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The impact of deprivation and socioeconomic factors on inequalities in volatile organic compound emissions in communities in England

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Poor air quality is one of the leading environmental threats to global public health; deprived communities endure disproportionately higher ambient concentrations of primary pollutants such as NO_x and $PM_{2.5}$. Volatile organic compounds (VOCs) are ubiquitous in the indoor and outdoor environment and can be harmful to human health, yet their relationship with deprivation has not been widely explored. Modelled emissions of VOCs from 2019 across England are linked to indices of multiple deprivation (IMD), land classification, and ethnicity data, to explore the spatial relationship between VOCs, deprivation and social parameters within English communities. VOC emissions are shown to increase as deprivation increases across London and the rest of England, with higher emissions rates in London. Solvent emissions are the dominant source of VOCs across England, and the only source which exhibits a relationship with deprivation. Urban settings demonstrate a higher inequality in emissions in deprived communities, with relative contribution of different sources dependent on geographical location. Population density and minority ethnicity—both proxies for deprivation—correlate with higher VOC emissions, particularly in densely settled minority communities. This research identifies an association between VOC emissions and deprivation in England which has not been seen before. Communities at risk of environmental inequality from VOC emissions are areas of higher ethnic minority populations and increased population density. The relationship with solvent emissions helps to understand the emission sources within these communities, to try to reduce emissions and tackle inequality of air pollution.

Environmental significance

Existing research has shown an inequality in exposure to air pollution relating to deprivation. Volatile organic compounds (VOCs) are an important component of air quality owing to their ubiquity in the atmosphere and array of chemical compositions and health effects. This research is the first to explore inequality in exposure to VOCs in relation to deprivation within the UK, using VOC emissions as a proxy for exposure. This work explores inequalities within different land classifications, population densities, and ethnic groups, as well as different sources of VOCs emissions. An inequality in exposure to VOCs emissions is identified across different levels of deprivation within England, the dominant sources and areas of high-risk are identified to assist policy-makers with emission reduction strategies.

1 Introduction

Poor air quality (AQ) is the largest environmental risk to public health in the UK, with between 28 000 and 36 000 deaths every year attributable to anthropogenic air pollution.[1] Although national trends of key air pollutants have been declining in recent years, this is not ubiquitous across the UK, or for all pollutants, as some areas still exceed limit values set for regulated air pollutants.[2] Additionally, there are concerns over the health effects of unregulated air pollutants, such as the majority of volatile organic compounds (VOCs).[3] Research into the spatial variation of air pollution trends across the UK has identified that poorer and more deprived communities may be more likely to live in areas with worse air quality,[4–6] highlighting an inequality which could result in health disparities.[7,8]

The theme of environmental justice (EJ) is a growing research area in air quality, and is defined as equal access to a clean environment, and equal protection from possible environmental harm irrespective of race, income, class, or any other differentiating feature of socioeconomic status.[9] Early research within the UK into EJ and air pollution exposure identified these geographical and socio-economic inequalities in relation to air pollution exposure for common outdoor air pollutants such as, nitrogen dioxide (NO_2), particulate matter (PM), and sulphur dioxide (SO_2),[10,11] identifying that areas of higher poverty, more

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ethnic diversity, and increased overall deprivation experienced higher air pollution exposure. More recently, research has focused on the indoor environment,[12] emissions from specific sources,[4] and potential health impacts arising from exposure inequalities.[13] Research in England has shown that health inequalities have been increasing,[14] to which increasing inequality in exposure to air pollution has contributed.[15]

In order to quantify and study deprivation in England, the UK government uses the indices of multiple deprivation (IMD), which rank deprivation using a range of variables with different weightings. These variables include: income deprivation (22.5%), employment deprivation (22.5%), education skills and training deprivation (13.5%), health deprivation and disability (13.5%), crime (9.3%), barriers to housing and services (9.3%), living environment deprivation (9.3%). These indices are heavily weighted towards income and employment (combined 45%), meaning that a potential urban bias underestimates rural deprivation key drivers, including, access to services, higher cost of living, and seasonal employment.[16] An IMD score is then given to each lower-super output area (LSOA) within England, which are divided into deciles. This metric has been used to explore inequalities in exposure to ozone (O_3) and PM concentrations,[13] as well as NO_x emissions.[17]

Although key primary pollutants (NO_x, PM, O_3) have been studied with respect to inequality in AQ exposure in the UK, other air pollutants, such as VOCs, have not been addressed, owing to limited nationwide VOC datasets, and the fact that a wide number are not regulated in UK law. Research from other countries including, USA, France, and South Korea, have shown that lower socio-economic status is associated with exposure to elevated VOC concentrations.[18–20] A recent report by the UK government air quality expert group outlined a need for investigations into VOC exposure and deprivation within the UK.[21] VOCs are of interest owing to their wide array of sources, range of chemical compositions, and subsequently, a plethora of associated health concerns. As hundreds of different VOCs can be found in ambient air at relatively low concentrations, a total VOC (TVOC) metric can be a useful tool to understand overall VOC pollution. Worldwide, TVOC is dominated by ethane, butane, and propane,[22] with their relative contribution typically similar in different settings (urban/rural), but differences in absolute concentrations due to emission rates.[23] As TVOC provides an indication as to overall air quality relating to VOCs, it is a useful tool for a nationwide assessment, which can be investigated further by exploring toxicity of specific compounds.

