



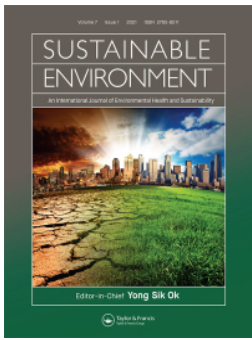
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# Respiratory effects of running in urban areas with high and low ambient air pollution: A scoping review

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## ABSTRACT

Running is a popular way for people to keep fit and healthy. With the majority of people living in urban areas, this popular method for staying fit may be a double-edged sword. Running in areas of high ambient air pollution causes a higher dose of inhaled pollutants. We sought to establish the degree to which this increased dose of pollution is detrimental to respiratory health or performance and if it outweighs the benefits of running in urban areas. We conducted a scoping review of the literature using PubMed, Scopus, Embase and the Cochrane library. While there were mixed results on the effect of running in high ambient air pollution, most of the evidence indicates that it is hazardous for respiratory health. Reports of falls in lung function, inflammatory markers and impaired nasal mucociliary clearance were some of the reported significant effects in the respiratory system of runners in highly polluted areas. There were also studies that reported non-significant effects. Other secondary effects were also reported in some studies such as increased systolic blood pressure and impaired cognition. Some studies found that reduced running performance was associated with running in high ambient air pollution, while others only found a significant association in female runners. Running is a cheap and convenient way for staying fit and healthy and should be promoted to reduce the incidence of non-communicable diseases, but more greenways and parks should be provided for runners in cities to mitigate against the effects of airborne pollutants

## ARTICLE HISTORY

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## KEYWORDS



runners; pollution;  
respiratory; lungs

## 1. Introduction

The number of people who choose to run for recreational or competitive purposes, in cities in particular, has increased in popularity in recent times. According to *Running USA*, the number of running event finishers in the United States increased from 8.62 million in 2000 to 17.11 million in 2015 (Davies et al., 2018). *Sport England* claims that recreational running has become one of the most common forms of exercise in the UK (A. Hodgson & Hitchings, 2018). More recently, a consumer research study found evidence to suggest that the COVID-19 pandemic in 2020 led to an increase in people exercising using running (Nielsen Sports, 2021). Indeed, most of the major capital city marathons across Europe and the United States sell out annually, and they often need to employ a lottery system to allocate places due to high levels of popularity. With non-communicable diseases (NCDs), such as cancer and cardiovascular diseases, accounting for approximately 70% of the global deaths annually, the World Health Organization (WHO) recommends regular

physical activity daily, which has been shown to reduce 6–10% of the major NCDs and increase life expectancy (Pun & K-F, 2019). According to Pun and Ho, 'running is the most common type of physical activity due to its convenience, low cost and minimal skill required' (Pun & K-F, 2019).

This convenient way to keep fit and healthy may be a double-edged sword for the approximately 55% of the world's population who live in urban areas (United Nations, 2018). Vigorous exercise increases lung ventilation and inspiratory flow rate, intensifying exposure of the lungs to airborne pollutants (Ferdinands et al., 2008). The biological mechanisms in the nasal cavity which usually filter toxins entering the lungs during normal inhalation are not as effective with more intense and faster breathing that occurs during vigorous exercise (Bennett et al., 2003). For runners, as exercise intensity increases, breathing switches from predominantly nasal to pre-dominantly oral (known as the 'oro-nasal switching point') and the majority of the air bypasses the cilia in the nose, designed to filter toxins

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entering the lungs (Bennett et al., 2003; Lv et al., 2014). In fact, it is mentioned that compared to rest or moderate exercise like walking, strenuous exercise like running can increase the amount of toxins by as much as 10-fold during high intensity training (Lv et al., 2014). This is worrying since a recent WHO report has said that almost the entire global population (99%) breathes air that exceeds WHO air quality limits (World Health Organisation, 2022).

