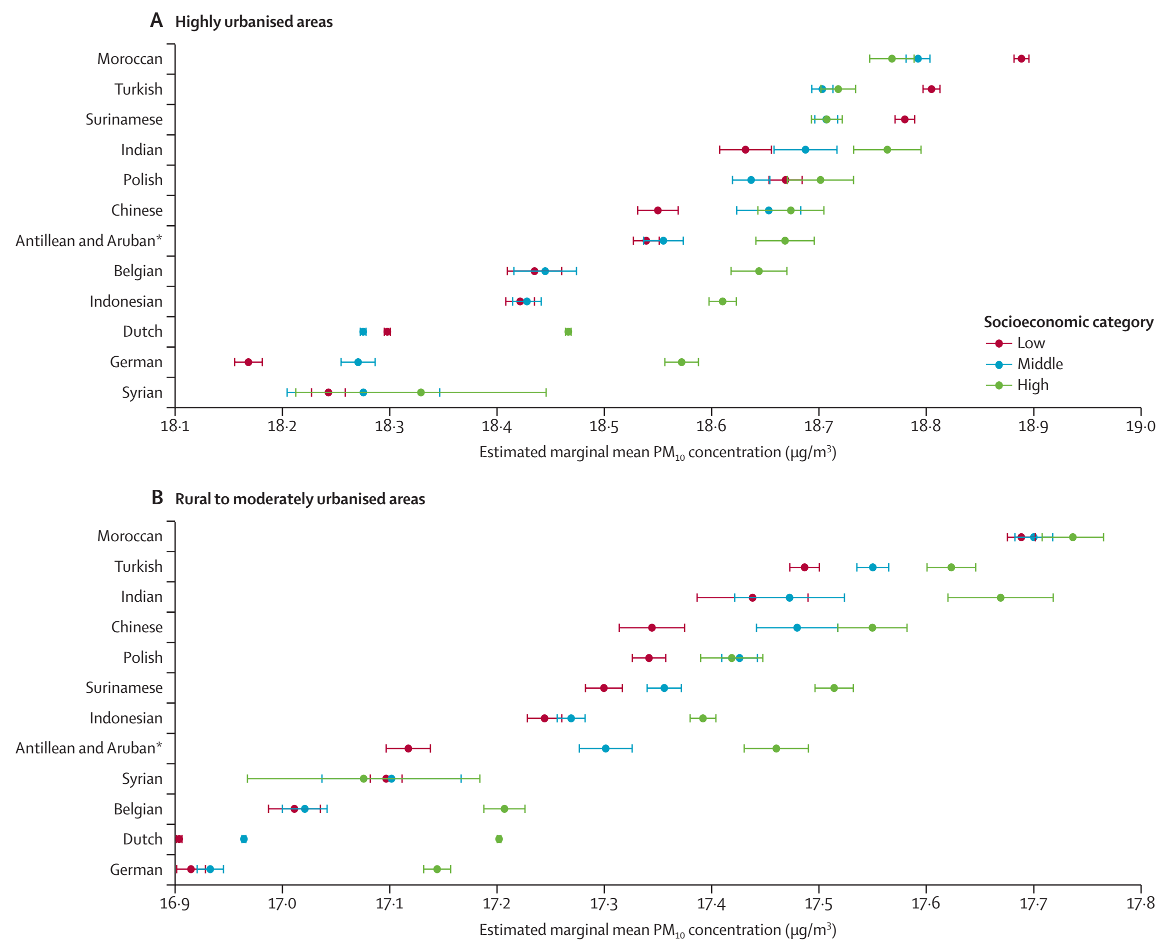

***Figure 3:* Estimated marginal mean PM_{10} exposure by socioeconomic and ethnic group**

Data are for (A) highly urbanised areas and (B) rural to moderately urbanised areas. Marginal means are adjusted for age and gender. Error bars show 99% CI. On the y axis, ethnic groups are ordered from highest to lowest exposure. The range of the x axis differs between A and B. PM=particulate matter. μg=micrograms. *Former Netherlands Antillean and Aruban.

socioeconomic position and lowest for the group with middle socioeconomic position in urban areas, suggesting a U-shaped relationship between socioeconomic position and air pollution exposure. In rural to moderately urbanised areas, the association between socioeconomic position and exposure to air pollution was more uniform between ethnic groups, with overall higher exposures among the group with higher socioeconomic position (figures 1B, 2B, 3B).

