Defra RDE Framework

RDE176: Quick scoping review to understanding the groups at increased risk from adverse effects of air pollution due to their exposure and activities undertaken

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1 Executive summary

1.1 Key messages

1.1.1 Review of the Air Quality Information System

In the UK, air pollution remains the main environmental threat to human health. Air pollution impacts peoples' health throughout their life course. Everybody is exposed to air pollution at some level. However, some groups and communities are more likely to experience disproportionately higher exposures. The Department for Environment, Food, and Rural Affairs (Defra) and the UK Health Security Agency (UKHSA) are undertaking the Air Quality Information System (AQIS) review, in order to improve the provision of air quality information to the public. As part of the AQIS review, Defra commissioned this quick scoping review (QSR) to identify evidence relating to population groups that may be highly exposed to air pollution from outdoor sources. In particular, evidence related to exposure to the pollutants that are used to construct the Daily Air Quality Index (DAQI) - nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ozone (O_3), particulate matter ($PM_{2.5}$ and PM_{10}) - are the main focus of this review.

1.1.2 High exposure groups

In the UK population, a number of groups of interest were identified prior to searching the literature. These were identified by the QSR team based on the research questions provided by Defra (Section 2.2) and are the groups which the QSR examined. These include people with protected characteristics and those who belong to an inclusion health group[1]. It also includes people who, because of their activities or where they live or work, spend their time in areas with higher outdoor air pollution.

Groups of concern identified prior to the literature search include:

- Professional or recreational athletes conducting physical activity outdoors
- Ethnic minorities
- Persons of specific sex (as defined by their reproductive organs e.g. Male/Female/Intersex)
- Persons who identify with a specific gender (based on a person's perception of their role in society independent of their sex)
- LGBTQ+ groups
- Commuters (primarily to/from work or school)
- Unsheltered homeless
- Persons suffering from substance misuse disorder
- Gypsies or traveller communities

[1] Inclusion health groups include: people experiencing homelessness, drug and alcohol dependence, vulnerable migrants, Gypsy, Roma and Traveller communities, sex workers, people in contact with the justice system, victims of modern slavery and other socially excluded groups

- Outdoor workers
- Children
- Pregnant people
- Persons with disabilities
- Persons living in socioeconomically deprived areas, and
- Persons who have low socioeconomic position

1.1.3 Availability of evidence

A range of different types of exposure studies was identified. Some studies used methods to assess personal level exposures, but most studies evaluated exposure at fixed locations, either at specific addresses or modelled for a wider area (e.g. neighbourhood). Most studies focused on urban air pollution, particularly traffic-related air pollution. NO_2 was the most studied pollutant followed by particulate matter (PM) and O_3. This is likely due to vehicles being one of the major outdoor sources of air pollution to which people in urban areas are exposed. NO_2 is commonly used as a marker of traffic -related air pollution. At least one quantitative study was found for most of the groups mentioned above. Exceptions to this were for gender, LGBTQ+, Gypsies/travellers and the homeless. Most studies identified were conducted outside the UK, although a greater proportion of studies on children were undertaken in the UK, compared to other groups.

1.1.4 Main conclusions

Distribution of exposure to high levels of air pollution across different population groups

There was sufficient empirical evidence to show that:

- Exposure to air pollution was often higher than average for those belonging to lower socioeconomic status (SES) groups (defined by income, education, occupation or residence), although this varied by study.
    - Low SES is often associated with worse health outcomes as a whole (Pearce et al. 2010), thus increasing the risks air pollution poses, especially when combined with individual characteristics, which may make a person susceptible (e.g. age, pregnancy, genetic factors).
- Persons belonging to ethnic minorities, not including the white ethnic group, were more likely to be more highly exposed. This disparity persisted across income levels and regions in the US as well as in the UK. However, further research is required to determine whether trends in London, where most of the UK studies identified on this subject were conducted, hold for other regions in the UK.
- Commuting sometimes results in higher exposures, but this varies by location and commuting mode.
    - Exposures during active commuting (defined as a mode which results in higher physical exertion and therefore breathing rates, e.g. cycling) could be higher than average when taking place in close proximity to air pollution sources e.g. walking or runny on pavements of busy roads, cycling on busy roads, or playing on sports

fields/courts near sources of pollution. This was of particular concern for children and elderly in studies.
  - Longer commutes tended to occur by vehicle and could also result in increased exposures due to the longer duration of exposure, however, this would depend on the level of pollution infiltration into the vehicle.

Considerations for reducing exposure to high levels of air pollution

Strategies for exposure reduction need to consider the following:

- The location of pollution and time spent in polluted locations.
- Local level and community engagement across the agencies that high exposure risk groups interact with is necessary to increase awareness of where and how people are exposed to pollution.
- Air quality advice needs to consider that some people have more agency to reduce their exposure than others.
- Additional microenvironment factors such as pollution infiltration that bring outdoor pollution to indoor spaces should also be considered in future air quality information.
- Research on exposure-response relationships indicate that for some pollutants (especially $PM_{2.5}$), even levels of exposure below regulatory limits are not without risk.

Further studies to gather exposure data for the UK context will help improve targeted messaging around both exposure reduction measures and air quality information. However, evidence gaps need not be a barrier to taking action based on currently available information.

2 Background

2.1 Air Quality Information System Review

In the UK, air pollution remains the main environmental threat to human health. Air pollution impacts peoples' health throughout their life course. Research has shown a range of impacts on the growing foetus in the womb, through childhood, and into old age. The heart, lung, and brain are among the organs that air pollution affects[2].

Everybody is exposed to air pollution to some degree. However, some groups and communities may be more likely to experience disproportionately higher exposures. The Department for Environment, Food, and Rural Affairs (Defra) and the UK Health Security Agency (UKHSA) are undertaking the Air Quality Information System (AQIS) review, in order to improve the provision of air quality information to the public. Currently, the government uses the Daily Air Quality Index (DAQI) to inform the public, and particularly those who may be susceptible to health effects, during short-term episodes of elevated levels of air pollutants. The DAQI covers the main pollutants regulated by the UK government: nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ozone (O_3), and fine particulate matter ($PM_{2.5}$ and PM_{10}).

The AQIS review is taking place over two years (December 2021-December 2023) and is guided by an external steering group consisting of multidisciplinary experts from air quality science, health and clinical science, behavioural science, digital communications, and representatives of the lay public, health charities, and local and central government. This steering group provides direction and oversight to the review and will propose a series of actionable and evidence-based recommendations for improvements to the current provision of air quality information by the government.

A series of evidence projects have been commissioned as part of this review, including primary research and literature reviews. This report covers a quick scoping review (QSR) which focuses on identifying population groups that may be highly exposed to air pollution from outdoor sources. The results of this report complement those from two other reviews that focus on identifying groups that may be more susceptible to health effects of air pollution, and impacts on those undertaking physical activity outdoors.

2.2 Review aims and research questions

The aim of this review is to identify a set of population groups that may be at risk of high exposure to outdoor air pollutants and to evaluate the availability of evidence in the literature for these groups being at higher risk of exposure. In particular, this review aims to explore the questions posed by Defra:

[2] Royal College of Physicians. Every breath we take: the lifelong impact of air pollution. Report of a working party. London: RCP, 2016.

- Which groups experience an increased risk of adverse health effects associated with air pollution as a result of being exposed to high concentrations or undertaking activities that mean they inhale more air?

More specifically:

- What evidence exists to indicate if any of the protected characteristics, or belonging to an inclusion health group, are associated with increased exposure to air pollution?
- What evidence exists to indicate that any occupations involve increased exposure to air pollution (including exposure to higher concentrations than the general public, more time than usual spent in high concentrations, or a higher inhalation rate resulting in higher exposure)?
- What evidence exists to indicate any recreational activities involve increased exposure to air pollution (including exposure to higher concentrations than the general public, more time than usual spent in high concentrations, or a higher inhalation rate resulting in higher exposure)?
- What evidence exists to suggest that any groups - additional to those specified above – experience increased exposure to air pollution?
- Are there any relevant intersections of risk that decision makers should be aware of when targeting air quality information provision?

2.3 General approach

2.3.1 Focus of review

This review focuses on groups which may be highly exposed, and their levels of exposure (Group A, Figure 1), rather than on health outcomes specifically, although there is consideration of whether groups susceptible from a health perspective (e.g. due to Individual characteristics such as age, sex, ethnicity, pregnancy, pre-existing medical conditions, underlying, genetic factors, Group B in Figure 1), may also have higher exposures due to where they live or work, or the activities they undertake. The focus is on air pollution derived from outdoor sources, and primarily on exposures outdoors. While indoor exposures are not specifically included, there is consideration of people that may e.g. live or work in high pollution areas. Although not the focus of this QSR, it is likely that policy makers may wish to provide targeted public health messaging to those who fall into both these groups (A and B) i.e. groups that are at increased risk of high exposure to air pollution, as well as having increased susceptibility to its impacts due to individual characteristics (such as age, sex, ethnicity, pregnancy, pre-existing medical conditions, underlying genetic factors).

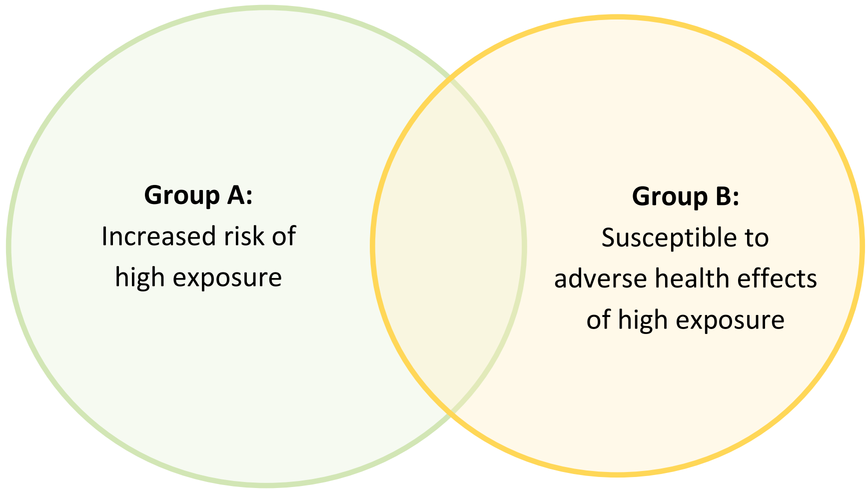

Figure 1: Basic model of the types of population groups AQIS is looking to address. This QSR focuses on Group A.

2.3.2 QSR definition and framework

The QSR methodology has been informed by the guidance document by Collins et al., (2015) – a publication from the UK government on the steps involved in QSRs and Rapid Evidence Reviews[3]. They define a QSR as "A type of evidence review that aims to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to a question". As such the focus of this QSR will be on exploring the adequacy of the evidence in support of defined groups that are at increased risk of exposure to air pollution that consequently increases their risk of associated adverse effects.

It should be noted that this is an exploration of available evidence identified under a QSR framework, and should not be treated as a systematic and comprehensive review of the literature. Figure 2 summarises the procedure for this QSR.