Within the UK, only benzene and 1,3-butadiene ambient outdoor concentrations are monitored across the country and regulated by UK law. A continuous monitoring network measuring 27 VOCs at four sites across the UK is also in operation,[24] these sites cover urban roadside, urban background, and rural background settings, and operate with Thermal Desorption coupled Gas Chromatography with Flame Ionisation Detection (TD-GC-FID) measurements. Assessments of air pollution exposure typically use either monitoring network data, personal exposure equipment, modelled data, or satellite data.[25] However, for VOCs, existing monitoring networks are too sparse, modelled data is not available, and satellite coverage is limited within the UK, whilst personal exposure equipment is not suitable for a nationwide assessment.

Gray *et al.* (2023)[17] used emissions inventory data to assess inequality in NO_x exposure assessment for England. By using the UK National Atmospheric Emissions Inventory (NAEI),[26] a novel approach was developed, that allowed greater dissemination of sources and generation of higher spatial resolution data than is possible with other air pollution exposure assessment tools. Air pollution emissions data has been used as an exposure tool in multiple studies.[4,17,27] Modelled air pollution concentration data is often only indicative of background concentrations, meaning localised sources and sinks may not properly be accounted for.[28] Additionally, emissions data may account for exposure risks which ambient concentrations may not, such as associated noise,[29] and provides a greater dissemination of sources and sectors. This study looks to build on this approach to assess the relationship between deprivation and exposure to VOC emissions within England at the LSOA level. Measurements of VOCs ambient concentrations in England are limited to two continuous monitoring sites, and a non-automatic network of 30 sites which only measures two VOCs, meaning a nationwide assessment is better suited for a 1 km^2 gridded emissions dataset. The English IMD deciles is compared to TVOC emissions, exploring relationships between variables such as sources of VOCs, land-use types, population density, and ethnicity. The aim of this study is to contribute to the developing knowledge on the relationship between local air pollution and deprivation within the UK with an assessment of outdoor VOCs.

2 Materials and methods

2.1 Data sources

A 1 km × 1 km gridded emissions map of England for total non-methane VOC (TVOC) in 2019 was obtained from the UK government NAEI (SI Fig. S1).[26] NAEI defines TVOC as all VOCs excluding methane that can react with nitrogen oxides (NO_x) in the presence of sunlight to form tropospheric ozone. This TVOC consists of over 600 compounds including alkanes, alkenes, aromatics, alcohols, ketones, aldehydes, ethers, halocarbons, and more. 2019 was selected on the basis of being the most up to date with no interference from COVID-19 lockdown restrictions on emissions and ambient air pollution concentrations.[30] The dataset included raster files for total NMVOC emissions, as well as for individual source emissions, including: industry, road, agriculture, and solvent. Emissions data is built on collating total UK emissions by sector from reported/observed activity data from governmental departments (BEIS, DfT, DEFRA, *etc.*), administrative data services (ONS), and industrial reports. This activity data is then multiplied by a given emission factor to give a total emission value. Geographical proxy datasets, such as road networks, industrial location databases, and land use, can then be used to spatially disaggregate emissions data into 1 km^2 grid cells across the entire country. For quality assurance and control, spatial uncertainty is estimated and scored in order to demonstrate the confidence in these datasets as accurate representations of nationwide emissions of pollutants. The non-methane volatile organic compounds (TVOC) dataset for 2019 was scored 2 on the spatial uncertainty scoring system (1 is highest, 5 is lowest), which is classed as "Use for grids which is based on good, relevant, data at high level of definition but with maybe some minor shortcomings",[31] with uncertainty calculated at 20%,[32] meaning an estimated 20% variability in modelled emissions.

The English IMD for 2019 was downloaded at an LSOA geographical resolution to best match the 1 km × 1 km emissions grid (SI Fig. S2). LSOAs provide high resolution small area statistics, on the basis that each LSOA contains approximately 1000 to 3000 people and 400 to 1200 households, dividing England into 33, 755 individual LSOAs ranging in size from 0.1 to 673 km^2. These social factors can all lead to different types of deprivation, so combining them creates a more comprehensive tool to assess deprivation. LSOAs are then divided into deciles (ten equal groups) of relative deprivation, meaning group 1 are the 10% most deprived within England, whilst group 10 is the 10% least deprived. Land classification was performed using the Rural Urban Classification[33] for each LSOA from the Office for National Statistics (ONS), where an LSOA is classified as either: major urban conurbation, minor urban conurbation, urban city and town, rural town, rural village, or rural dispersed (SI Fig. S3). Examples of the types of areas which are included in each category are; Greater London and West Midlands (major urban conurbation), Nottinghamshire and South Yorkshire (minor urban conurbation), Coventry and Slough (urban cities and towns), Solihull and Windsor (rural towns), areas of The Cotswolds and Cornwall (rural villages), and areas of Northumberland and Norfolk (rural dispersed). Ethnicity statistics were taken from the ONS 2021 census at LSOA level. This is the closest census population data to the 2019 emissions and deprivation data, although there will be some shifts in population demographics, significant changes to population demographics are typically long-term gradual shifts,[34] although it is uncertain how the Covid-19 pandemic may have had an effect on this. The percentage of the total LSOA population belonging to one of 4 broad ethnic groups White (British), White (other), Black, and Asian was calculated, in order to better understand the overall representation and demographic within each area.