We compared exposure disparities across three age groups (<25 years, 25–60 years, >60 years) and found that air pollution exposures were higher at lower ages (appendix p 15). The complete case analyses included all individuals older than 25 years, with a final number of 6 337 468 (36·7%) for inclusion. The complete case analysis compared the use of socioeconomic position index as the indicator for socioeconomic position with use of income and assets as the indicator and showed slightly greater exposure inequalities for minority ethnic groups when the index was used (appendix p 18).

Stratifying mean exposure concentrations by immigrant generation showed slight differences in exposure inequalities: 16·4% higher NO_2 concentrations for first-generation immigrants compared with the ethnic Dutch group versus 13·3% higher for second-generation immigrants compared with the ethnic Dutch group (appendix p 21). However, excluding second-generation immigrants (n=1 362 869, 8%) from the regression analyses negligibly changed the estimated exposure inequalities (appendix p 22).

Adding a random intercept for neighbourhood to the models attenuated the exposure inequalities to null (appendix p 25) and explained almost all the variance in air pollution exposure with conditional R^2s ranging from 0·910 to 0·991 (appendix p 31). Adding neighbourhood socioeconomic position to the models increased the explanatory power of the models (appendix p 31). However, this addition resulted in negligible changes in the exposure differences between minority ethnic groups and the ethnic Dutch group (appendix p 28).

Discussion

This nationwide, cross-sectional study of air pollution exposure inequalities reveals environmental injustice in the Netherlands. We found that minority ethnic groups are consistently exposed to higher levels of NO_2, $PM_{2·5}$, PM_{10}, and elemental carbon than the ethnic Dutch population, even after adjustment for socioeconomic position and urbanicity. The magnitude of the inequalities in air pollution exposures varied greatly between the minority ethnic groups. By evaluating patterns of exposure to air pollution at the intersection of ethnicity and socioeconomic position, we observed two important findings. First, air pollution exposure was the largest for Surinamese, Moroccan, Turkish, and Indian ethnic groups with lower socioeconomic position living in highly urbanised areas. Second, the relationship between socioeconomic position and exposure to air pollution differed depending on ethnicity, implying that the role of socioeconomic position in determining residential location and air pollution exposure differs between ethnic groups.

A study in England, Wales, and Ireland establishing mean air pollution concentrations at the local authority level between 2002 and 2011 found higher exposures among Pakistani, Bangladeshi, Indian, African, and Caribbean populations compared with the majority population.[12] The mean concentration of NO_2 was found to be 50% higher for Indians compared with the White population, while $PM_{2·5}$ was 21% higher, and PM_{10} was 19% higher. These findings have a larger disparity than for the Indian ethnic population in our study. Other previous studies on ethnic inequalities in air pollution exposure in Europe do not provide detailed comparisons between different ethnic groups, limiting comparability with our findings.[5,29] A systematic review of social inequalities that included studies predominantly from the USA, found that minority ethnic groups, notably African American, Latin American, Asian American and native American populations, are exposed to higher concentrations of industrial hazardous pollutants.[5] A review of the WHO European region found that communities around industrially contaminated sites were characterised by a higher proportion of immigrant residents.[6] A neighbourhood-level study in the Netherlands found 39% higher concentrations of NO_2 and 5% higher concentrations of PM_{10} in neighbourhoods with at least 20% immigrants from LMICs compared with neighbourhoods with less than 20% immigrants from LMICs.[11] Although evidence in Europe of higher exposure to industrial air pollution for minority ethnic groups is fairly consistent, patterns of exposure to overall air pollution, including traffic-related pollution, are more inconsistent, with some studies reporting similar and sometimes lower exposures for broadly defined minority ethnic groups than for the majority ethnicity alongside studies showing higher exposures.[12,29,30]