Therefore, running in urban areas with high levels of pollution could be detrimental to respiratory (or general) health, both in the short-term and/or the long-term. If there are health implications for inhaling such toxins whilst exercising, then both city planners and public health officials may need to collaborate in order to find solutions. In particular, it is important to know whether the benefits of running in urban areas with high levels of pollution outweigh the potential damage of inhaling extra doses of toxins.

There have been some reviews conducted on this topic. A review entitled *Small Things Make a Big Difference*, published in 2012 by Cutrufello et al., reviewed studies examining the health effects of exercising whilst exposed to particulate matter (PM) (Cutrufello et al., 2012). It is difficult to study how one pollutant affects human health since people are usually exposed to many pollutants simultaneously (Cutrufello et al., 2012). Hence, while PM is determinantal to human health, this review determined that further research is needed to examine how PM exposure, specifically, affects people who exercise in its presence (Cutrufello et al., 2012). The review by Qin et al. dealt with the general health effects of people who exercised while exposed to air pollution (Qin et al., 2019). This study found that the combined effect of air pollution and exercise was associated with the increased risk of potential health problems of cardiopulmonary function, immune function, and exercise performance (Qin et al., 2019). The review by Tainio et al. found some evidence that exercising in air polluted areas can lead to acute health outcomes and while they found mixed evidence for long-term effects, there were several studies that suggested there were only small diminishing health gains from physical activity due to exposure to air pollution (Tainio et al., 2021).

We sought to review studies that specifically examined respiratory impairment for runners in areas of high ambient air pollution. Moreover, we examined studies published during the last two decades with respect to this important issue both in the sports science and environmental science literature. Prior to conducting this review, we considered that there would be a wide variety in the studies in many respects: in terms of the

spectrum of perceived high and low ambient air pollution in the location in which the study was conducted; the variety of confounding variables, such as temperature and humidity, given the myriad of different climates of the primary studies; or, the various levels of fitness of the participants from a casual runner to a competitive athlete. With this in mind, we deemed that a scoping review, rather than a systematic review, was the most appropriate design for this study. In particular, we sought to establish if increased inhalation of toxins in people who run in areas of high pollution leads to impairment or damage to the respiratory system in the short- or long-term. Ultimately, we aim to ascertain if the risks of running in high-polluted conditions outweigh the health benefits. We conducted this scoping review to see what research has been utilised to study this important topic.

With so many people choosing to use running as a means of exercise, and with most of the world's population living in urban areas, this is a vitally important subject for which an updated review is needed. If there is robust evidence to suggest that the health benefits of running in urban areas are diminished significantly in areas of high ambient air pollution, then public health workers and city planners will be needed to coordinate efforts to ensure that safer locations for running exist in our cities.

## 2. Methods

We followed the PRISMA Extension for Scoping Reviews (PRISMA-ScR) checklist for conducting this study (Tricco et al., 2018). A review protocol was established for this work but it was not pre-registered as this is a potential precursor to a more refined systematic review and PROSPERO does not register scoping review protocols at present (Research NIo H, 2022).

### 2.1. Search strategy and definitions

The PECO (population, exposure, comparison, outcome) framework was used for the search strategy in this scoping review. For the population of interest, we chose to consider 'regular runners' in this review as people who ran for at least 30 minutes three times a week, approximately. The fitness spectrum included people who run regularly to maintain fitness up to competitive athletes who take part in international competitions. While we expected that this could result in heterogeneity between the included participants, we also concluded that each individual athlete will train at a rate that is intense relative to their fitness and at a rate, as explained earlier, that would result in the athlete

breathing in a high quantity of toxins, compared to being at rest or walking. Ultimately, we sought to examine if exposure to pollutants causes impaired respiratory function in individuals who exercise vigorously that is 'intense' for them. This would include all athletes from the casual runner to the competitive athlete.