2.2 Data linkage and analysis

Data linkage and analysis was performed using ArcGIS Pro and R. IMD, Rural and Urban Classification, and ethnicity data were all acquired at an LSOA level, so data linkage was possible *via* LSOA ID codes. Linking the 1 km × 1 km gridded emissions data to the LSOA was performed *via* a spatial join. All 1 km × 1 km grid cells which intercepted with each LSOA polygon were assigned to that polygon, if multiple grid cells intercepted with one polygon an average TVOC emission was calculated. Grid cells without available data are not considered in the average. The same process was performed for each source type. All LSOAs within each IMD decile (1 to 10) were grouped together, and an average TVOC emission value (tonnes per km^2) for each IMD decile was calculated. The 95% confidence for each grouping was calculated *via* sample mean ± margin of error, where margin of error was calculated as t_a (critical value) multiplied by standard deviation divided by the square root of the sample size.

The Rural and Urban Classification classifies all LSOAs as either; urban major conurbation, urban minor conurbation, urban city and town, rural town, rural village, and rural dispersed. Each land-use classification was then separated by deprivation deciles, and an average TVOC emission value was calculated for each deprivation decile within each land-use classification. For source-specific emissions, solvent, road, agricultural, and industrial processes TVOC emissions were linked to LSOA polygons, grouped into deprivation deciles and averaged for an average emission value for each source across each deprivation decile. For further exploration of social determinants of exposure to TVOC emissions, an assessment of population density and ethnicity were conducted. LSOA area size is used as a proxy for population density, as LSOAs are created to contain a certain population size or number of households, therefore, their size varies significantly across the country, and areas with higher population density have smaller LSOAs. For example, greater London, an area of 1569 km^2 contains 4825 LSOAs, whilst greater Manchester, an area of 1277 km^2 contains 390 LSOAs. 10 deciles were created (0–0.18 km^2, 0.19–0.24 km^2, 0.25–0.29 km^2, 0.3–0.36 km^2, 0.37–0.46 km^2, 0.47–0.61 km^2, 0.62–0.95 km^2, 0.96–2.1 km^2, 2.2–9.2 km^2, and 9.3–685 km^2), and an average TVOC emission value was calculated for each size grouping. For ethnicity, the percentage of each identified ethnic group within each LSOA were calculated and grouped into each 10% increase from 0 to 100%, and an average TVOC emission value for each grouping was calculated.

One-way analysis of variance (ANOVA) was conducted to test if a statistically significant difference between TVOC emissions and deprivation deciles, land classification, population density, and ethnicity was present. An ANOVA test will give a ratio of variance (*F*-statistic value), where a higher *F*-value indicates greater differences between group means. ANOVA tests also generates the probability that differences in mean values occurred by chance as a *P*-value. When a *p*-value is below 0.05, that means occurring by chance is extremely unlikely and so can be considered statistically significant. A Tukey's Honestly Significant Difference (HSD) test was then performed to determine within which groups the statistically significance differences are present. A Tukey's HSD is a *post-hoc* test used after a significant ANOVA, which compares all group means against each other. It calculates a single critical value, any groups with absolute differences greater than this value are considered statistically significant.

Global Moran's *I* was used to assess the spatial autocorrelation of TVOC emissions and IMD deciles independently and identify clusters. An index (*I*) is calculated, with a value between 1 and −1, where a positive *I* indicates spatial clustering, a negative *I* indicates dispersion, and close to 0 indicates random spatial distribution, with a *P*-value below 0.05 rejecting the null hypothesis of spatial randomness. Then, bivariate spatial analysis was conducted *via* cross tabulation to identify the frequency of different classes of LSOA by two variables (*e.g.*, TVOC and deprivation), with Pearson's χ^2 testing if variables are independent, and Cramer's V quantifying the effect size. Pearson's χ^2 tests if the two variables are independent or associated. A high χ^2 value with P-value below 0.05 indicates an association between the variables, and the null hypothesis of independence can be rejected. Cramer's V is a value between 0 and 1 indicating the strength of association between variables, with 1 being a perfect association. It is calculated by the square root of χ^2 divided by the sample size, multiplied by the minimum dimension of the table (rows or columns, minus 1). Finally, a spatial autoregressive (SAR) model was utilised to test the influence of neighbouring LSOAs on individual LSOAs TVOC emissions, whilst also estimating the independent effects of confounding variables; deprivation, population density, ethnicity and land classification. The estimate gives the direction and magnitude of the effect, the standard error quantifies uncertainty, the z-value measures how far the estimate is from zero relative to that uncertainty, and the p-value indicates whether the effect is statistically distinguishable from zero after accounting for spatial dependence.