[3] https://www.gov.uk/government/publications/the-production-of-quick-scoping-reviews-and-rapid-evidence-assessments

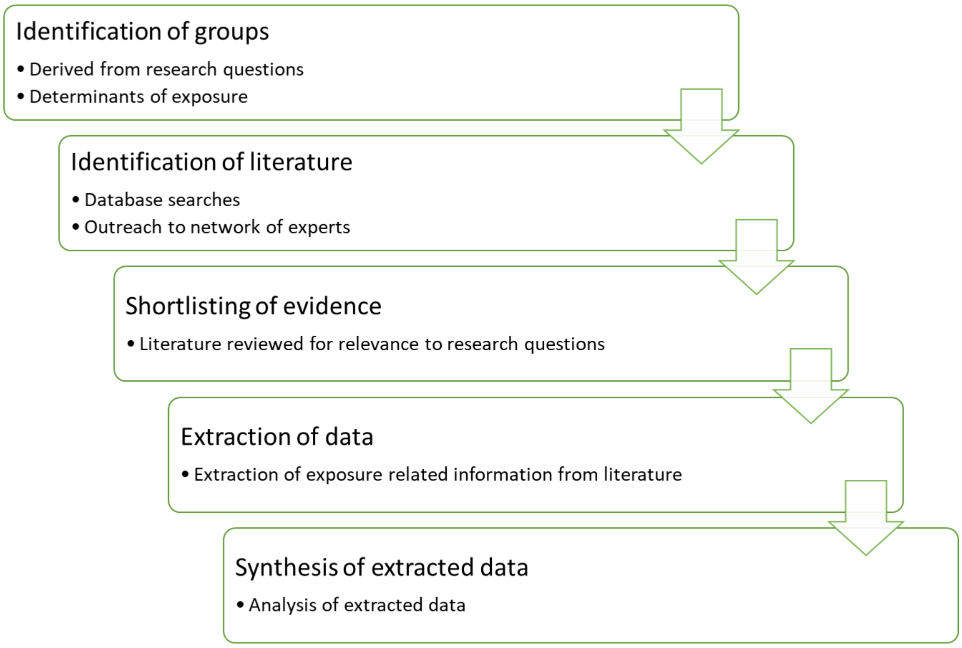

Figure 2: Steps taken in the search for evidence of groups with high exposure to air pollution

The search for evidence entailed the following steps:

- Identification of groups of interest based on the research questions set out by Defra (section 2.2) and the factors that are likely to determine exposure.
- Search of literature using various online literature databases and a call for evidence from a network of experts including atmospheric scientists and social scientists[4].
- Evaluation of this literature to understand the types of studies available to support the hypothesis that the groups identified are likely to be highly exposed, and the key factors that influence that exposure.

2.3.3 Determinants of exposure

Exposure to an air pollutant is often expressed as a time-weighted average concentration over the duration and frequency of exposure. A person's exposure is determined by

1) the *concentration* of air pollutants they encounter

[4] This included UK based organisations and some based in the EU, specifically UKCEH, Imperial College London, the Universities of Leeds, Birmingham, York and Edinburgh, Aether Ltd, CERC Ltd, EMRC, RIVM and TNO (the Netherlands), Ineris (France), IIASA (Austria). This also included the HEICCAM network (https://heiccam.org/, including Universities of Edinburgh, East Anglia, Lancaster, York, Oxford Brookes, Birmingham, Cranfield, Cambridge, Imperial College, University College London, London School of Hygiene and Tropical Medicine, Institute of Fiscal Studies, UKHSA)

2) the *amount of time* they spend in contact with air pollutants at a given concentration, and

3) the *amount of pollution* they breathe in.

These three variables that determine exposure, are in turn influenced by several layers of wider determinants. Figure 3 organises these contextual layers into a hierarchy, showing that individuals' behaviours and time-activity patterns are directly influenced by the context that they live and work in, and that context is reflective of the larger scale socioeconomic, cultural, and environmental factors in the society in which individuals live. This hierarchy implies that changes in the outer layer are likely to trickle down through to the individual level at the innermost layer, where the most direct impact on exposure would be.

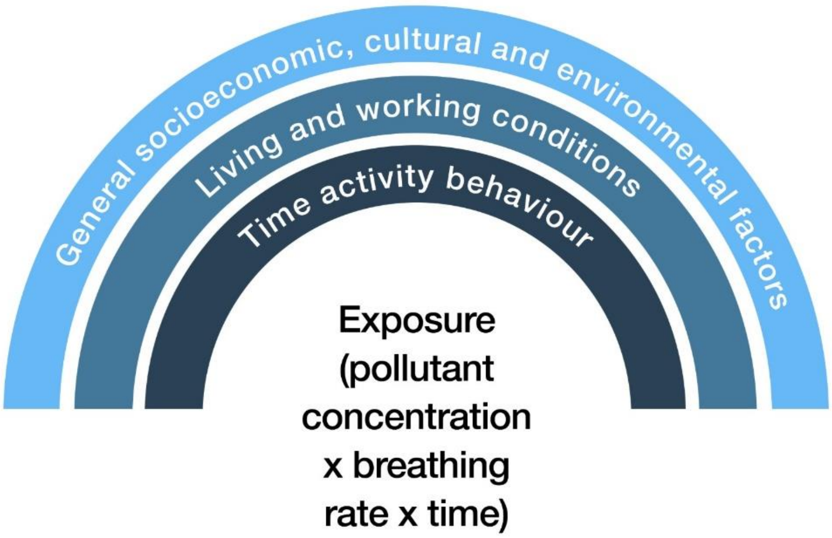

Figure 3: Model of the wider determinants of exposure

Time-activity patterns of behaviour

Time-activity patterns describe how long, how often, and where people spend their time and is an important predictor of exposure. When evaluating exposure, it is useful to define a unit called a microenvironment, which is a location category in which a person spends time. Air pollutant concentrations differ among microenvironments (e.g. indoor, outdoor, transit, school), as does the time spent in each. Exposure is the product of the amount of time spent in each microenvironment and the concentration found in that microenvironment (see Figure 3).

The location of microenvironments relative to outdoor air pollution sources is also an important predictor of the concentration of air pollution at that place. These may be outdoor microenvironments, such as the pavement of a busy street an urban green space, or indoor microenvironments, such as a home or office. The pavement of a busy street or a home and office located in a high-traffic area will likely have higher air pollution concentrations.

A person's behaviour in that microenvironment also determines their breathing rate. If they are exerting themselves through exercise or manual labour, they will have a higher breathing rate leading to inhalation of larger volumes and thus intake of a larger mass of the air pollutants in that air.

Living and working conditions

Time-activity patterns are influenced by many living and working conditions that are closely related to socioeconomic factors, e.g. income, education, employment, access to services. Work plays a large role in determining activity patterns, with the flexibility in contract, location (fixed, domestic, international) and holiday entitlement varying by SES. Likewise, the places in which people spend leisure time in will depend on access to financial and social resources.

Living and working has a bi-directional relationship with health. This is expressed in the health selection and social causation literature. Health status can have a large influence on time-activity patterns by restricting or enhancing the ability to choose where one lives and works. For, example, a person with mobility limitations may not be able to move out of a polluted zone because of a lack of street infrastructure (e.g. traffic lights, dropped kerbs etc). Living with certain health conditions, like anxiety, depression, asthma and Chronic Obstructive Pulmonary Disease (COPD) may contract the size of a person's 'activity space', limiting people to daily activities close to their home.

General socioeconomic, cultural and environmental factors

The living and working conditions described in the last section are subject to influences from wider society. These may include events such as the COVID-19 pandemic, climate change, urban planning policies, or technological changes such as vehicle electrification and shifts to renewable energy. The pandemic, for example, resulted in lower NO_2 levels in some urban areas. It also resulted in large changes in persons' time-activity patterns, with many people spending even more time at home and much less in transport. Moving to electric vehicles may reduce emissions of NO_2 but potentially not impact $PM_{2.5}$ levels[5]. Unintended consequences of policies may shift pollution from one area to another. Increasing home prices in city centres may result in more people living further away and therefore spending more time commuting to jobs in the city, thus changing the relative importance of various microenvironments to exposure (e.g. commuting, home).

2.3.4 Definition of high exposure groups

Population groups of interest were identified based on the research questions set out by Defra. These included people with protected characteristics[6] and health inclusion groups[7].

There is evidence to suggest that populations living in poorer areas (Barnes et al. 2019); certain groups of outdoor workers (Brauer et al. 1996; British Safety Council, 2020); and athletes or individuals walking and exercising outdoors (Carlisle and Sharp, 2001; Pasqua et al. 2018; McConnell et al. 2002) are exposed to higher levels of air pollution. In the latter two groups, the risk is exacerbated by their higher breathing rates and change in breathing patterns during activities that

[5] Due to the extremely low levels of tail-pipe emissions of $PM_{2.5}$ in modern combustion powered cars and the continued presence of tyre, brake and road wear emissions in electric vehicles.

[6] As defined in the UK - age, disability, gender reassignment, marriage and civil partnership, pregnancy and maternity, race, religion or belief, sex, sexual orientation

[7] Inclusion health groups include: people experiencing homelessness, drug and alcohol dependence, vulnerable migrants, Gypsy, Roma and Traveller communities, sex workers, people in contact with the justice system, victims of modern slavery and other socially excluded groups

require higher energy expenditure (Carlisle and Sharp, 2001; Madureira et al, 2019). Other groups that are potentially at increased risk are persons with a low socio-economic status (Padilla et al. 2016) including members of marginalised communities such as persons experiencing unsheltered or chronic homelessness, individuals who suffer from substance abuse disorder or members of certain ethnic minority groups. These and other groups may benefit from tailored communication on air pollution exposure and personal mitigation measures.

Table 1: Groups of interest and hypothesised reasons they may be highly exposed

Group	Potential reasons for high exposure
Professional/recreational athletes	• A greater fraction of air is inhaled through the mouth during exercise, effectively bypassing the normal nasal filtration mechanisms • Increased inhalation rate during exercise • Increased airflow velocity carries pollutants deeper into the respiratory tract • More time spent outdoors
Ethnic minorities	• SES determined – living/working in more polluted areas (e.g. schools – Osborne et al., 2021), more limited access to resources to mitigate exposure (i.e. spend more time close to home)
Persons of specific sex	• Differences in time-activity patterns, including employment and commute options
Persons of specific gender	• Differences in time-activity patterns, including employment and commute options
LGBTQ+ groups	• Differences in time-activity patterns
Commuters (walk/cycle/car/bus/train/subway)	• More time outdoors • Closer proximity to traffic sources • Potential higher inhalation rate if cycling or running or some other form of transport which results in higher metabolic activity

Group	Potential reasons for high exposure
Homeless	• If rough sleepers, vastly higher time spent outdoors than other groups • If not rough sleepers, hostels, shelters, refuges or other temporary circumstances more likely to be in dense urban areas
Persons suffering from substance misuse disorder	• Differences in time-activity patterns • Potentially linked to SES
Gypsies/travellers	• SES determined - Living close to busy roads
Outdoor workers (e.g. farmers, construction, traffic police)	• High occupational time outdoors (in daytime whilst road traffic at its busiest) • Mixture of pollutants (e.g. generated from work activities + general outdoor)
Children	Schools more likely to be in busier areas. Breathe more rapidly, closer to ground where pollutants more concentrated. More time outdoors for recreation than adults (Chakraborty et al. 2020)
Pregnant people	• Increased inhalation rate for higher oxygen requirements of the developing foetus (Soma-Pillay et al. 2016)
Persons with disabilities	• Differences in time-activity patterns • Potentially linked to SES
Persons living in socioeconomically deprived areas	• Deprived areas may have greater likelihood of more pollution sources
Persons who have low socioeconomic position	• More likely to live/work in areas with more pollution • May have jobs which increase their exposure

3 Methodology

3.1 Search protocol

Details of how studies for the review were identified are described below. PubMed, Web of Science, and Google Scholar were searched using terms related to the research questions and groups of interest. The main focus was on exposure assessment, but other types of studies, such as epidemiological and health impact assessment studies were also considered if there was a clear description of the exposure assessment approach and results. Additionally, a request for evidence was made to colleagues from our networks who had the relevant expertise. The focus was on outdoor air pollution with a priority on the air pollutants considered for the current Daily Air Quality Index (DAQI). As the AQIS review focuses on the UK, studies from the UK, Europe, and North America, were prioritised because the transferability of findings to the UK context were expected to be highest for those regions.

Criteria for study selections are detailed in the following sections.