In terms of exposures, for the most part we considered the following urban air pollutants: ultrafine particulate matter (usually PM<sub>2.5</sub> or PM<sub>10</sub>), ground-level ozone (O<sub>3</sub>), carbon oxides (CO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), and sulphur oxides (SO<sub>x</sub>). Ultrafine particulate matter PM<sub>2.5</sub> and PM<sub>10</sub> have aerodynamic diameters of less than 2.5 µm and 10 µm, respectively. Sources of PM include wood/fossil fuel burning, candle burning, oxidation of gases emitted from automobiles and power plants, dust and wildfires; sources of O<sub>3</sub> include chemical reactions involving nitrogen dioxide, sunlight and hydrocarbons; and, the sources of CO include car fumes, heating/power generation plants, smoke and gas-powered engines (Lv et al., 2014). Emission of nitrogen oxides in the atmosphere usually comes from electricity generation and road transport and sources of sulphur oxides typically come from international shipping and industry (UK Air Pollution Information System, 2022).

The comparison involved people who exercised in less polluted areas, i.e. runners whose exposure to these pollutants was lower.

The primary outcome of interest was a respiratory disease or respiratory infection of any kind or reduced or impaired respiratory function. As the review unfolded, however, other related health issues, such as cardiovascular issues, emerged as secondary outcomes that were unintended but warranted reporting for further potential research. Furthermore, we also reported on running performance as a secondary outcome, since it is likely that it would be impacted by respiratory impairment. Thus, reduced running performance could be an indicator of respiratory, cardiovascular or other health impairments in the presence of ambient air pollution.

The databases used for the purpose of this scoping review were PubMed, Scopus, Embase, and the Cochrane library. The search included published articles from the year 2000 up until July 2021. This was to ensure that our scoping review was based on recent findings from the last two decades and to ensure that our review provided a recent and contemporary overview of recent results. The search strategy, designed by DMcE and CB, involved Boolean operators and the wildcard function for terms relating to 'runners', 'pollution' and 'respiratory'. A librarian from the Royal College of Surgeons Ireland (RCSI) was consulted with respect to the search strategy. The full format of this search strategy is given here:

*((runners OR running OR jogging OR joggers) AND ("Air Pollution" OR "Air Pollutant" OR "Air Pollutants" OR "Environmental" OR "Environmental Air Pollutants" OR "Environmental Pollutants")) AND (pulmonary OR lung OR respiratory OR breath\*)*

Following this, the results from the mentioned databases were compiled together by DMcE using the free online software Rayyan for screening titles and abstracts for various types of reviews (Ouzzani et al., 2016).

## 2.2. Primary screening (eligibility criteria)

A set of inclusion/exclusion criteria was predetermined by DMcE and CB. We included studies published in English and peer-reviewed since the year 2000. The included studies needed to specifically examine runners and the effect that ambient air pollution had on their respiratory (or other health) system. Some studies used race times as a measure of performance and, as mentioned before, these were also included since they may be an indicator or a proxy measure of the effect that pollution can have on the respiratory (or other health) system in runners. Any studies involving animals or studies relating to specific diseases (like asthma or HIV) were excluded. All the participants needed to be healthy adults (without a pre-existing respiratory disease like asthma) for the study to be included. Studies with either elite athletes or recreational runners who ran 'regularly' as per the definition mentioned above were included. Studies that involved other athletes like hockey players or cyclists were excluded. If a study examined other factors, such as temperature or humidity, as well as examining pollution, then they were included. On the other hand, if the study exclusively examined one of these factors (such as solely examining temperature, for example) and did not examine pollution, then it was excluded. Altogether, each included study had to examine running, pollution and respiratory (or other) health outcomes. Furthermore, during the primary screening process, DMcE removed any duplicates and screened the titles and abstracts of each study according to the inclusion/exclusion criteria.