3 Results

3.1 Volatile organic compounds emissions in England and London

Fig. 1 illustrates the average TVOC emissions in each deprivation decile in London and England. The same trend is observed for both London, and the rest of the country, with the highest average emissions in the 10–40% most deprived areas and the average emissions decreasing as deprivation decreases, meaning the least deprived areas have the lowest emissions of TVOCs. Although the trend is the same for London and England, emissions of TVOCs in London were on average 46% higher for the deprivation deciles, with the 10% least deprived in London experiencing similar emissions to the 30–40% most deprived nationwide, and the 10% most deprived in England averaging similar emissions to the 70–80% least deprived within London. One way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) tests showed statistically significant difference between TVOC emissions in different deprivation deciles (SI Table S1), the largest significant differences were between deciles furthest apart (*e.g.*, 1 and 10, 1 and 9), whilst deciles close together (*e.g.*, 1 and 2, 9 and 10) were not statistically significant in their difference of TVOC emissions (SI Fig. S4). Global Moran's I analysis shows that IMD Deciles (0.16, <0.05) and TVOC emissions (0.17, <0.05) are spatially autocorrelated, meaning clusters of LSOAs are present and the distribution is not random spatially (SI Fig. S5 and S6). Bivariate spatial analysis shows 47% of high TVOC LSOAs are within high deprivation LSOAs, whilst 58% of low TVOC LSOAs are within low deprivation LSOAs, with a statistically significant moderate effect size (SI Table S2), with high deprivation, high TVOC LSOAs mainly being in major cities (SI Fig. S7).

3.2 Land classification of TVOC emissions

TVOC emissions by deprivation decile for different land classifications of LSOA across England are shown in Fig. 2 and 3, for urban and rural areas, respectively. Differences between urban and rural in terms of calculated emissions values are not substantial, with only slightly higher values for urban settings across the deprivation deciles. For urban settings, major conurbations, cities and towns, a clear trend of decreasing TVOC emissions as deprivation decreases is evident, whilst minor conurbations show the same trend with a less pronounced decrease. The difference in TVOC emissions from the least deprived to the most deprived deciles for major conurbations, cities and towns, and minor conurbations are increases of 15.1, 21.2, and 7.3 tonnes per km^2, respectively.

In rural settings, towns and villages demonstrate a linear decline in TVOC emissions as deprivation decreases, whilst dispersed rural settings show a sharp decrease, from relatively high emissions in the most deprived deciles to much lower emissions values around decile 4 which plateau to show no strong relationship between emissions and deprivation at this stage. Table 1 displays the average emissions in each land classification type for a few select sources across England in 2019. Emissions from industrial process are fairly uniform, suggesting their spatial distribution across land classifications in England are quite even. Solvent emissions are much higher in urban areas, demonstrating a more productive or a higher density of sources in these settings. Road emissions are

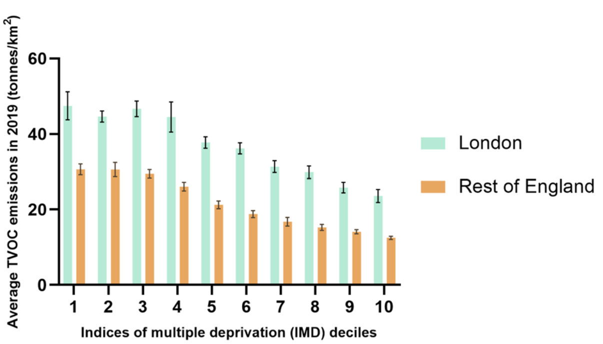

Fig. 1 Average TVOC emissions (tonnes per km^2) in deprivation deciles across London and the rest of England with 95% confidence interval error bars.

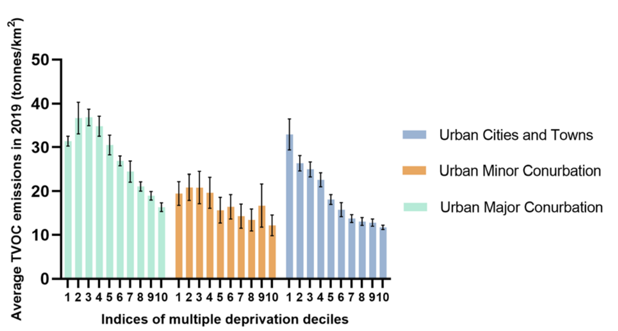

Fig. 2 Average TVOC emissions (tonnes per km^2) in deprivation deciles across England in different urban settings with 95% confidence interval error bars.