3.1.1 Study types

- Exposure studies including measurement and modelling and spatial analysis of exposure
- Exposure component of the following types of studies investigating health impacts:
    - Health risk assessment/analysis
    - Health Impact Assessments
    - Epidemiological studies including:
        - Observational (cross-sectional, case-control, cohort, ecological)
        - Intervention studies
        - Longitudinal studies
        - Time series analysis
        - Natural experiments
- Types of publications to include:
    - Systematic reviews with transparent methodology
    - Primary research peer-reviewed studies
    - Grey literature from nationally or internationally recognised sources. These include technical and unpublished research reports from government agencies, national or international public health entities or reputable scientific research groups (e.g. World Health Organisation (WHO); United States, Environmental Protection Agency (US EPA); European Environment Agency (EEA))
- Subject of studies may include:
    - Investigations into direct or indirect exposure to any of the air pollutants or investigations into exposure and related human health outcomes.
    - Investigations using validated risk- or exposure- assessment models to evaluate the exposure levels experienced by the general population including susceptible sub-groups or studies using such models to examine related health risks

  - Intervention studies investigating mitigation measures to reduce exposure to any of the air pollutants or studies where such interventions have been used to investigate impact on risk estimates to specific health outcomes.
- Language of studies will be limited to English.
- Time of publication will be limited to studies published from 2010 up to January 2023

3.1.2 Population

Studies where the participants belonged to at least one of the following sub-populations of interest, were included:

- persons belonging to marginalised communities,
- persons with protected characteristics[8] or belonging to an inclusion health group[9]
- persons conducting recreation or other activities outdoors such that there is an increased likelihood of them being exposed to air pollutant levels that are higher than for members of the general public not engaged in such activities
- persons conducting work activities outdoors such that there is an increased likelihood of them being exposed to air pollutant levels that are higher than for members of the general public not engaged in such activities
- persons living in areas where the air pollution levels are likely to be above health-based guidance values and/or relatively high in comparison with those of other residential areas considered as having normal/average levels of air pollution

Specific groups related to these criteria are noted in Section 2.3.4.

3.1.3 Exposure

Studies investigating exposure to (ambient) outdoor air pollution in general or specific constituents of outdoor air pollution were considered regardless of whether they pertain to primary or secondary sources or result from re-emissions. However, particular attention was given to the air pollutants considered for informing the UK's Daily Air Quality Index (DAQI): NO_2, SO_2, O_3, PM_{10}, $PM_{2.5}$. This covered studies looking at exposure due to specific known sources (e.g. traffic-related pollutants).

3.1.4 Comparators

High exposure concentrations of air pollutants were compared with low / average / normal exposure expressed quantitatively or qualitatively and based on suitable exposure assessment methods or established and/or validated exposure models. It was intended that comparisons would also be made with Defra's Air Quality Standards.

3.1.5 Geographical reference

The research questions were considered within the very specific physical, infrastructural and social circumstances of the UK. Priority was therefore given to studies conducted within the UK. However,

[8] As defined in the UK based on the Equality Act 2010- age, disability, gender reassignment, marriage and civil partnership, pregnancy and maternity, race, religion or belief, sex, sexual orientation

[9] Inclusion health groups include: people experiencing homelessness, drug and alcohol dependence, vulnerable migrants, Gypsy, Roma and Traveller communities, sex workers, people in contact with the justice system, victims of modern slavery and other socially excluded groups

studies conducted in Europe and North America were considered where there was sufficient evidence for the transferability of contexts relevant to the UK.

3.2 Search methods

Searches comprised combinations of the source, exposure, health-related terms and terms for specific socio-economic, activity or occupational contexts. Search strings based on the search terms listed in Appendix 1 were designed to identify eligible studies in Web of Science Core Collection and subsequently adapted, for searching PubMed and Google Scholar. For PubMed searches keyword search terms were be mapped to their subject headings and a combination of keyword and Medical Subject Headings (MeSH) terms[10] were used to systematically search the database. Relevant studies from the reference lists of identified studies were also included. Searches were limited to selection of articles published between January 2010 and January 2023.

3.3 Selection of studies for full text review

One reviewer screened the abstracts and titles of the literature to identify the articles that might be relevant for full text review with a subset of articles (10-15%) screened by a second reviewer. Any disagreements were discussed between the reviewers and an outcome agreed upon. Full text copies of articles with seemingly relevant titles but no abstract were obtained to determine their suitability for review.

3.4 Data synthesis

Preliminary synthesis included tabulation of key information from each study. Following examination of the information, a final synthesis of the literature was conducted. This included, were possible, outline of exposure scenarios that describe population subgroup, location, activities performed, type of pollution, duration and level of pollution, and potential vulnerabilities than increase health risks. The amount and type of evidence available for the various *a priori*-identified groups, were also noted.

3.5 Study quality assessment

Typically, a QSR does not include a formal quality assessment of the studies identified. It is useful, however, to examine characteristics of the studies to understand whether the evidence supports the selection of the groups in Table 1 as likely to have high exposure.

As detailed earlier, exposure is a function of the concentration of air pollution encountered at specific microenvironments and the amount of time spent in those microenvironments. We therefore laid out a hierarchy of study types for understanding the exposure of different groups. These were as follows:

- Quantitative (personal) exposure study: This could be a measurement or modelling study but the key feature would be assessing a person's exposure with respect to their time-activity patterns. This type of study will most accurately reflect the concentration of air

[10] MeSH refers to the vocabulary used for indexing articles in PubMed.

pollution that a person breathes in during the time they spend in the area of interest. For example, a person's commuting exposure will be a time-weighted concentration they encounter while travelling between home and work. This may be measured by the person carrying an air sampler during their commute, or modelled by multiplying the concentration in the area they are walking along by the amount of time they spend walking.

- Measurement or model of air pollution concentration at a specific location: This type of study will generally assess air pollution concentration at a fixed location (e.g. a home address) for a particular averaging time (e.g. one year). The air pollution data may be obtained by installing a monitor for a fixed period of time or by using a method such as land-use regression or dispersion modelling to estimate the information. Generally, this method does not necessarily include information on time spent at that location.
- Area measurement or lower spatial resolution modelling: This refers to a measurement or estimate of air pollution concentrations at a larger spatial scale than the assessment at a specific location. This method does not necessarily include information on time-activity patterns and is less likely to capture spatial variability.

Qualitative exposure assessments do not include any quantitative measurements or link to the concentration of air pollution people may be exposed to. Rather, they categorise or describe a group as being more highly exposed based on descriptive information (e.g. lives close to a busy road). This type of study was not included in the overall review, but any identified are included in the discussion.

An abbreviated quality assessment, ranking studies based on a few key variables (e.g. clarity of study questions / hypotheses and description, sample size, study design, comparator) was conducted to help judge potential evidence gaps. Particular attention was given to the quality of the exposure assessment reported in studies.

4 Results summary and synthesis

4.1 Overall evidence summary

4.1.1 Literature identified

After database searching, screening, and full text evaluation, 61 papers were included in the final synthesis (see Figure 4). In the screening, the exclusion criteria were literature related to indoor source air pollution and studies involving animals.

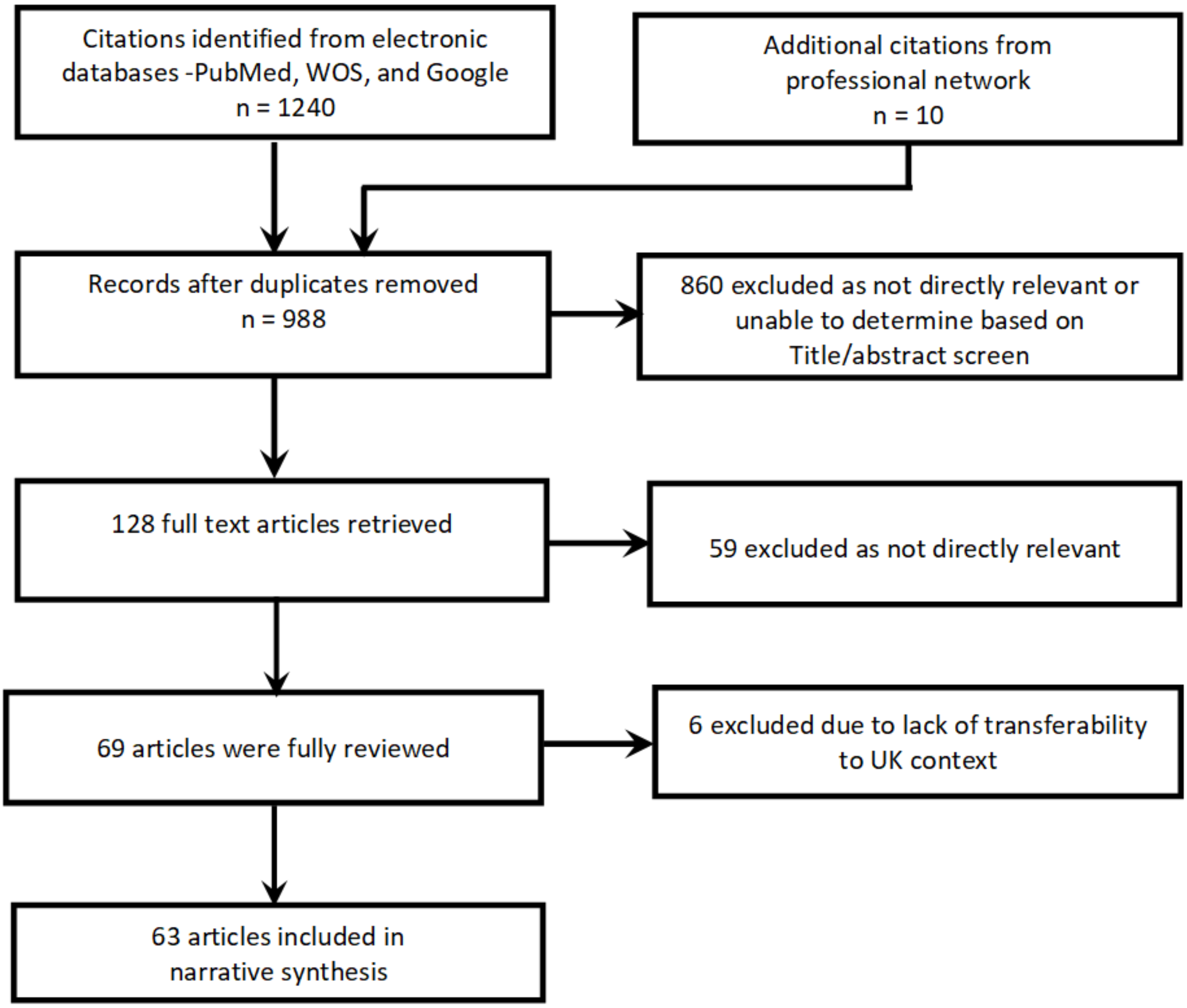

Figure 4: Process flow for selecting final list of citations for synthesis

4.1.2 Summary of findings

Evidence around exposures for the *a priori*-identified risk groups are summarised in Tables 3 – 9. The number and types of studies are displayed in Table 2. The number of studies per pollutant combination are shown in Figure 4.

The largest volume of literature was available for exposure related to persons living in socioeconomically deprived areas (number of studies, n = 21). This was followed by ethnicity (n= 12) and children (n = 9) and then by workers, pregnant people and athletes and persons doing outdoor physical activity (with n = 7 for each of these groups). Commuters were next with 8 articles. Additional groups identified for which there were fewer than three studies were Gypsies/travellers, people with disabilities, and gender. For the groups LGBTQ+, persons who identify with a specific gender, the unsheltered homeless and persons afflicted with substance misuse disorder, no studies were found or retained for inclusion in the narrative synthesis.

Overall, most of the studies focused on $NO_{2,}$ followed by $PM_{2.5}$ (Figure 4). Measurement studies were more likely to include PM, while modelling studies were more likely to be done for $NO_{2.}$ Some studies looked at other aspects of PM such as different size fractions other than PM_{10} and $PM_{2.5,}$ and black carbon. The focus of many of the studies for all groups tended to be related to urban exposures, particularly to traffic -related pollutants. Some consideration for O_3 was also included in studies of pregnant people, children, physical activity/athletes. SO_2 exposure was less commonly studied.

For all groups, SES played an important role in determining exposure, and any relevant messaging needs to address those living in more deprived areas or who have lower SES. In the studies looking at SES, certain groups were over-represented (e.g. ethnic minorities) compared to others (e.g. people experiencing homelessness, Gypsies/travellers), for which little to no quantitative studies were found. Lower SES is often also associated with a susceptibility to poorer underlying health, and higher air pollution exposures, thus compounding the potential impact of pollution on health of low SES groups. Pregnant people, children, and elderly who live/work/go to school in more deprived areas may therefore be more at risk of higher exposures both at home and at school/work.