## 2.3. Secondary screening (study selection)

The included studies from the primary (title and abstract) screening then went through a full-paper secondary screening phase (by DMcE in consultation with CB as a critical friend). If any reviews were included from the primary screening phase, they were then checked to identify any additional references; these were then screened using the same criteria mentioned above. The reviews were then excluded.

## 2.4. Data extraction and quality assessment

The following data were extracted for each study: the authors' names and year of publication; the source of the data; the location for the study; the type of study that was conducted; the time frame in which the study took place (if available); the number of participants; the age, sex and fitness profile of the participants; the pollutants in the study; and the main results of the study. A full table was completed to summarise the above data extraction.

Furthermore, a quality assessment was carried out for each of the included studies under the following four headings: sample size, measurement bias, other biases, and external validity.

Full details of this quality assessment can be found in the supplementary material.

## 3. Results

There were 861 articles compiled in Rayyan from PubMed (386), Scopus (74), Embase (401), and the Cochrane library (0). Following this, there were 247 duplicates removed leaving 614 articles for the primary (title and abstract) screening process. During the primary screening process, 564 articles were deemed

irrelevant leaving 50 articles for the secondary (full paper) screening process. During the secondary screening process, there were 34 articles (deemed to be irrelevant) and one review excluded. This left 16 articles for data extraction and quality assessment. There was one review by Giles and Koehle that was included in the primary review (Lv et al., 2014). The references from this paper were checked along with other papers to see if there were any additional references to be included. Three more articles (El Helou et al., 2012; Guo & Fu, 2019; Rundell et al., 2008) were attained since they were relevant references in the secondary screening process. Hence, there were 19 articles in total for data extraction and quality assessment. A summary of the screening process can be seen in Figure 1.

The characteristics of each study included in this review are outlined in Table 1.

### 3.1. Characteristics of the studies

In terms of location, four were based in the United States; three were based in Brazil; one from China; one from Hong Kong; one from India; one from New Zealand; and, six were based in Europe (two from Italy and one from each of Belgium, Turkey, Poland, and the

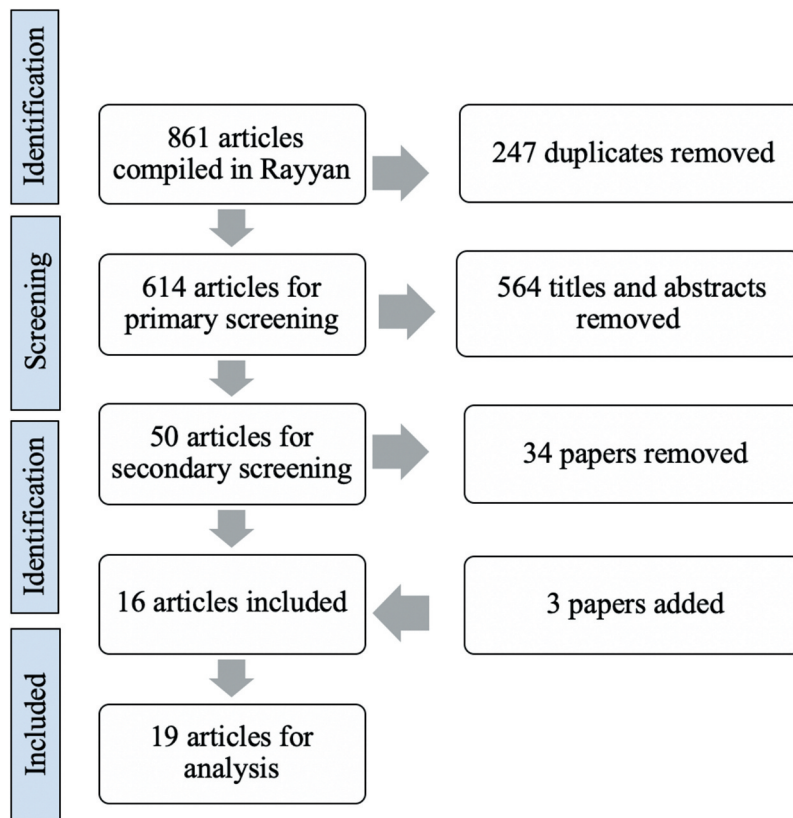


Figure 1. The search process for the scoping review.