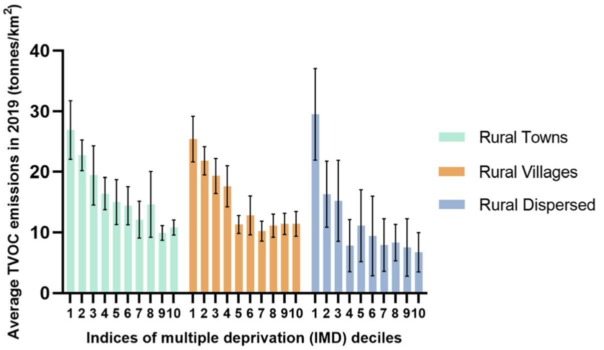

Fig. 3 Average TVOC emissions (tonnes per km^2) in deprivation deciles across England in different rural settings with 95% confidence interval error bars.

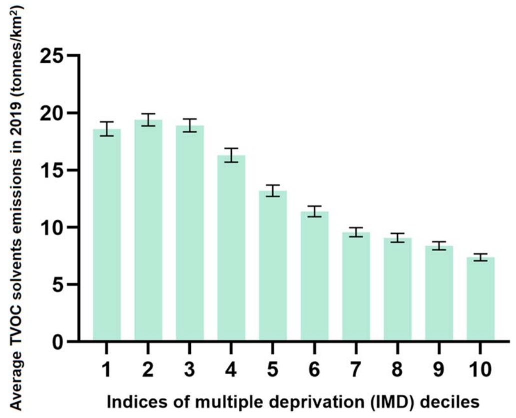

Fig. 4 Average TVOC solvent emissions (tonnes per km^2) in deprivation deciles across England with 95% confidence interval error bars.

consistent across urban areas, but not substantial in rural settings, whilst agricultural emissions exhibit the exact opposite relationship, with only a significant presence in rural areas. ANOVA and Tukey's HSD tests show statistically significant differences in TVOC emissions by deprivation deciles for all land classifications, except rural dispersed. The largest mean differences in TVOC emissions occur between the most deprived and least deprived deciles. Bivariate analysis shows that over 60% of high TVOC areas are within urban conurbations, whilst low TVOC areas are strongly clustered in rural and semi-rural areas, with a strong statistically significant effect size (SI Table S3).

3.3 TVOC emissions by source

Fig. 4 shows TVOC emissions for each decile by solely solvent emissions. Solvents are by far the largest emission source of VOCs within England, demonstrating the trend of decreasing emissions as deprivation decreases. Other key sources of VOCs (industrial production, roads, and agriculture) contribute significantly less to total emissions and also do not exhibit the same trend associated with deprivation. The highest TVOC emissions for solvents and roads on average occur in decile 2 at 19.4 and 1.5 tonnes per km^2, respectively. The average highest emissions from industrial production are in decile 6 at 2.9 tonnes per km^2, whilst agricultural emissions are highest in decile 7 at 1.2 tonnes per km^2. Average TVOC emissions from solvents in the most deprived areas in England are 18.6 tonnes per km^2 and 7.4 tonnes per km^2 in the least deprived areas, showing a 253% increase in TVOC emissions relating to deprivation. However, solvent emissions in the least deprived deciles are on average 530%, 2610%, and 350% higher than emissions from road, agriculture, and industrial production sources in the least deprived deciles, respectively. ANOVA and Tukey's HSD tests show statistically significant differences in TVOC emissions by deprivation deciles for solvent, road, and agricultural emissions, but not in industrial processes emissions. Solvent and road emissions are significantly higher in more deprived areas, with a larger mean difference for solvent emissions, whilst agricultural emissions are significantly higher in less deprived areas.

3.4 TVOC emissions by population density

As LSOAs are determined by a population, they can be used as a proxy for population density, as the smaller the area size of an LSOA, the more densely populated that area is. Fig. 5 shows the average TVOC emissions for 10 decile groupings of LSOA area size with a 95% confidence interval. A clear trend is noticeable, where LSOA size increases lead to decreases in the amount of TVOC emissions within those areas, meaning, that highly populated areas experience higher emissions of TVOCs on average. The most densely populated areas in particular experience much higher emission than the 90% larger LSOAs, whilst the largest 10% of LSOAs experience significantly less TVOC emissions, with much more similar emissions in the communities in between. ANOVA and Tukey's HSD tests show statistically significant differences in TVOC emissions by LSOA area size, with the largest mean difference between the smallest and

Table 1 Average TVOC emissions (tonnes per km^2) by source in different land classifications in England, 2019

	Industrial processes	Solvents	Road	Agriculture	Total
Major urban conurbations	2.4	19.0	1.6	0.2	23.2
Minor urban conurbations	2.1	13.2	1.1	0.3	16.7
Urban cities and towns	2.3	12.6	1.0	0.6	16.4
Rural towns	1.8	3.0	0.1	2.1	7.0
Rural villages	2.9	0.1	0.0	3.3	6.3
Rural dispersed	2.7	0.0	0.0	1.7	4.4