Some groups were more likely to be of high risk to exposure because of their outdoor time-activity patterns. This included outdoor workers, commuters, children playing outdoors, athletes or recreational exercisers.

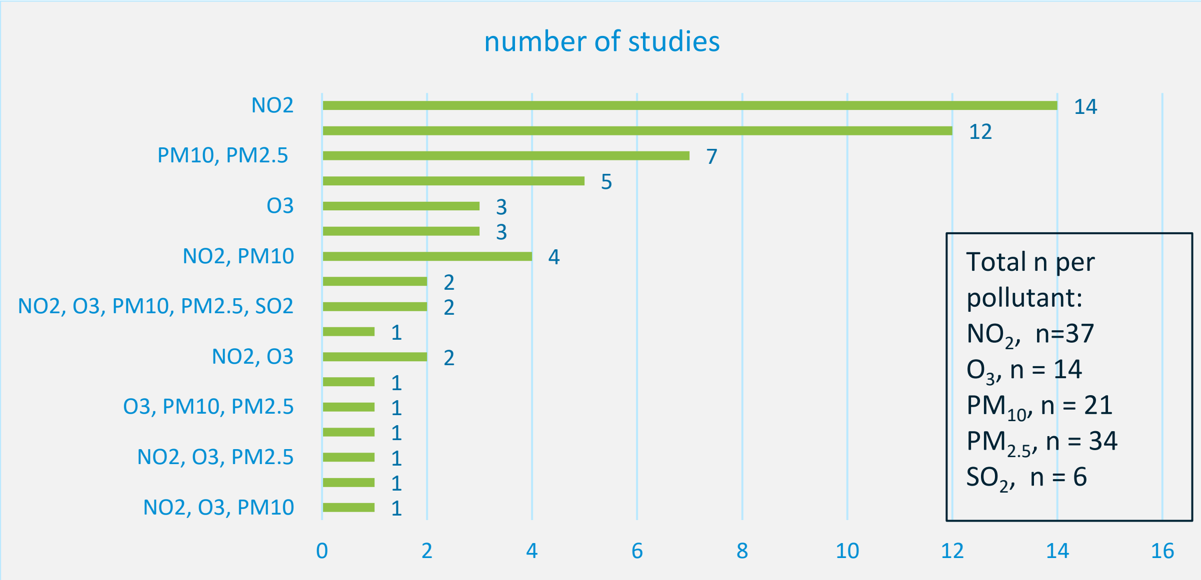

Figure 5: Number of studies (n) focussing on the DAQI pollutants.

Relatively few studies overall were specific to the UK, although about half of the studies on children were (Table 2). Most studies used modelled exposure estimates, primarily looking at fixed locations, although some also incorporated time-activity data to simulate personal level exposure. Studies on children, workers, and commuters were more likely to use personal exposure monitoring, or to use time-activity information to estimate exposure if modelled. A similar number of studies estimated exposures using either extrapolations from air monitoring stations or larger scale models.

Table 2: Number of studies by exposure methodology and directly relevant to UK

	Total number of studies	UK studies	Personal Exposure measurement	Modelled exposure	Area/low spatial resolution estimate
Professional /recreational athletes/exercising outdoors	7	1	4	1	3
Ethnicity	12	6	0	9	3
Commuters (walk/cycle)	8	0	4	2	0
Gender	1	0	0	1	0
Gypsies/travellers	1				
(Outdoor) workers	9	4	1	3	4
Children	9	4	1	3	4
Pregnant people	6	0	1	5	1

	Total number of studies	UK studies	Personal Exposure measurement	Modelled exposure	Area/low spatial resolution estimate
Persons (children) with disabilities	1	1	0	1	0
Persons living in socio-economically deprived areas	21	9	2	13	4

Summaries of the studies by population group can be found in Tables 3-9 with related insights and uncertainties following.

4.2 Persons conducting physical activity outdoors

Table 3: Location, population, and pollutants evaluated in literature identified regarding physical activity

Population group: Physical activity	Number of studies: 7
Cities / Countries	Canada (Stieb et al. 2017; 2018) USA (An et al. 2022; Lovinsky-Desir et al. 2021) Portugal (Slezakova et al. 2019; 2020); Europe wide including the UK (Laeremans et al. 2018).
Who is exposed?	Persons exercising outdoors or doing recreational activities outdoors
	Professional or amateur athletes training outdoors
Pollutants	Two studies looked at NO_2, O_3 and SO_2 exposure (Stieb et al. 2017; Stieb et al. 2018). One study looked at PM_{10} exposure together with black carbon levels (Laereman et al 2018) and all studies looked at $PM_{2.5}$ exposure. In 4 studies, exposure to multiple pollutants was investigated.

4.2.1 Insights and conclusions

4.2.1.1 Proximity of exposure sources

The proximity to exposure sources during typical physical activity exposure scenarios influences exposure levels. Levinksy-Lesir et al. (2020) showed that in a city such as New York the majority of moderate to vigorous activities of children were near traffic sources, and occurred when commuting to and from school. Modelled exposure to $PM_{2.5}$ was highest travel (unspecified mode) while for NO_2 it was highest along pavements/roads while for NO_2 it was highest along pavements/roadbeds and sports fields/courts. However, exposure during commuting was lower than when conducting sport activities and lowest for activities conducted in city parks (Slezakova et al. 2020).

4.2.1.2 Influence of outdoor air pollution on indoor levels

One study found that exposure levels to PM when exercising outdoors are considerably higher than indoor levels with the median particle number concentration (# cm-3) of ultrafine particulate (UFP) across a diverse range of outdoor sites reported to be 12563 # cm-3 versus 7653 # cm-3 for indoor sites (Slezakova et al. 2019). When indoor exercise facilities are sited in high pollution areas air quality control should be via mechanical rather than natural ventilation so that infiltration of outdoor air pollutants is limited.

4.2.1.3 Influence of personal factors and local microenvironment

Age and gender and the local microenvironment also influence exposure. Slezakova et al (2020) found that UFP concentrations were positively correlated with temperature and inversely with wind speed and relative humidity and Slezakova et al. (2019) reported a 3-fold difference in UFP levels between sites 1500 metres apart highlighting the importance of local exposure factors. Slezakova et al. (2020) observed that males experienced higher exposure levels than females, and children and youth had the highest exposure of all age groups. However, the driver of the sex difference is thought to be due to different activity patterns between sexes (Slezakova et al. 2020) while age-related differences are thought to be due to more vigorous activity of the younger age groups (Slezakova et al. 2020).

4.2.2 Relevant items for health messaging

Due to increased respiration rate and increased time spent outdoors, those who are participating in vigorous activity outdoors will have considerably higher absolute exposure when pollutant concentrations are high. Providing information on location-specific exposure risks would support informed decision-making on the best times and locations for participating in moderate or vigorous activity.

Air quality indices could be accompanied by guidance that encourages outdoor exercise in locations with less traffic or avoiding exercising during peak traffic periods.

Special attention should be given to populations identified as susceptible to the adverse effects of air pollution exposure such as the elderly, and those with existing lung or heart health conditions. For these groups the message around net positive health benefit of exercising outdoors needs to be sensitively communicated. However, it should firstly be determined whether the methodology behind the threshold values suggested by An et al. (2022) is sufficiently robust for these values to be used to inform guidance on outdoor physical activity.

Persons with relatively high levels of outdoor activity such as athletes and children should be considered for targeted messaging.

On high pollution days, targeted health messaging should also be considered for susceptible individuals who engage in moderate to vigorous activity in indoor fitness and sport facilities that depend primarily on natural ventilation.

4.2.3 Gaps & uncertainties

Additional research is needed to determine at what pollutant concentrations outdoor activity should be avoided (Stieb et al. 2017).

Contextual information such as the type of physical activity and whether it took place in urban or rural settings were not often reported. This type of information would help inform health messaging for different types of exposure scenarios.

Many studies utilised static sensors and modelling techniques (Lovinsky-Desir et al. 2021, Stieb et al. 2017, Stieb et al. 2018) rather than conducting personal exposure monitoring that more accurately represents personal exposure.

Some of the samplers used in studies had lower limit cut-off values of <20 nm (Slezakova et al. 2020), which may result in underestimated UFP number concentrations. It is important to obtain information on particle concentrations <20 nm as UFP deposition within the respiratory system is size–dependent. Therefore, information on particle size distributions would be important for the accurate estimation of dose rates. In most cases where particle concentrations were measured, information on respective distributions that would allow better assessment of the particle deposition within the human respiratory system was not included (Slezakova et al. 2019).

Studies did not always include a control group that had not participated in exercise (Stieb et al. 2017, Stieb et al. 2018) therefore comparisons could not be reported.

An et al (2022) indicated that the low $PM_{2.5}$ in their study – the only pollutant they investigated – was not necessarily reflective of other air pollutants' concentration levels. When all air pollutants are considered the optimal outdoor moderate physical activity (MPA) durations would need to be adjusted downwards. The current lack of data on other pollutants meant that subpopulations who are highly vulnerable or sensitive to any of the other air pollutants could not be modelled.

An et al (2022) also warned against making the assumption that people could freely choose the locations and durations of outdoor physical activity since this may not reflect the real case scenario of having to balance considerations based on budget and time available.

4.3 Persons belonging to ethnic minority groups

Table 4: Location, population, and pollutants evaluated in literature identified regarding ethnic minority groups

Population group: Ethnic minorities	Number of studies: 12
Cities / Countries	**UK** London, UK (Aether, 2013; 2017; 2019; 2023);

	London, UK (AQC, 2021) England (Fecht et al. 2015) **US** The contiguous United States (Chambliss et al. 2021) The contiguous United States (Clark et al. 2014; 2017) The contiguous United States (Tessum et al. 2021) San Francisco Bay Area, USA (Chambliss et al. 2021) Southern California (Lu, 2022)
Who is exposed?	Persons not belonging to the white population
	Ethnic minorities
	Populations of high social deprivation
Pollutants	NO_2 (Aether, 2013; 2017; 2019; 2023; AQC, 2021; Chambliss, 2021; Clark, 2014; 2017; Fecht et al. 2015) $PM_{2.5}$ (Aether, 2013; 2017; 2019; 2023; AQC, 2021; Lu, 2022; Tessum et al. 2021) PM_{10} (Fecht et al. 2015) Nitrogen Oxide, NO (Chambliss et al. 2021) Black Carbon, BC (Chambliss et al. 2021) Ultra Fine Particulates, UFP (Chambliss et al. 2021)

4.3.1 Insights/Conclusions

4.3.1.1 Higher exposure of ethnic minorities (excluding the white ethnic group) relative to the white ethnic group is consistent across income levels and regions

In a series of studies by Aether and Air Quality Consultants (AQC) it was found that the areas in London with the lowest air pollution concentrations of NO_2 and $PM_{2.5}$ have a disproportionately white population. White and Asian populations were under-represented in the most polluted areas in comparison to the general population, whereas Black, Mixed Multiple and Other populations were overrepresented. Whilst the improvements in air quality across London benefit everyone, clear inequalities in exposure to poor air quality remain. A separate study (Fecht et al. 2015) found that PM_{10} and NO_2 concentrations were statistically higher at the national level in English neighbourhoods with >20% non-White residents compared to those with <20% non-White residents. This was equally true for NO_2 when examining cities and regions, but there were some cities with <20% non-White residents with higher PM_{10} concentrations (East of England, Yorkshire, Leeds).

4.3.1.2 Higher exposure of ethnic minorities are consistent across borders

These findings were similar to those found in studies in the USA that used census data of communities in California and modelled and measured exposure data. Ethnic minorities had higher exposure (NO_2 and $PM_{2.5}$ across the US, and additionally BC and UFP in California) compared to white populations. These disparities were persistent across income levels and regions in the contiguous United States (Tessum et al. 2021). Furthermore, although the most highly exposed groups had the greatest reductions in NO_2 between the 2000 and 2010 Census, the disparities between people of colour and the white ethnic groups persisted, with ethnicity being the most significant predictor of that disparity (Tessum et al. 2021).