Table 1. Characteristics of the included studies

Study	Location/ Source of data	Study design	Study period	Population	Pollutants Data	Main findings
Laurino et al., 2021 (Laurino et al., 2021) The Smart Healthy ENV project	Pisa, Italy (primary data)	Proof-of-concept pilot study <ul style="list-style-type: none"> <li>Breath analysis</li> <li>Questionnaires</li> <li>Personal monitoring</li> </ul> Runners and walkers compared on polluted 'red' and less polluted 'green' routes	9 days from May-July 2017	N = 15 healthy volunteers Aged 31–57 (different ability levels)	Red route mean value ranges CO (1.2–2.8 ppm) CO <sub>2</sub> (333–428 ppm) HC (3.1–6.6 ppm) O <sub>3</sub> (27.2–42.2 ppb) PM <sub>2.5</sub> (3–18.5 µg/m <sup>3</sup> ) Green route mean values ranges CO (1.5–1.9 ppm) CO <sub>2</sub> (322–371 ppm) HC (3.3–5.1) O <sub>3</sub> (48.1–58.7 ppb) PM <sub>2.5</sub> (1.8–14.5 µg/m <sup>3</sup> )	<ul style="list-style-type: none"> <li>Two running routes in Pisa were identified: a red route with high traffic volume and a green route with vegetation and limited traffic with higher concentrations of most pollutants in the red route.</li> <li>For running on the green route: a positive and significant correlation between the RR interval and atmospheric pressure was found (<math>R = 0.74</math>, <math>p</math>-value = 0.015). (RR interval increases could mean increased effort - heart rate data (the RR interval is the time elapsed between two successive R-waves of the EKG signal)</li> <li>For running on the red route: positive and significant correlations between the RR interval and relative humidity (<math>R = 0.54</math>, <math>p</math>-value = 0.046) and CO concentration (<math>R = 0.56</math>, <math>p</math>-value = 0.036).</li> <li>For walking on the red/green routes: no significant correlations between heart rate and meteorological/pollutant data.</li> <li>There were higher mean values of CO, CO<sub>2</sub>, and PM<sub>2.5</sub> for the red route but higher O<sub>3</sub> values in the green route.</li> <li>HC was higher in the red route for running but slightly higher in the green route for walking.</li> <li>Stratified analysis further shows that the significant adverse association between increased systolic blood pressure and black carbon was only observed in the polluted route (e.g. relative risk = 4.51, 95% CI: 0.75, 8.27).</li> <li>No significant associations of black carbon and pulmonary functions and O<sub>3</sub> with all clinical measures were observed upon adjusting for confounders.</li> <li>There was an 8-fold difference in black carbon levels between the two running routes.</li> </ul>
Pun and Ho 2018 (Pun & K-F, 2019)	Hong Kong (two running routes with high and low ambient air pollution)	Crossover study between more polluted KC Sports Ground and CC College	August 2015	N = 30 healthy adult runners (aged 14 to 26)	KC Sports Ground mean values: Black carbon 5.4µg/m <sup>3</sup> (range 3.0–8.6) O <sub>3</sub> 73.5 ppb (range 14.4–173.4) CC College mean values: Black Carbon 1.3 µg/m <sup>3</sup> range (0.5–5.9) O <sub>3</sub> 57.6 ppb (range 22.0–252.1)	<ul style="list-style-type: none"> <li>Each participant ran a 3200-metre time trial on a green AQI day with PM<sub>2.5</sub> &lt; 12 microgramd.m<sup>-3</sup> and on a yellow or orange day PM<sub>2.5</sub> &gt; 12 microgramd.m<sup>-3</sup></li> <li>Post exercise forced vital capacity was not significantly different (<math>p=0.846</math>) between low and high PM<sub>2.5</sub> conditions.</li> <li>Neither run time nor pulmonary function of healthy adults was adversely affected by an acute bout of exercise in elevated ambient PM<sub>2.5</sub> conditions, equivalent to yellow or orange on the air quality index.</li> </ul>
Wagner and Brandley 2019 (Wagner & Brandley, 2020)	Cache County, Utah, United States of America	Crossover study	February 2016	N=10 (aged 18–35-years with good respiratory fitness)	Low PM <sub>2.5</sub> trial: 4.3±4.2 µg/m <sup>3</sup> (0.6–14.7) High PM <sub>2.5</sub> trial: 37.7±7.9 µg/m <sup>3</sup> (19.1–42.5)	<ul style="list-style-type: none"> <li>Neither run time nor pulmonary function of healthy adults was adversely affected by an acute bout of exercise in elevated ambient PM<sub>2.5</sub> conditions, equivalent to yellow or orange on the air quality index.</li> </ul>