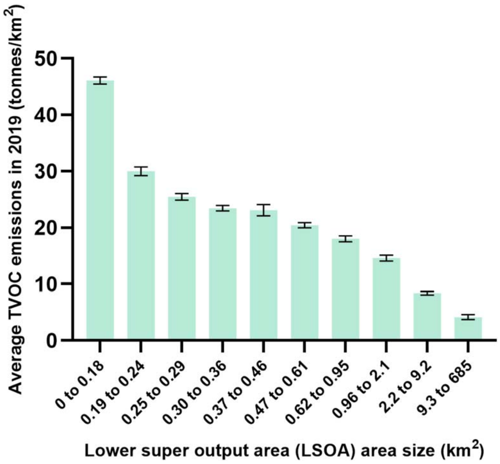

Fig. 5 Average TVOC emissions (tonnes per km^2) by LSOA area size (km^2) deciles across England with 95% confidence interval error bars.

largest LSOAs. Bivariate analysis shows that 64% of high TVOC LSOAs are high-density communities, whilst 74% of low TVOC LSOAs are low-density communities with a statistically significant strong effect size (SI Table S4), with high density-high TVOC emission LSOAs focused around large cities (SI Fig. S8).

3.5 TVOC emissions by ethnicity

ONS 2021 census data was utilised to explore the percentages of different ethnicities within each LSOA. White British representation within English LSOAs ranged from 0.2% to 99.2%, Asian ranged from 0% to 96.6%, White (other) ranged from 0% to 54.3%, and Black ranged from 0% to 64%. An average TVOC emission value was calculated for each 10% increase in each ethnicity's representation in LSOAs across England, and is shown in Fig. 6. A positive association is evident for White (other), Asian, and Black communities, where as they are more represented within an LSOA, their exposure to TVOC emissions increases. The highest exposure across all groups was in LSOAs with 90–100% Asian population (85.9 tonnes per km^2), with a 379.8% increase on TVOC emissions comparative to LSOAs

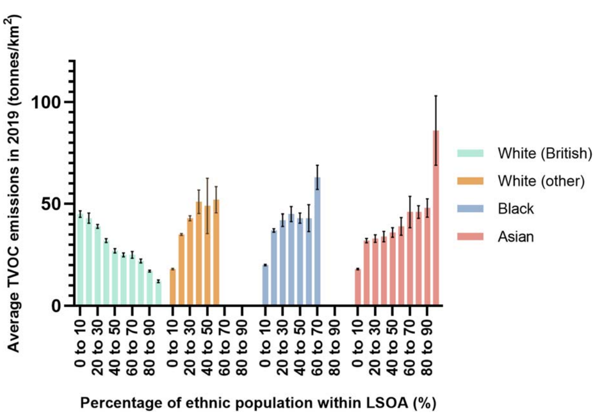

Fig. 6 Average TVOC emissions (tonnes per km^2) by ethnicity percentage within LSOA across England with 95% confidence interval error bars.

with 0–10% Asian people. White (other) and Black people also had the highest TVOC emissions within LSOAs with their highest population percentage, at 52.3 and 62.6 tonnes per km^2, respectively. For white British, the opposite trend occurs, where an increase in the population within an LSOA is associated with a decrease in TVOC emissions. LSOAs with 90–100% white British experienced the lowest TVOC emissions of all groups (12.1 tonnes per km^2), a 72.9% decrease on emissions within LSOAs with 0–10% white British (44.6 tonnes per km^2). ANOVA and Tukey's HSD tests show statistically significant differences in TVOC emissions for all ethnic groups. Communities with a higher percentage of black, Asian, and white (other) populations had the largest mean difference compared to communities with small populations of black, Asian, and white (other) people, with the former living in areas of the highest TVOC emissions. Whereas, white British communities experienced the inverse with the highest TVOC in low percentage white British communities, with the biggest mean difference to areas of high percentage white British people.

Bivariate analysis for ethnicity is conducted by calculating a percentage ethnic minority population for each LSOA. 66% of high TVOC LSOAs fall within high ethnic minority communities, whilst 62% of low TVOC LSOAs are low ethnic minority communities, with a statistically significant strong effect size (SI Table S5). High TVOC areas with high ethnic minority populations are focused around large urban conurbations (SI Fig. S9).

3.6 Spatial autoregressive (SAR) model

The SAR model accounts for the TVOC emissions in neighbouring LSOAs whilst estimating the effects and confounding for factors, deprivation, population density, ethnic minority, and land classification. The spatial lag parameter ($\rho = 0.7163$, $p < 0.001$) shows that TVOC levels are significantly influenced by neighbouring LSOAS, which is to be expected with small-size geographic disaggregates such as LSOAs, and the nature of ubiquitous TVOC emissions. After considering spatial clustering and other variables, the model shows that a statistically significant strong association with high population density, high deprivation, high ethnic minority communities, and urban land classifications is still present for TVOC emissions (SI Table S6).

4 Discussion

The results presented in this paper demonstrate a spatial relationship between TVOC emissions and deprivation within England. By exploring different factors relating to TVOC sources and social factors relating to deprivation, several key questions arise as to why these inequalities occur.