The higher exposures to air pollution found among Turkish and Moroccan populations in the Netherlands in this study are in line with studies showing that these populations more often live in neighbourhoods with a high proportion of immigrants,[31] and these neighbourhoods have higher concentrations of air pollution.[11] Of the Syrian war refugees, a large proportion resided in allocated reception centres, which are mostly in rural to moderately urbanised areas, which is reflected in the low exposure concentrations among this group. Air pollution exposure among the Indonesian ethnic group was more similar to that of the ethnic Dutch group than among some of the other minority ethnic groups. In the USA, a 22% higher exposure to $PM_{2·5}$ for Chinese individuals compared to White individuals was found,[9] which is a larger difference than the 4% higher exposure to $PM_{2·5}$ for Chinese individuals in our study.

The relationship between socioeconomic position and air pollution exposure differs between countries. A U-shaped pattern between socioeconomic position and exposure was previously reported.[32] Another study report inverted U-shaped relationships between socioeconomic position and air pollution (ie, highest exposures for the middle socioeconomic position group).[30] Although, our results in the total study population suggest a U-shaped pattern, which socioeconomic position group had the highest exposure depended on urbanicity and ethnicity. The highest exposed subgroups in our study were of minority ethnicity with a low socioeconomic position in urban areas. This finding is in line with a US-wide study,[17] which found up to 45-times higher air toxicity scores for census tracts with a high percentage of Black residents, a high percentage of female-headed households, lower educational attainment, and lower income in urban areas. Most other US-based studies also report the highest air pollution exposure at the lowest socioeconomic positions.[5] In this study, the high-socioeconomic position subgroups in some ethnic groups did not always have the lowest exposures, which might reflect the fact that populations of high socioeconomic position tend to live in the inner centres of cities or towns. A study in Austria[13] found a positive correlation between income and exposure to industrial air pollution in rural areas, but a negative correlation in urban areas. Some China-based studies[5,33] report higher air pollution exposures at higher socioeconomic position also, in both urban and rural areas.

We found a consistent disparity in exposure across all pollutants. The largest differences in NO_2 exposure are probably related to its greater spatial variability. The significant contribution of vehicular traffic to NO_2 exposure suggests that reducing vehicular emissions reduces exposure inequalities. The random effects analysis shows that differences in exposure are largely explained by the clustering of social groups within polluted neighbourhoods. Several mechanisms are presumed to contribute to this, including lower housing prices in polluted areas and racial discrimination in the (privatised) housing market.[34,35] Furthermore, polluting companies might be more likely to locate near marginalised communities because of the often cheaper land prices, lower wages, and less organised (political) resistance.[34] In Germany, part of the ethnic disparities in air pollution exposure are explained by the geographical centrality of industrial facilities in city centres where minority ethnic groups tend to cluster.[36]

Although adjusting for neighbourhood socioeconomic position did not substantially change the exposure inequalities identified here, the additional value of assessing neighbourhood socioeconomic position alongside individual socioeconomic position indicators in relation to air pollution exposures has been shown before.[37] Future studies could combine multiple socioeconomic position indicators and assess interactions between individual-level and neighbourhood-level socioeconomic position to further assess the role of socioeconomic position in ethnic exposure inequalities.