Although persons belonging to other than the white ethnic group are more likely to experience higher levels of exposure, exposure disparity among different ethnic groups result from a complex mix of factors and there is limited transferability of findings among countries and even within countries. (Clark et al. 2014). However, findings relevant for the UK context discussed above indicate the relevance of these findings for this region.

4.3.1.3 Source of exposure across different ethnic groups

Tessum et al, (2021) found that of the groups studied, black people had higher-than-average exposure to PM2.5 resulting from all emission sectors. People of colour, Hispanics, and black people were more likely to be affected by emissions from industry sources than whites and Asians, and that all ethnic minorities were also most likely to be exposed to vehicle pollution. The transferability of these findings to the UK is unknown.

4.3.2 Relevant items for health messaging

Ethnic minorities may be at higher risk of exposure to air pollution. This is compounded if they also have a lower SES or live in a socially disadvantaged neighbourhood.

4.3.3 Gaps & uncertainties

There may be differences in exposure-related factors such as time-activity and living and working situations.

Most studies looked at the whole country using modelled concentrations, only two in California used measurement data, but this was not on a personal exposure level. The London studies looked at population level exposures and the overall distribution of air pollutant concentrations.

There is a need for evaluating exposures to air pollution to ethnic minorities in the UK besides London, and to understand potential disparities in exposure across the whole population.

4.4 Commuters

Table 5: Location, population, and pollutants evaluated in literature identified regarding commuters

Population group: Commuters	Number of studies: 8
Cities / Countries	**Europe** Milan/Rome, Italy (Borghi et al. 2020; Manigrasso et al. 2017) Barcelona, Spain (Moreno et al. 2015) Basel, Switzerland (Ragettli et al. 2015) Lisbon, Portugal (Correia et al. 2020) Hamburg, Germany (Ramacher et al. 2020) **US**

	Texas, US (Askariyeh et al. 2019). **Various** International review (Mitsakou et al. 2021)
Who is exposed?	Commuters characterised by their mode of transport: • walking (Moreno et al. 2015; Ragettli et al. 2015; Borghi et al. 2020; Manigrasso et al. 2017; Ramacher et al. 2020), • bus (Moreno et al 2015, Ragettli et al. 2015, Correia et al. 2020; Ramacher et al. 2020), • bike (Ragettli et al. 2015; Borghi et al. 2015; Correia et al. 2020; Ramacher et al. 2020), • car (Ragettli et al. 2015; Borghi et al. 2015; Correia et al. 2015; Askariyeh et al. 2019; Ramacher et al. 2020), • subway (Moreno et al. 2015; Borghi et al. 2020; Correia et al. 2015; Ramacher et al. 2020), • train (Ragettli et al. 2015; Borghi et al. 2020; Ramacher et al. 2020), • tram (Moreno et al. 2015) Note that exposure during each specific mode of transport was not necessarily reported in all studies (e.g. modelling studies in particular reported exposure over all commute routes)
	Commuters additionally characterised by their: distance travelled, travelling through high/medium/low traffic areas, COPD status, commuting day of week (weekdays vs weekends), time period (lockdown period relative to the previous three-year average)
Pollutants	Four of the six studies measured PM_{10} and $PM_{2.5}$ (Moreno et al. 2015; Borghi et al. 2020; Correia et al. 2015; Manigrasso et al. 2017), with NO_2 measured additionally in one (Borghi et al. 2020). One of the studies modelled NO_2 (Ragettli et al. 2015) while another modelled $PM_{2.5}$ (Askariyeh et al. 2019). One study modelled both NO_2 and $PM_{2.5}$ exposure (Ramacher et al. 2020). One study included PM_1 (Moreno et al. 2015) while BC was also included in two studies (Moreno et al. 2015; Correia et al. 2015).

4.4.1 Insights/Conclusions

4.4.1.1 Transport mode determines exposure characteristics

The average number concentrations, coarseness and inhalable particle chemistry vary by mode of transport (Moreno et al. 2015).

4.4.1.2 Commuting mode with highest exposure potential is unknown

There was no consensus, across the studies, on which commuting mode resulted in the highest air pollution exposure. In Hamburg, Ramacher (2020) found that drivers and passengers in cars were exposed to the highest $PM_{2.5}$ and NO_2 concentrations followed by pedestrians. Similarly, Texas traffic related $PM_{2.5}$ was highest when participants were driving compared to when they were outdoors or indoors (Askariyeh et al. 2019). Others found that cyclists inhaled the highest exposure dose (Ragettli et al. 2015; Correia et al. 2020), or that underground passengers inhaled the highest doses of particulate matter but pedestrians the highest doses of NO_2 (Borghi et al. 2020).

A large ambient concentration decrease was observed during a period of low general commuting, i.e. COVID-19 lockdown (Kazakos et al. 2021).

4.4.1.3 Contribution of commuting to total exposure could be significant

Not accounting for commuting exposures significantly biases overall exposure estimates downwards, especially for those travelling long distances (Ragettli et al. 2015) (i.e. may be underestimating pollution related health impacts by not factoring in commuting exposures).

4.4.1.4 Factors other than transport mode influence personal exposure

There is a large dose increase (deposited in human respiratory tract) for those with COPD (higher respiratory rate) and those commuting on weekdays (Manigrasso et al. 2017). Route choice, car ventilation settings, position in transport, and cycling/walking position relative to vehicles also influence exposure (Mitsakou et al. 2021).

4.4.2 Relevant items for health messaging

Commuters could consider varying their mode of transport, day of travel (if hybrid) or route of commute (shorter duration, low air pollution zones) to lower their exposure, especially during times of forecasted high air pollution.

This messaging is particularly pertinent for cyclists, who based on the reviewed evidence, seem to have the potential to have highest dose due to greater inhalation rates, being close to traffic sources and lengthier travel times.

4.4.3 Gaps & uncertainties

The majority of the studies had very low sample sizes. Three studies had a sample size of one, another had a sample size of two but all employed personal monitoring. A future study with a larger cohort would facilitate assessment of the variability in exposure and help identify key determinants of commuter-related air pollution exposure.

Different conclusions in different cities suggest location-specific results, and more research is needed in the UK to be sure of the applicability of exposure differentials.

An uncertainty that affects commuting in particular is the information on infiltration of outdoor to in-transport concentrations of pollutants (Ramacher et al. 2020).

Studies generally did not use a comparative approach where they monitored the same routes during the same times travelled using different transport modes.

One study found profound differences in commuting-related exposure in London during the COVID-19 pandemic due to population lockdowns. Modelling studies that investigate different scenarios of population-level hybrid working (e.g. using data from the census) should be conducted to understand whether interventions that encourage temporal (time-activity) and/or spatial changes in behaviour would enable less direct exposure to the commuter and indirect exposure to more deprived neighbourhoods.

4.5 Workers

Table 6: Location, population, and pollutants evaluated in literature identified regarding workers

Population group: Workers	Number of studies: 9
Cities / Countries	London, UK (Bos et al. 2021, Jones et al. 2021, Rawlings et al. 2021, British Safety Council and Kings College 2020) Madrid Spain (Vega-Calderon et al. 2021); Stockholm, Sweden (Lewne et al. 2011) Paris, France (Hachem et al. 2021) USA (Jones et al. 2021) Quebec, Canada (Adam-Poupart et al. 2015)
Who is exposed?	Outdoor workers in the sectors: construction, demolition, agriculture, forestry, livestock and fish farming (Vega-Calderon et al. 2021)
	Outdoor workers with job titles: garage workers, bus and lorry drivers and taxi drivers (Lewne et al. 2011), taxi drivers (Bos et al. 2021, Hachem et al. 2021)
	Indoor workers from a range of business concerns (architecture firms, software companies, real estate companies, and engineering firms) where exposure was a result of transfer from outdoors (Jones et al. 2021)
	Outdoor workers in a range of urban professions (not specified) which may include street cleaners, telecom engineers, teachers, traffic police, cycle couriers, construction workers (British Safety Council and King's College 2020)
Pollutants	Five studies looked at exposure to NO_2 (Bos et al. 2021, Lewne et al. 2011, Hachem et al. 2021, Vega-Calderon et al. 2021, Rawlings et al. 2021) mostly in combination with other pollutants (O_3, PM_{10}, SO_2) while two studies looked solely at $PM_{2.5}$ or O_3 exposure (Jones et al. 2021, Adam-Poupart et al. 2015). One study looked at NO_2, $PM_{2.5}$, PM_{10}, and O_3 (British Safety Council and King's College 2020).

4.5.1 Insights/Conclusions

4.5.1.1 Indoor workers.

Studies have shown that there is infiltration of air pollutants ($PM_{2.5}$) from outdoor to indoor. Effective control measures such as mechanical ventilation and filtration (Jones et al. 2011) in buildings can result in reductions in indoor $PM_{2.5}$ by as much as 39.4% (Jones et al. 2021) and is, in part, responsible for the lower exposure levels experienced by indoor workers. However, the clear correlation between indoor and outdoor concentrations mean that indoor workers' exposure is influenced by outdoor concentrations.

4.5.1.2 Taxi drivers

Taxi drivers experience very high traffic-related exposure to air pollutants during their working hours compared to the general population and their own non-work exposure levels. This is partly due to infiltration of outdoor air pollutants via frequent opening of windows and doors and the mode of in-vehicle air circulation system. Bos et al. (2021) reported an increase in exposure to black carbon during work time of up to four times that of non-work time and Hachem et al. (2021) saw a negative association between the level of in-vehicle ultrafine particle concentrations and lung function. Vehicle cabin design, ventilation mode and filter type were stronger exposure determinants than vehicle type (diesel or petrol vs electric) although vehicle type has wider impacts with respect to general population exposure by reducing ambient air pollution (Bos et al. 2021).

4.5.1.3 Outdoor security staff.

Rawlings et al. (2021) investigated background levels of NO_2 and O_3 experienced by personnel on guard gate duty at Tidworth Military Camp in the UK. They concluded that background workplace contaminant levels were within recommended limits. However, the transferability of this finding is limited given the limited scope of the study.

4.5.1.4 Urban outdoor workers.

Outdoor workers in London were more likely to have higher exposures to NO_2, $PM_{2.5}$, and PM_{10} compared to indoor (office) workers (British Safety Council and King's College 2020). O_3 to indoor workers, however, were higher, although the study points out this may be due to some of these locations being suburban.

4.5.2 Relevant for public health messaging

Given that outdoor air may infiltrate indoors, public health messaging should take into account vulnerable workers who may experience adverse health effects on days of high outdoor pollution levels despite being indoors.

Switching to electric taxis from petrol or diesel taxis would significantly reduce general air pollution but exposure on an individual level for taxi drivers is driven by cabin design and the in-vehicle circulation mode.

Targeted messaging for all taxi drivers could be beneficial, given the links between cabin-level exposure levels and lung function reported in the literature (Hachem et al. 2021). There should also be special emphasis on vulnerable drivers with respiratory or other health complaints that could be exacerbated by high air pollution.

Effective control measures to lower in-cabin exposure such as keeping windows closed and using air circulation, needs to be balanced against the safety risk of increased concentration of CO_2 that results from low exchange rates (Bos et al. 2021).

4.5.3 Gaps & uncertainties

Most of the studies on outdoor workers focussed on associations of air pollution exposure with specific health outcomes (Adam-Poupart et al 2015; Vega-Calderon et al. 2021) and while they stated that outdoor workers were more highly exposed these data or evidence to support this were not presented. Exposure assessment studies that gather actual exposure levels along with contextual information for a range of outdoor professions is required to inform public health messaging for this group.