4.1 Disaggregation of TVOC emissions in London and England

Although the same linear trend of increasing TVOC emissions and increasing deprivation is observed for London and the rest of England, there is a disparity in the total emissions within these communities. In London for example, the 10% least deprived areas had on average a TVOC emission of 23.6 tonnes per km^2 for 2019, which is a similar emission quantity to 30–40% most deprived areas in the rest of the country (Fig. 1). A similar trend was observed by Gray *et al.* (2023)[17] for NO_x emissions within IMD LSOAs, with higher emissions in more deprived deciles, and a higher average emission in all deciles in London comparative to England as a whole. Continuous monitoring of VOCs concentrations currently taking place at four sites across the United Kingdom and Ireland, show that typically VOC concentrations are higher in London than in other areas,[35] resulting from a greater density of the dominant VOC sources.[36] Additionally, inequalities in air pollution exposure resulting from social inequalities has been shown for London,[12,37] and England,[38,39] with a higher gradient of inequality in London. The TVOC results in this study show that the gradient of inequality is stronger in London, meaning that deprivation is a strong indicator of higher TVOC emissions within an area. The bivariate clustering of TVOC emissions and deprivation across England (SI Fig. S7) also shows that high deprivation and high TVOC LSOAs are predominantly in large cities (London, Birmingham, Liverpool, and Manchester), whilst low deprivation and low TVOC emissions occur more across more rural regions.

4.2 Specific sources of TVOC and deprivation

In order to identify key sources of TVOC emissions, it is important to understand the quantity of TVOCs emitted by each source, and also the spatial relationship each source may have with deprivation, to try and identify the distribution of these point sources across communities. Solvent usage is the dominant source of TVOC emissions and ambient concentrations within England, contributing 40% to overall in emissions in 2017,[35] with other key sources including industrial processes, agriculture, and fugitive emissions from fuels. Historically road transport has been a dominant source of TVOC emissions, contributing over 30% to total emissions in the 1990s, declining to contributing less than 10% since 2010 as a result of more stringent emission standards, improved technology and emission reduction strategies.[40] As a result, a strong relationship is not shown between deprivation and TVOC emissions for road transport emissions, as well as agriculture and industrial processes. However, there is a strong relationship between decreasing deprivation and decreasing solvent emissions within LSOAs in England (Fig. 2).

Solvent emissions are the dominant source owing to their widespread use in domestic and industrial applications, as a result, their regulation and control is more complex.[41] Agriculture emissions and road transport are more confined to specific spatial locations and activities, which can be controlled to reduce emissions.[42,43] Industrial processes emissions have also largely been identified as the food and drink industry,[44,45] meaning the source can be controlled and is spatially restricted. As solvents are emitted by diverse sources, their association with deprivation is probably confounded by covariates such as population density.

4.3 TVOC emissions by land classification

An insight into different sources of TVOCs in England and their spatial distribution means that land classification is a key dataset for understanding the key sources which may affect each community. Deprived communities exist in all types of rural and urban settings. However, the sources of pollution which pose a threat will likely differ. Fig. 3 and 4 highlight that in all urban and rural classification in England on average TVOC emissions are higher in the more deprived communities than the least deprived. Research into other key primary air pollutants has shown that NO_x and particulate matter are usually lower ambient concentrations in rural areas,[13,45] and the relationship with deprivation is not as pronounced as it is in urban settings.[4,13] This analysis shows that TVOC exhibit slightly higher concentrations in urban areas on average, but a similar relationship with deprivation is present in urban and rural. In deprived areas, emission values are similar for urban and rural, but in less deprived areas, there is more disparity, which drives the difference between urban and rural average emissions. Data from DEFRA's automatic hydrocarbon network sites in urban London (Marylebone Road), and rural Hampshire (Chilbolton) (SI Table S7), show that on average for 2019 ambient TVOC concentrations were 40.1 μg m^{-3} and 11.5 μg m^{-3}, respectively. Individual speciation of TVOC also showed that 4 of the 5 most dominant VOCs were the same in the rural and urban setting (ethane, propane, butane, iso-butane), with similar relative contributions to TVOC. These compounds are globally the largest contributors to TVOC inventories,[22] with emissions from natural gas and oil production (62%), biofuel combustion (20%), and biomass burning (18%).[46,47]

Table 1 shows that emissions of TVOCs from industrial processes are on average the same across different land classifications, meaning that these industrial point sources are not disproportionally distributed across deprived or urban/rural areas. Road emissions were not associated with deprived areas, however, they were higher in urban areas, which are the location of major roads (A-roads and motorways), although their emitted volumes were very low. Agricultural emissions were also not strongly associated with deprivation, but were much higher in rural settlements than urban areas, as a result of the spatial distribution of agricultural land across the country. Solvent emissions were shown to be higher in more deprived areas, and higher in urban areas opposed to rural areas, meaning solvent emission spatial inequality is typically a concern of urban deprived communities, likely resulting from population density and increased domestic emissions. It is therefore likely that the association across all land classifications for deprivation and TVOC from all sources is still a result of solvent emissions, even if their relative contribution to TVOC varies by land classification (Table 1). This is likely due to the domestic emissions of solvents, as deprived areas often have higher density of housing in rural and urban areas.[48]