To our knowledge, this study is the first to evaluate environmental injustice related to air pollution at the intersection of ethnicity and socioeconomic position in Europe. A strength of this study is that we used individual-level information in this nationwide analysis, which allowed detailed stratification by ethnicity, socioeconomic position, and urbanicity. However, this study comes with limitations. First, the cross-sectional design did not allow analysis of temporal trends of exposure disparities. Second, we recognise that reluctance is warranted with categorising ethnic groups; country of birth as the indicator for ethnicity does not capture the multidimensionality of the construct. Misclassification will have occurred, especially for people of mixed ethnicities and for people self-identifying their ethnicity other than based on their country of birth. The Surinamese population in the Netherlands is especially heterogeneous but was simplified to one ethnic group in this study. Nevertheless, we are confident that we have reliably shown trends in exposure to air pollution by broad ethnic groups, as country of birth has proven to be a fair indicator to distinguish between ethnic groups in the Netherlands.[38] Third, income and taxable assets are incomplete measures of socioeconomic position. However, the sensitivity analyses with the composite socioeconomic position index and adding neighbourhood socioeconomic position to the models, led to only minimal changes to the results. Finally, in addition to air pollution concentrations at the residential address, other factors contribute to total air pollution exposures and to inequalities. These factors include time–activity patterns, indoor air pollution, and occupational exposures. If alternate factors have biased our results, the exposure inequalities found are likely to be underestimated, as access to the housing market, housing quality, and hence indoor air quality might be lower for minority ethnic and lower socioeconomic position groups, resulting in higher concentrations of indoor air pollution.[39,40]

Further research should address several points. First, the air pollution exposure inequalities observed in this study warrant further investigation of health effects. Second, focusing on areas with high concentrations of air pollution in the Netherlands and assessing the relationship between clustering of social groups and air pollution sources could provide insight into the factors contributing to unequal exposures and opportunities for more targeted interventions. Finally, future studies should investigate the combined effects of air pollution and other risk factors in the social and built environments on disease inequalities between social groups.

Minority ethnic groups in the Netherlands are exposed to higher concentrations of air pollution ($PM_{2·5}$, PM_{10}, NO_2, and elemental carbon) than the ethnic Dutch population, with variation between minority ethnic groups in the magnitude of the exposure inequalities. Air pollution exposure concentrations are highest for Surinamese, Moroccan, Turkish, and former Netherlands Antillean and Aruban ethnic groups with low socioeconomic position in highly urbanised areas, which shows environmental injustice at the intersection of social determinants. Policies to reduce air pollution should prioritise groups that are highly exposed and should aim to reduce inequalities. The health consequences of the observed exposure inequalities and the underlying processes causing them warrant further investigation.

Contributors
LvdB, VL, JDM, GH, DEG, and IV conceptualised and designed the study. LvdB did the formal analysis and drafted the first version of the manuscript. LvdB and VL accessed and verified the underlying data. LvdB, VL, JDM, GH, JL, DEG, and IV interpreted the results. AW extracted and curated the air pollution data. All authors critically revised the manuscript, read the final version of the manuscript, and agreed upon submission for publication. All authors had full access to the data upon signing a confidentiality agreement.

Declaration of interests
We declare no competing interests.

Data sharing
Results are based on calculations using geodata and non-public microdata from Statistics Netherlands. Under certain conditions, the underlying encrypted microdata are accessible for statistical and scientific research. For further information contact microdata@cbs.nl. If verification of the analyses is desired and Statistics Netherlands provides access to the microdata, we will provide the R-scripts for cohort-building and analyses upon request to the corresponding author. The geodata can be downloaded from www.atlasleefomgeving.nl or requested from the Geoscience and Health Cohort Consortium (www.gecco.nl).

Acknowledgments
This work is supported by EXPOSOME-NL. EXPOSOME-NL is funded through the Gravitation programme of the Dutch Ministry of Education, Culture, and Science and the Netherlands Organization for Scientific Research (NWO grant number 024.004.017). Geodata were obtained via the Geoscience and Health Cohort Consortium, which was financially supported by the Netherlands Organisation for Scientific Research, the Netherlands Organisation for Health Research and Development, and Amsterdam University Medical Center.

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