4.6 Children

Table 7: Location, population, and pollutants evaluated in literature identified regarding children

Population group: Children	Number of studies: 9
Cities / Countries	**UK:** (Brown et al. 2021; Emerson et al. 2019; Kumar et al. 2020; Osborne et al. 2021a; 2021b) **Europe**: Barcelona and Sant Cugat de Vallès, Spain (Rivas et al. 2016) Europe (Athens, Greece; Lisbon, Portugal; Porto, Portugal; Treviso, Italy; Kuopio, Finland) (Korhonen et al. 2021) **US**: Texas, USA (Chakraborty 2022) **Global:** (Osborne et al.2021a; Oliveira et al. 2019)
Who is exposed?	Schoolchildren during school hours (Korhonen et al. 2021; Kumar et al. 2021; Oliveira et al. 2019; Rivas et al. 2016) (Osborne et al. 2021b) (Osborne et al. 2021a); (Brown et al. 2021); Kumar et al. (2020)
	Socially disadvantaged children (racial/ethnic minority, foreign-born, disabled, and socioeconomically vulnerable children) (Chakraborty, 2022; Osborne et al. 2021a; 2021b).
	Children with intellectual disabilities (Emerson et al. (2019).
Pollutants	NO_2, O_3, OM10, $PM_{2.5}$, SO_2 (Osborne et al. 2021a) NO_2, $PM_{2.5}$ (Osborne et al. 2021b) NO_2 (Chakraborty, 2022; Brown et al. 2021) NO_2, PM_{10}, SO_2 (Emerson et al. 2019) $PM_{2.5}$ (Korhonen et al. 2021)

	PM_{10}, $PM_{2.5}$ (3) (Kumar et al. 2020; Oliveira et al. 2019; Rivas et al. 2016)

4.6.1 Insights/Conclusions

4.6.1.1 The contribution of the school commute to children's exposure

Exposures during the school commute represents the most significant contribution to total exposure to air pollutants on school days. Rivas et al. (2016) found that children spent 6% of their time on the school commute but this contributed 20% of their daily Black Carbon dose. This was due to co-occurrence of their commute with rush hour traffic and close proximity to exposure sources. Others have reported on the impact of the school commute on air pollution levels. Kumar et al. (2020) observed a nearly three-fold increase in the concentrations of $PM_{2.5}$ during drop-off hours compared to off-peak hours highlighting the significant contribution of car queuing in the school premises to total air pollution exposure. Based on a basic descriptive and time series analysis/visualisation, Brown et al. (2021) showed that the lockdown measures in England resulted in the reduction of non-essential traffic as well as school runs, and had significantly reduced air pollution in the vicinity of English schools.

4.6.1.2 Exposure to outdoor air pollutants in the indoor school space

There is consensus that the air quality in schools significantly contributes to schoolchildren's total exposure to PM and polycyclic aromatic hydrocarbons (PAHs) and on potential health risks (Oliveira et al. 2019). Exposures to outdoor air pollutants may occur during the school commute, during activities in the surrounding environment of the school and, less obviously, while indoors due to infiltration of e.g. vehicular $PM_{2.5}$. Korhonen et al. (2021) found that although outdoor exposure levels of PM were up to 1.8 times and traffic exposures up to over 2 times higher in comparison to indoor microenvironments, 80–84% of exposure to the outdoor-originated $PM_{2.5}$ occurred indoors. Kumar et al. (2020) noted that there was a trade-off between controlling infiltration of vehicular $PM_{2.5}$ and maintaining thermal comfort during class occupancy in a naturally ventilated classroom).

4.6.1.3 Inequity in air quality in schools

Osborne et al. (2021b) found that English schools with high annual mean $PM_{2.5}$ concentrations had a higher average proportion of pupils on free school meals; were more likely to be in areas with high levels of child income deprivation; and were more likely to have an ethnically diverse mix of pupils, compared to schools with low $PM_{2.5}$ levels.

Chakraborty (2020) found greater traffic proximity and NO_2 exposure in school districts with higher percentages and density of children, as well as districts with higher percentages of minority children, foreign-born children, and renter-occupied homes with children. In particular, poorer neighbourhoods have higher pollution levels Osborne et al. (2021).

Emerson et al. (2019) showed that British children with intellectual disabilities (IDs) were significantly more likely than their peers to live in localities with high rates of outdoor air pollution.

4.6.2 Relevant items for health messaging

Children spend the majority of their weekdays at school, including in the outdoor spaces around school and commuting to school. Poor air quality near schools therefore can have a strong contribution on children's total exposures to AP and on the respective health effects (also because children's breathing rates are higher than adults').

In particular, the commute and time spent at the gates and on playgrounds have been found to result in pollution peaks, with traffic being the main contributor. This calls for traffic management solutions such as preventing idling of vehicles, a reduction in the number of vehicles driving to school gates, promotion of active travel as a commuting mode, and establishing green barriers or solid fences near schools.

The review by Osborne et al. (2021) concerning air quality around schools in high-income countries found that the choice of route during the commute can help to reduce exposure.

Adverse effects of AP (especially from traffic) on exercising individuals also highlights the need for land use planning and the selection of exercise and competition locations.

Several studies investigated socioeconomic inequalities and found that schools in poorer neighbourhoods, for example, are in areas with more roadways and less greenspace and thus increased exposure to air pollution around schools. Further, children with intellectual disabilities (IDs) were significantly more likely than those without IDs to live in areas with high outdoor air pollution. Messaging for minority and disadvantaged groups/disadvantaged areas may need to be prioritised and tailored to the specific circumstances.

4.6.3 Gaps & uncertainties

Rivas et al (2016) did not report PM size but just BC.

Chakraborty (2022) did not provide base level information (no white population data)

4.7 Pregnant people

Table 8: Location, population, and pollutants evaluated in literature identified regarding pregnant people

Population group: Pregnant people	Number of studies: 6
Cities / Countries	Texas, USA (Askariyeh et al. 2019); Barcelona, Spain (Schembari et al.2013); France (Blanchard et al. 2018, Mariet et al. 2018, Ouidir et al. 2017). USA, China, Iran, South Asia, Africa, Australia, England, Israel, and Korea. (Ha et al (2022)
Who is exposed?	Pregnant people (general) Ouidir et al. 2017
	Pregnant people in their third trimester (Askariyeh et al. 2019)

	Pregnant people commuting to/from work (Blanchard et al. 2018)
	People with multiple pregnancies: Results separated into defined pregnancy periods (each trimester, entire pregnancy and two months before delivery) (Mariet et al. 2018)
Pollutants	Four studies looked at exposure to NO_2 (Mariet et al. 2018, Schembari et al. 2013, Blanchard et al. 2018, Ouidir et al. 2017), and three studies looked at exposure to $PM_{2.5}$ (Askariyeh et al. 2019, Schembari et al.2013, Ouidir et al. 2017) and one study looked at PM_{10} exposure (Ouidir et al. 2017). One review article looked at studies investigating effects of NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2 (Ha et al. 2022).

4.7.1 Insights/Conclusions

4.7.1.1 Exposure of pregnant people is driven by their personal circumstances.

There is evidence that exposure to air pollution is associated with negative effects with regards to reproductive and pregnancy health (e.g., pregnancy loss, foetal growth restriction). However, the risk of exposure to air pollution in pregnant people is not well characterised.

In the studies included, most aimed either to associate air pollution exposure to negative health effects (Mariet et al. 2018) or simply to quantify the air pollution concentration to pregnant people (Askariyeh et al. 2019, Ouidir et al. 2017, Schembari et al.2013, Blanchard et al. 2018). The results showed that exposure to air pollution for pregnant people was largely associated to either contextual or personal characteristics, such as socioeconomic considerations, commuting time and mode, and level of urbanisation. For example, in French urban areas exposure to air pollution was greatest for pregnant people from the most deprived neighbourhoods (Ouidir et al. 2017), and in Texas traffic related $PM_{2.5}$ was highest when participants were driving compared to when they were outdoors or indoors (Askariyeh et al. 2019).

4.7.1.2 Changes in pregnant people's time-activity patterns during the pregnancy period influences the relative contribution of indoor and outdoor sources to their air pollution exposure

Studies did assess time spent indoors during pregnancy, which appeared to be the same as the general public (approximately 79%, Schembari et al. 2013). The more time spent indoors the stronger the association between personal exposure levels and indoor air pollution levels than with ambient air pollution levels (Schembari et al. 2013). As pregnancy progresses, the time spent working reduces and time-activity patterns change. At this and latter stages of pregnancy considerations of residential characteristics become more important and effects relating to commuting will likely reduce.

4.7.2 Relevant items for health messaging

As pregnant people are particularly vulnerable to negative health effects of air pollution exposure, they should be informed when outdoor air pollution levels are particularly high. Measures they can take to avoid high exposure would need to be sensitively communicated so as to avoid causing undue anxiety, and suggested measures should consider the trade-offs between e.g. exposure

reduction and the need for physical activity. Suggestions that can be made include choosing commuting times, routes and modes that are least likely to lead to high exposures. As the most vulnerable trimester for reproductive and teratogenic effects is unknown, they should be informed throughout the pregnancy.

Ha et al. (2022) also suggested that the role of healthcare providers can be critical in advising pregnant people of the risks to air pollution and provide practical suggestions on how to reduce exposure.

4.7.3 Gaps & uncertainties

Most studies looked at the association of exposure with negative foetal outcomes, rather than at the pattern of exposure to pregnant people (compared to general public). For example, factors such as breathing rate, walking pace, choice of commuting mode, and commuting time of pregnant women compared to non-pregnant people was not investigated.

Only one study utilised personal monitors to assess exposure to air pollution (Schembari et al. 2013), the remaining studies all used static monitors/modelling techniques that give less accurate exposure estimates and cannot account for socioeconomic characteristics that can act as confounders when studying the effects of air pollutants on pregnancy outcomes (Ouidir et al. 2017). Askariyeh et al. (2019) showed that personal exposure assessment using area (i.e fixed location sampling) compared to personal exposure monitoring (i.e. sampler co-located with participant) approaches found no statistical difference for pregnant people in their third trimester, as the people in the study spent most of their time at home. However, the approach by Mariet et al. (2018) using static approaches (50 m from mother's address) across the entire pregnancy may not have accurately estimated the exposure levels earlier in the pregnancy.

No studies looked at UK only.

Efforts still required in defining the windows of susceptibility and vulnerable subpopulation (Ha et al. 2022).

4.8 Role of socioeconomic status

Table 9: Location, population, and pollutants evaluated in literature identified regarding socioeconomic status

Population group: Low SES	Number of studies: 20
Cities / Countries	**UK** Wales, UK (Brunt et al. 2017) England and Wales, UK (Barnes et al. 2019) London, UK (Aether, 2013; 2017; 2019; 2023; AQC, 2021) Scotland (Bailey et al., 2018) England (Fecht et al. 2015)

	Europe Asurias, Spain (Fernandez-Somoano et al. 2013) France (Lavaine et al, 2012; 2015; Padilla et al. 2014) Rome, Italy (Cesaroni et al., 2012) Western Europe, 16 cities (Temam, 2017) **USA** Camden, New Jersey, USA (Wu, 2010) New York City, USA (Goodman, 2017) All US public housing developments (using Census, Chakraborty, 2022) The contiguous United States US (Zhao, 2018) The contiguous United States (Clark et al. 2017) Southern California, USA (Lu et al. 2022)
Who is exposed?	In USA studies, generally SES as defined by employment rate (Wu, 2010), public housing developments (associated with lower SES areas, Chakraborty, 2022), racial/ethnic minorities (Zhao, 2018)
	Occupational grades in Spain (Fernandez-Somoano, 2013)
	Cities in Europe from ESCAPE study (Temam, 2017)
	General populations in France, Wales, and UK, using national statistics (Lavaine, 2015; Brunt, 2017; Barnes, 2019) General populations in UK using Index of Multiple Deprivation (Aether, 2013; Aether, 2017; Aether, 2019; AQC, 2021; Aether, 2023).
Pollutants	$PM_{2.5}$ (Wu, 2010; Chakraborty, 2022; Goodman, 2017; Zhao, 2018; Brunt, 2017; Bailey et al, 2018; Aether, 2013; Aether, 2017; Aether, 2019; AQC, 2021; Aether, 2023) PM_{10} (Lavaine, 2015; Brunt, 2017; Barnes, 2019; Laurent, 2012; Cesaroni et al., 2012; Fecht et al. 2015) NO_2 (Fernandez-Somoano, 2013; Lavaine, 2015; Brunt, 2017; Barnes, 2019; Temam, 2017; Laurent, 2012; Cesaroni et al., 2012; Aether, 2013; Aether, 2017; Aether, 2019; AQC, 2021; Aether, 2023; Padilla et al., 2014; Fecht et al. 2015) O_3 (Goodman, 2017; Lavaine, 2015) SO_2 (Laurent, 2012)

4.8.1 Insights/Conclusions

4.8.1.1 Difference in time spent outdoors among different SES groups

One study specifically looked at time-activity patterns and found that in Camden, NJ, time spent outdoors was significantly greater than that of the general US population, particularly in lower socio-economic status (SES) groups (Wu, 2010).