4.4 TVOC emissions by population density

As discussed in Sections 4.2 and 4.3, population density is likely a key factor in the concentration of emissions of TVOCs in

England into typically more deprived communities, as one of the key sources is domestic solvent use. LSOA size is a good metric for population density as they are geographical boundaries defined by populations and households, of typically 1000–3000 persons, and 400–1200 households. Fig. 5 showed that average TVOC emissions decreased as population density decreased, and densely populated LSOAs were more likely to be deprived (SI Fig. S10), and sparsely populated LSOAs were less likely to be deprived. Therefore, a spatial inequality exists in densely populated deprived communities in terms of TVOC emissions. In terms of the spatial distribution of these densely populated communities, 59.4% of the 3284 smallest LSOAs (10%) in England are situated in London. Bivariate analysis of TVOC emissions and population density shows that 64% of high TVOC LSOAs have high population density, whilst 74% of low population density LSOAs have low TVOC emissions (SI Table S4). Areas where there is high TVOC and low population density appear to be in the outskirts of cities and in more rural towns (SI Fig. S8).

4.5 TVOC emissions by ethnicity

A social parameter often found to be linked to deprivation,[49] and inequality in air pollution exposure,[38] is ethnicity. Fig. 6 highlighted how communities in England with higher proportions of Asian, Black, and White (other) populations were on average areas with higher emissions of TVOC. The opposite trend was present for the White British demographic, with the lowest average emissions in communities with the highest proportion. Similar relationships are shown for ethnicity proportion with population density and deprivation, with the proportion of Asian, Black and White (other) communities increasing as population density and deprivation increases, whilst White British proportion decreases as population density and deprivation increases. This demonstrates that ethnicity is also an important factor to consider for spatial inequalities in TVOC emissions across England, alongside population density and deprivation. Bivariate analysis shows that 66% of high TVOC LSOAs are areas with a high percentage of ethnic minority residents, with low TVOC in communities with a high percentage of white British residents (SI Table S5). The bivariate ethnicity and TVOC emissions map (SI Fig. S9) show similar hotspots to the population density and deprivation maps, with high ethnicity and high deprivation clustered in large cities across England.

4.6 Controlling for confounding variables

Deprivation, population density, land classification and ethnicity have all shown to be spatially related with TVOC emissions across England independently. High deprivation scores, high population density, urban land classifications and a high percentage of ethnic minority residents are all features of a community which makes high TVOC emissions within that area more likely. However, these features are also associated with each other. Deprivation scores are higher in urban, high population, ethnic minority areas, for example.[49] The spatial autoregressive (SAR) model allows to test for the significance of each association whilst controlling for confounding variables which may impact the association. After controlling for the covariates, high deprivation scores, high population density, urban land classifications and a high percentage of ethnic minority residents were still shown to have statistically significant associations with high TVOC emissions (SI Table S6). This observation supports the case that spatial inequalities for TVOC emissions are present in England and areas of high deprivation, high population density, urban land classifications, and a high percentage of ethnic minority residents, which are focused predominately around large cities, are exposed to higher TVOC emissions than other areas of England.

5 Conclusions

TVOC emissions are shown to be significantly associated with deprivation across England, with areas of higher deprivation experiencing higher TVOC emissions in 2019. The largest urban conurbation in the country, London, exhibits the same trend as the rest of the country, with higher overall emissions across all levels of deprivation. Solvents are the dominant emission source component of TVOCs across England, which also demonstrate the same relationship with deprivation as all-source TVOCs, whilst other key sources, agriculture, road, and industrial processes, do not show this association with deprivation. Social factors which are related to deprivation include, land-classification, population density, and ethnic minority populations, are all also independently associated with TVOC emissions. Areas of high TVOC emissions are dominated by, urban classified, densely populated, high ethnic population LSOAs. The association between these social factors is still significant when controlling for covariates. The dominant source of TVOCs, solvents, is emitted from various domestic and industrial activities, which makes it difficult to regulate and control its usage. Urban, deprived, densely populated communities with high ethnic minority populations were identified as hotspots of high TVOC emissions in this research, which are of particular concern due to the potential health effects of this environmental inequality. This research demonstrates the importance of identifying sources of air pollution emissions and potentially vulnerable communities in attempting to reduce inequalities in air pollution emissions and exposure across England.

Author contributions

Conceptualization – CJY, data curation – CJY, formal analysis – CJY, RLC, PSM, funding acquisition – PSM, investigation – CJY, RLC, PSM, methodology – CJY, project administration – CJY, RLC, PSM, resources – CJY, RLC, PSM, software – CJY, supervision – RLC, PSM, validation – CJY, visualization – CJY, RLC, PSM, writing (original draft) – CJY, writing (review & editing) – RLC, PSM.

Conflicts of interest

There are no conflicts to declare.

Data availability

This study was carried out using publicly available data from the National Atmospheric Emissions Inventory at https://naei.energysecurity.gov.uk/data/maps/download-gridded-emissions and the UK Government at https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019.

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