(Continued)

Table 1. (Continued).

Study	Location/ Source of data	Study design	Study period	Population	Pollutants Data	Main findings
Cavalcante de Sá et al. 2016 (De Sá M et al., 2016)	São Paulo, Brazil.	Randomised crossover study with two different locations: a street in downtown São Paulo and a less polluted urban forest	Between August and November	N=38 young healthy athletes	Street concentrations: NO <sub>2</sub> 236 ± 54 µg/m <sup>3</sup> O <sub>3</sub> 21.6 ± 1.8 µg/m <sup>3</sup> PM <sub>2.5</sub> 65.1 ± 39.1 µg/m <sup>3</sup> Forrest concentrations: NO <sub>2</sub> 177 ± 49 µg/m <sup>3</sup> O <sub>3</sub> 24.2 ± 3.9 µg/m <sup>3</sup> PM <sub>2.5</sub> 22.6 ± 15.3 µg/m <sup>3</sup>	<ul style="list-style-type: none"> <li>• There were no significant differences in NO<sub>2</sub> or O<sub>3</sub> between the two locations.</li> <li>• The street presented 3 times higher PM<sub>2.5</sub> concentrations and lower temperature than the forest.</li> <li>• Street running was associated with higher heart rates and impaired nasal mucociliary clearance (MCC).</li> <li>• Exhaled breath condensate (EBC) pH acidification was not detected in athletes running in the most polluted environment.</li> <li>• Those who ran in the less polluted area did show raised pH levels.</li> <li>• 20 road runners ran for 60 minutes on a city street with heavy traffic. One week later they ran 60 minutes outside the city centre on a running track.</li> <li>• There was a reduction in nasal resistance, which was statistically significant in city centre runners but was not statistically significant in those running outside of the city centre after the exercise.</li> <li>• There was no statistical significance in the difference in nasal transport times between inside and outside city centre running.</li> <li>• When compared to the runners in the city centre, it was found that air pollutants and diesel exhaust particles more frequently get stuck in the nasal filtration mechanisms of runners outside the city, and this positively affects the health of outdoor runners outside the city.</li> </ul>
Bos et al. 2013 (Bos et al., 2013)	Brussels and Mol, Belgium	Crossover study with one location on a busy street and another outside the city centre on a track one week later	Unclear	N = 20 healthy male runners aged 20–41	No details of pollutants specified	<ul style="list-style-type: none"> <li>• There were 21 and 13 individuals that initially participated in urban and rural environments, respectively, to test the effect of PM on pulmonary and cognitive brain function but 15 participants from the urban group and nine participants from the rural group completed the training program.</li> <li>• Fitness levels improved equally (<math>p &lt; 0.0001</math>) in both groups.</li> <li>• The levels of inflammatory markers, more specifically leukocyte counts (<math>p = 0.02</math>), neutrophil counts (<math>p = 0.04</math>), and exhaled nitric oxide levels (<math>p = 0.002</math>) increased after training in the urban group, whereas these parameters did not change in the rural group.</li> <li>• Personal PM exposure positively correlated with white blood cell count (leukocytes) not there was no association within the counts of the eosinophils, the monocytes, and the basophils.</li> <li>• There was improved cognitive performance (measured by the Stroop task) in healthy subjects in response to aerobic training in the rural environment but not in response to aerobic training in an urban environment, where traffic-related air pollution was substantially higher.</li> </ul>
Bos et al. 2013 (Bos et al., 2013)	Brussels and Mol, Belgium	Non-randomised comparison design.	9 February – 2 March 2011	N=24 healthy untrained individuals	Ultrafine Particulate Matter (UFP) mean (SD) levels: Urban area: 7244 (2559) Rural area: 5625 (1896) Unit is particles per cubic metre The average particle number measured at each location differed significantly (Mann–Whitney U test, $U = 393$ ), $P = 0.006$	<ul style="list-style-type: none"> <li>• There were 21 and 13 individuals that initially participated in urban and rural environments, respectively, to test the effect of PM on pulmonary and cognitive brain function but 15 participants from the urban group and nine participants from the rural group completed the training program.</li> <li>• Fitness levels improved equally (<math>p &lt; 0.0001</math>) in both groups.</li> <li>• The levels of inflammatory markers, more specifically leukocyte counts (<math>p = 0.02</math>), neutrophil counts (<math>p = 0.04</math>), and exhaled nitric oxide levels (<math>p = 0.002</math>) increased after training in the urban group, whereas these parameters did not change in the rural group.</li> <li>• Personal PM exposure positively correlated with white blood cell count (leukocytes) not there was no association within the counts of the eosinophils, the monocytes, and the basophils.</li> <li>• There was improved cognitive performance (measured by the Stroop task) in healthy subjects in response to aerobic training in the rural environment but not in response to aerobic training in an urban environment, where traffic-related air pollution was substantially higher.</li> </ul>