4.8.1.2 Complex mix of factors influence exposures of different SES groups

In general, lower SES was associated with higher pollutant exposure, but this is not a universal finding and varies from location to location. Studies in London and Scotland found that the most deprived areas were on average exposed to higher $PM_{2.5}$ and NO_2 concentrations than the least deprived. Similar findings held for PM_{10} and NO_2 in England (Fecht et al. 2015). In the UK, two studies indicated higher exposures to NO_2 with lower SES (Brunt, 2017; Barnes 2019), with one finding this association to be stronger for children and young adults (Barnes, 2019). Another study included the cities of Ipswich and Norwich, but found different patterns in each city (Temam, 2017), although effects were not strong.

In one Spanish study, lower SES in rural areas was associated with higher NO_2 exposure while in urban areas it was associated with lower exposure. (Fernandez-Somoano, 2013). In the same study, results were slightly different if education was used instead of occupation as an SES index. In Lille, Marseille and Lyon, the most deprived areas experienced greater concentrations of air pollution as they are found in the urban centres. In Paris, the opposite was found, where the least deprived areas were found in the centre (Padilla et al., 2014). Cesaroni et al., (2012) found that higher SES populations experienced greater concentrations of air pollution compared with more deprived areas in Rome.

4.8.2 Relevant items for health messaging

Low SES is often associated with higher air pollution exposures, and efforts to reach out to these communities are needed.

Both lower SES-associated occupations and residential areas should be targeted.

4.8.3 Gaps & uncertainties

The relationship between socioeconomic status and air pollution exposure varies between cities.

The studies reviewed used different indicators of deprivation and socioeconomic status, so generalisations from studies should be cautious. Understanding the differences in effect for indicators of SES can help in better targeting messages.

5 Evidence gaps and future research needs

5.1 Evidence gaps

For some groups identified *a priori*, there were very few studies that took place in the UK. Children was one group with more studies (n=4) done in the UK than other groups. Given the number of outdoor workers, relatively few air pollution focussed studies were identified, particularly in the UK.

While there were a fair number of physical activity studies, most were focussed on health outcomes rather than exposure. Similarly, with pregnant people, studies primarily focussed on foetal outcomes. Studies focussed on health outcomes (usually epidemiological studies) do not necessarily distinguish differences in exposure, but examine the exposure-response functions, hence the risk of high exposure will depend on the range of exposures examined in the studies. It is not clear that population groups that are more susceptible to the effects of air pollution due to underlying health conditions are necessarily highly exposed to air pollution. It is more likely that societal level determinants such as SES are more likely to predict these groups' exposure to air pollution.

While studies often find that people of lower socioeconomic status, or who live in more deprived areas are more likely to be exposed to pollution from both traffic and industrial sources, this relationship may vary locally. Within the UK, further work on SES and air pollution beyond London to understand this variation is needed.

Some groups identified *a priori* had little or no information on exposures, such as Gypsies/travellers or homeless, who could possibly have greater exposures. Occupational exposure studies may focus on other hazards (e.g. pesticides, PAHs) more related to their profession (e.g. farmers, road pavers) and therefore few occupations were specifically addressed in identified studies. However, due consideration to the added impact of air pollution exposures on top of their occupational hazard exposures should be considered.

Air pollution exposures to commuters can be quite variable across transportation modes and locations. Furthermore, the amount of time spent commuting can be an important predictor of the contribution of these microenvironments to overall exposure. The studies examined did not necessarily provide enough contextual information to fully determine how different commute variables contribute to exposure in that mode. This includes information on personal level exposure while commuting compared to background or roadside urban monitoring, vehicle features that may influence infiltration of outdoor pollution into the vehicle, the influence of the built environment and green space on commuting exposure, and trip length associated with the use of different modes.

5.2 Study limitations and key uncertainties

This work was a quick scoping review, which is typically a review undertaken to explore the availability of evidence for a given research question. QSR's are undertaken on a short time scale – usually around 3-6 months and do not include an in-depth review of the quality of the literature. This QSR used a systematic approach, but given the short time scale, a thorough exploration of the literature was not possible. The search was supplemented by reaching out to other experts in the fields of air pollution and inequalities, receiving eight additional citations from this. Potentially there may be more in the grey literature, and future work could address this. However, due to time limitations it was not possible to assess all of these sources.

The body of literature identified was a mix of exposure-specific studies and epidemiology studies, with an occasional study from the economic field. Some of the literature involved development of environmental (in)justice tools, but these were not generally included unless they provided specific air pollution exposure data for certain groups. While studies with exposure information were included, in epidemiology studies particularly, it was not always possible to identify clear exposure differences between groups.

As a full quality assessment to evaluate risk of bias in studies was not done, specific conclusions about the strength of evidence for the risk of exposure for the population groups identified cannot be given. However, the type of study done was assessed, prioritising measurement and personal exposure studies, as this was felt to provide the most directly relevant information. As these may not be as likely to have large sample numbers, value was also placed on fixed location measurement or modelling studies that use a finer spatial resolution. Some of the latter also incorporate time-activity information, which also strengthens the study, as exposure includes both air pollution concentrations and duration of exposure time.

5.3 Future research needs

This section covers recommendations for research to address the above-mentioned evidence gaps and limitations. Overall, to better understand patterns of exposure among population groups in the UK, more exposure assessment studies are needed. While ecological or fixed site exposure studies are useful and needed, personal exposure studies would help us better apportion exposures, so that we can understand the relative levels of exposure in the different microenvironments in which people spend time. Additionally, studies are needed that improve our understanding of how outdoor air pollution contributes to in-microenvironment exposures (e.g. indoors, in transportation modes or job locations).

For occupationally exposed workers, further work is needed to systematically categorise the occupations that are exposed to outdoor air pollution (i.e. a job exposure matrix) and consider the added exposure and risk that this poses to their overall exposures.

Urban areas have been the primary focus of most studies identified in this review, with traffic related air pollution the primary source of interest. Further research could also examine suburban and rural population exposures, as there are likely to be similar groups as those identified in this review, living and/or working in these areas. Away from cities, O_3 exposures may be greater. Compared to $PM_{2.5}$ and NO_2, however, fewer studies examine O_3, possibly because of the urban focus of the studies reviewed.

5.3.1 Examples for future work

This section explores some potential ideas around air quality messaging for different population groups.

Area-level interventions on mitigating air pollution exposure for high-risk groups

Some of the groups identified in this review are at risk primarily due to the places where they reside or work (e.g. low SES, ethnic minorities). As previously identified, there is a need to better understand the spatial variation of air pollution exposure with respect to the groups identified in this review. One potential way to identify 'hotspot' areas for these groups by using the most recent environment and administrative data. The 2021 census has provided opportunities to map groups at high risk of air pollution exposure at a very high spatial resolution (output areas: 188,880). The Office for National Statistics have produced a tool (https://www.ons.gov.uk/datasets/create) that allows creation of maps related to where the groups identified in this report live. A future research project could be to create a dataset of high air pollution risk group prevalence, background $PM_{2.5}$ concentrations and susceptibility factors. The next stage would be to identify spatial clusters in the output areas. This information could be used to target the relevant organisations, such as the local council or a large employer, in these areas to identify and deploy the most appropriate exposure mitigation interventions (e.g. removing high point pollution sources, creating low traffic/emission zones etc).

Guidance on activity changes for high-risk groups to reduce exposures

Some of the high-risk groups identified have more agency to change their exposure – recreational athletes, commuters, and potentially (to a lesser extent) pregnant people and the elderly. Each of these groups has some capacity to decide when, where and how they spend their time outdoors. High exposures that are faced by these groups could be substituted with lower exposures through greater time spent in areas of lower air pollution (either well-ventilated indoor areas, in different parts of their own microenvironments or with different modes of transport). The optimal amount of time to be spent in lower air pollution zones depends on the trade-off with the health benefits of the behaviour. This is because partaking in outdoor activity comes with the risk of poor health outcomes due to inhalation of air pollutants; but it also provides a health benefit due to undertaking physical activity.

A modelling framework (risk-benefit study design) was identified during our review (An, 2022) as a case study for generalizing guidance on mitigating air pollution exposure for high-risk groups (Figure 6). The key variables for this framework include the inhalation rates during activities undertaken, air pollution exposure levels, and the risk ratio for health effects. The risk ratio can be altered to account for susceptibility of the population.

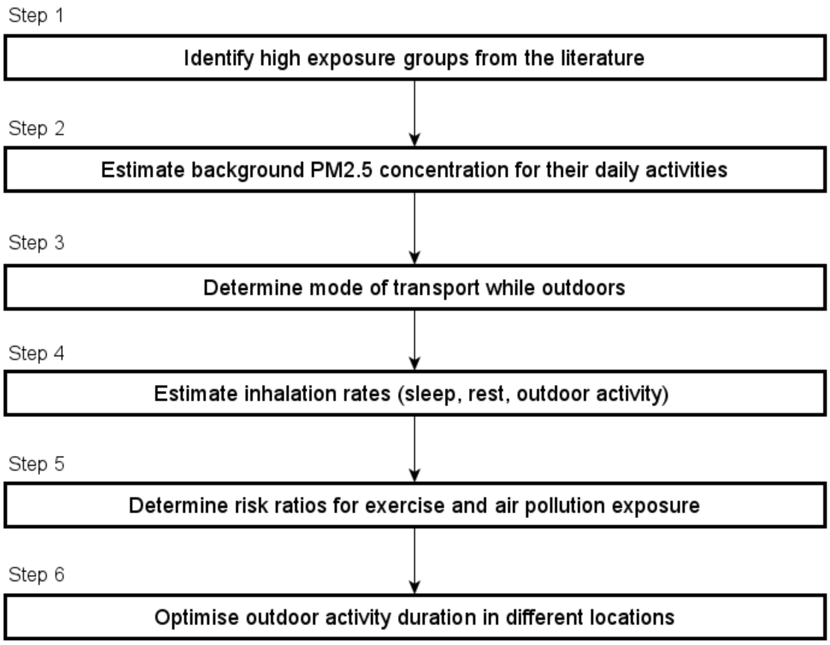

Figure 6: Flow chart of steps to provide guidance for outdoor activity for high risk exposure groups based on (An et al. 2022) for physical activity

In the physical activity example (An et al. 2022), this framework can be used to estimate the optimized outdoor activity duration for different air pollution levels (Figure 6). This would allow communication around the intensity level and duration of physical activity advised to be performed outdoors under different scenarios of $PM_{2.5}$ concentration. For instance, Figure 6 shows that when the $PM_{2.5}$ concentration is approximately 45 µg/m^3 and 202 µg/m^3, the moderate-intensity physical activity duration would be 8 and 25 hours per week, respectively. It would therefore allow communication of very specific advice around how to achieve a net positive health benefit at different pollutant concentration levels.

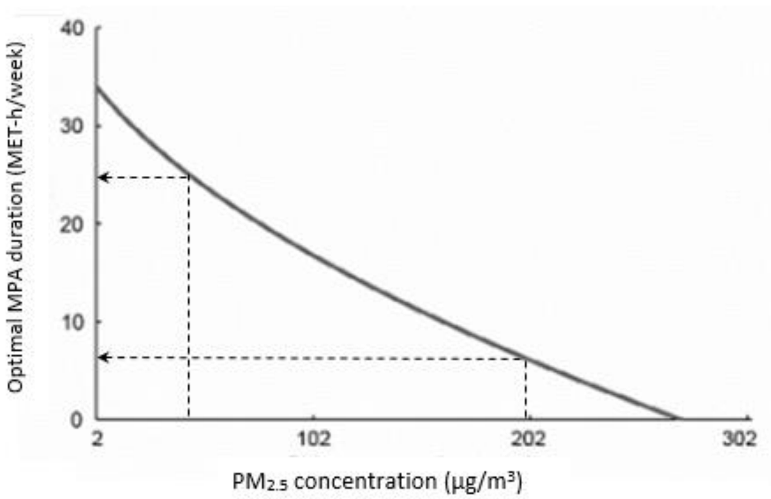

Figure 7: Estimated optimal outdoor duration at varying background $PM_{2.5}$ concentrations; Extracted from (An et al. 2022). MPA indicates moderate physical activity, MET-hours indicates hours at that level of activity.

6 Conclusions

6.1 Summary of conclusions

Of the different groups identified for this review, evidence of their risk of being highly exposed to air pollution is mixed. Studies used different methodologies, and took place in different locations, making it hard to compare them all directly. For most groups (except children), few studies were done in the UK, and therefore it is useful to consider how extrapolation to the UK context should be done, and if UK-specific studies are needed.

For some groups, such as those of lower SES, evidence was strong that they are likely to have higher exposures, although more research for UK-specific contexts is needed to better understand this relationship across the UK. There is good evidence but in a limited number of studies that outdoor workers in transport industries or those spending a lot of time near busy roads have higher exposures than indoor workers.

Across the population, SES plays an important role in determining exposure, and any relevant interventions need to benefit those living in more deprived areas or who have lower SES. Lower SES is often also associated with poorer underlying health, therefore resulting in an intersection of risk where high exposure and health susceptibility overlap (Figure 1).

Gender (between male and female) did not necessarily appear to result in differential exposures on average. There was not enough evidence related to exposure related to other genders to draw conclusions regarding exposure although qualitative evidence suggests a possible link (Goldsmith and Bell, 2022). However, this study was not included in the review synthesis as it included no quantitative evidence.

Pregnant people, children, and elderly are of concern because of their susceptibility to health effects of air pollution exposure. These three groups are not necessarily at higher risk of exposure *per se*, but some may be more likely to be highly exposed, particularly if they live, work, or spend time commuting or exercising outdoors in areas of greater pollution. Again, SES is an important predictor of exposure for these groups. Health providers, schools, or other institutions which these groups are likely to engage with could provide avenues of outreach to these communities. Advice about exercising outdoors in high pollution areas or during episodes could also protect these groups.

Exposure of pregnant people puts the foetus at risk of various adverse health effects such as lower birth rate and intra-uterine restricted growth, or potentially of future health impacts (Royal College of Physicians, 2016). Children are also in a rapid physiological development part of life, and breathe at a higher rate than adults, therefore breathing in more air per unit body weight than adults, increasing the risks from air pollution exposure for children. Finally, air pollution has demonstrated effects on cardiovascular and respiratory health in the elderly, who are likely to already have increased susceptibility due to underlying morbidities, and may be more likely to be exposed to high levels of air pollution.

Most people spend 80-90% of their time indoors, on average (Schweizer et al. 2007). Most exposure will happen indoors. While time outdoors exercising, playing, or commuting can increase exposure to air pollution, consideration needs to be given to how outdoor air infiltrates indoors. Buildings located in more polluted areas may not necessarily provide sufficient protection against pollution, and indoor air quality is not always better than outdoor air pollution, especially for poorer housing areas. The spatial distribution of air pollution on a fine scale is an important consideration, as is the quality of building stock, in reducing people's exposure to air pollution.

Groups which are likely to be at risk due to spending a larger amount of time outdoors include commuters, outdoor workers, and those doing physical activity outdoors. For these groups, those who may be of lower SES, or of a health susceptible group, would be at increased risk of harmful health effects from pollution if outdoor pollution levels are high. Workers such as taxi drivers are exposed to outdoor air pollution within their vehicles. Other workers may face exposure to additional hazards beyond their air pollution exposures (e.g. farmers, construction workers) and therefore ambient air pollution should also be considered as part of their occupational exposures.

For commuters, time spent commuting is an important predictor of exposure. Walkers and cyclists are more likely to be highly exposed on busy streets, and cyclists tend to breathe in more pollution, resulting in a larger dose for a comparable commute along the same streets. Advice to change their route to quieter ones, if possible, could reduce their exposure. However, longer commutes via bus, train, or private vehicle or taxi can also result in higher exposures, depending on the infiltration of outdoor pollution to the vehicle. There is also a risk of self-pollution in the vehicles, depending on the age of vehicle, and whether windows are open or outside air is being circulated. While breathing rates are much lower in transport compared to walking or cycling, transport commutes are more likely to be longer than walking and possibly cycling commutes.

6.2 Recommendations for AQIS

It is important to incorporate information on health susceptibility and physical activity with exposure into any information system going forward. Although exposure-specific data in the UK is limited outside of London, information on the spatial and temporal distribution of exposure could be overlaid with data on SES and where susceptible groups spend their time to target messaging. Engaging with communities, e.g. through community groups or non-governmental organisations, and having champions from target risk groups can help bring the relevant information about air pollution and related health risks to these groups. Health care providers, schools, employers are also institutions which engagement can help educate and take action around reducing risks to potential high-risk groups. Much of the evidence focuses on urban air pollution, and local authorities have a key role in creating a network within the communities of concern for improving and targeting air quality information messaging. Messages may involve changes in activity, but not all people have agency to easily control their exposures, so efforts still need to be taken to reduce outdoor levels in areas of high pollution.

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Appendices

A1 Search terms

Based on the search terms listed here search strings were designed to identify eligible studies in Web of Science Core Collection and subsequently adapted, where necessary, for searching the PubMed and Google Scholar

Table: A1.1 Search terms used to design search strings

Terms for identification of populations of interest	**athletes exercising outdoors**	**physical exercise**
	BAME	sport outdoors
	civil partnership	poor households
	cyclists	poverty
	deprivation index	pregnancy
	disability	race
	disadvantaged	racial/ethnic disparities
	environmental inequality	religious belief
	environmental justice/injustice	runners
	environmental racism	school children
	ethnic minority	sex
	exercising outdoors	sex worker
	gender reassignment	sexual orientation
	gypsies	social disparities
	health inequity	social exclusion
	hidden populations	social inequality
	homeless	socio-economic position
	labourers	socio-economic status
	marginalized groups/communities	sporting activities
	marriage	susceptible
	maternity	travellers
	migrants	under-privileged
	neighbourhood deprivation	unsheltered or chronic homelessness
	non-white	vulnerable
	outdoor workers	walking/cycling school bus
Exposure	ambient (outdoor) air pollution	
	Daily Air Quality Index (DAQI)	
	emissions	
	exposure	
	NO_2, SO_2, O_3, PM_{10}, $PM_{2.5}$	
	traffic-related air pollution	

A2 Data extraction and quality assessment forms

Table: A2.1 Information extracted to data extraction form in MS Access

1	**Specific hypothesis/objective of the study**
2	Study type
3	Air pollutant(s) (NO_2, SO_2, O_3, $PM_{2.5}$ and PM_{10})
4	Source of air pollution
5	Characteristics of the population (e.g. age, gender, race)
6	Protected characteristics relevant to the study population(s) [11]
7	Inclusion health groups to which the study population(s) belongs [12]
8	Job title of study population (i.e. if they are classified as an outdoor worker[13] or one that is required to spend a large proportion of their work time outdoors.
9	Where relevant for question 8, describe what part of their work tasks is associated with exposure.
10	Particular characteristic or circumstance of the study population(s) (not included under q6, q7 or q8) that might result in higher exposure relative to a comparison group (i.e. one that has a normal/average/lower exposure level) or relative to a stated exposure threshold or guidance value.
11	Recreational or other outdoor physical activity *(not in relation to outdoor workers)*
12	In relation to q11, describe comparative activit(ies)/situations.
13	Exposure assessment approach. Briefly describe.
14	Exposure level and metric.
15	Exposure level of the comparator group or other comparator *(e.g. threshold or guidance value)*
16	Time and/or duration of the exposure.
17	Sample size and method of estimation.
18	Data handling and statistical analysis

[11] As defined in the UK: age, disability, gender reassignment, marriage and civil partnership, pregnancy and maternity, race, religion or belief, sex, sexual orientation

[12] Inclusion health groups include: people experiencing homelessness, drug and alcohol dependence, vulnerable migrants, Gypsy, Roma and Traveller communities, sex workers, people in contact with the justice system, victims of modern slavery and other socially excluded groups.

[13] commercial drivers, commercial motorcyclist, construction workers, cycle couriers, delivery cyclist, endurance athletes exercising outdoors, farmers, gardeners working in urban parks, HGV drivers, lollipop ladies/men, maintenance workers, newspaper sellers, parking attendants, post delivery persons, railroad workers, recyclers, refuse workers / garbage collectors, school crossing patrol guards, security guards who work on or near busy roads, solid waste management , street cleaners, telecom engineers, traffic coordinators, traffic police, traffic wardens

A2.2 Information extracted for quality assessment of exposure assessment

1	Is there a clearly defined research question?
2	Is the population(s) of interest clearly defined?
3	Were similar exposure groups[14] defined? *(relevant for occupational expo studies only)*
4	Is the sampled population representative of the general population?
5	Is the sampled population representative of the population of interest?
6	Are the criteria for the sample size selection stated?
7	How were study participants selected? *(e.g. randomly, volunteers, specific interest group)*
8	Was exposure determined by direct[15] or indirect[16] exposure assessment approaches?
	Qualitatively
	a. Objective measure
	b. Self-reported (non-standardised or non-validated questionnaire)
	c. Self-reported (standardised, validated, questionnaire)
	(semi) Quantitatively
	d. Personal exposure monitoring (air measurements, biological monitoring)
	e. Distance from source (e.g. linear distance; inverse distance weight)
	f. Validated dispersion models (e.g. average annual atmospheric concentration)
	g. Non-validated dispersion model
	h. Mechanistic or statistical exposure model (validated)
	i. Mechanistic or statistical exposure model (not-validated)
	How was the population distribution defined? At what spatial resolution?
	j. Geocoded address / individual house
	k. Community level I [postcode, zipcode, census block, raster size]
	l. Community level II [town, municipality, specific raster size]
	m. Regional scale
9	Was exposure retrospectively or prospectively assessed?
10	Were comparable exposure methods used to assess populations that are being compared?
11	Were exposure data appropriately handled and statistically analysed *(LOD handling, calculation of exposure metrics etc)*
12	Were appropriate exposure metrics defined?
13	Was exposure variability considered?
14	Were the strengths and weaknesses of the exposure approach detailed and discussed?

[14] Similar Exposure Group (SEG): a group of workers who have similar exposure profiles and common risks. SEGs are created based on knowledge of employee activities, assuming that similar tasks with similar regularity will result in similar exposures (qualitative approach), or based on exposure measurements (quantitative). (Mulhausen and Damiano, 1998)

[15] point of contact, biological monitoring, or biomarkers

[16] monitoring at various locations or during specific activities

15	Can the conclusions about exposure be generalised to all members of the population of interest?
16	Were authors' conclusions consistent with the reported results?

A3 List of literature evaluated by group

Persons doing physical activity outdoors/professional and amateur athletes

An, R., Kang, H., Cao, L., & Xiang, X. (2022). Engagement in outdoor physical activity under ambient fine particulate matter pollution: A risk-benefit analysis. J Sport Health Sci, 11(4), 537-544. doi:10.1016/j.jshs.2020.09.008

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Slezakova, K., Pereira, M. C., & Morais, S. (2020). Ultrafine particles: Levels in ambient air during outdoor sport activities. Environmental Pollution, 258. doi:10.1016/j.envpol.2019.113648

Stieb, D. M., Shutt, R., Kauri, L., Mason, S., Chen, L., Szyszkowicz, M., . . . Luginaah, I. (2017). Cardio-Respiratory Effects of Air Pollution in a Panel Study of Outdoor Physical Activity and Health in Rural Older Adults. J Occup Environ Med, 59(4), 356-364. doi:10.1097/jom.0000000000000954

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Persons belonging to ethnic minority groups

Aether (2023). GLA LAEI AQ Exposure and Inequalities study Part 1 - London analysis. [pre-print]

Aether (2019). Air Pollution Exposure in London: Impact of the London Environment Strategy.

Aether (2017). Updated analysis of air pollution exposure in London.

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