(Continued)

Table 1. (Continued).

Study	Location/ Source of data	Study design	Study period	Population	Pollutants Data	Main findings
Rundell et al. 2008 (Rundell et al., 2008)	Pennsylvania, United States of America	Crossover study	Unclear	N = 12 non-asthmatic males	Low pollution area: PM <sub>1</sub> 7382 ± 1727 particles Higher pollution area: PM <sub>1</sub> 252,290 ± 77529 particles	<ul style="list-style-type: none"> <li>Participants exercises in two areas in high or low PM<sub>1</sub> ambient air.</li> <li>This study demonstrated statistically significant PM dose-dependent falls in lung function in healthy non-asthmatic subjects after high PM exercise but not after low PM exercise.</li> </ul>
<b>Pre- and post-exercise studies</b>						
Chimienti et al. 2009 (Chimienti et al., 2009)	Sicily, Italy	Longitudinal field study	Unclear	N = 9 healthy male amateur athletes	Approximate ranges: NO <sub>2</sub> (µg/m <sup>3</sup> ) 29.7–88.4 PM <sub>10</sub> (µg/m <sup>3</sup> ) 13.1–52.9 O <sub>3</sub> (µg/m <sup>3</sup> ) 45.5–121	<ul style="list-style-type: none"> <li>9 amateur athletes had cell composition, apoptosis, and inflammatory mediators measured in induced sputum collected at rest (baseline) and the morning after races held in the fall (21 km), winter (12 km), and summer (10 km).</li> <li>Mild bronchial epithelial injury is associated with intense exercise irrespective of the environmental conditions, but this injury was deemed to be mild.</li> <li>O<sub>3</sub> and PM<sub>10</sub> affect apoptosis of neutrophils, suggesting activation of anti-inflammatory mechanisms in response to inhalation of pollutants during exercise.</li> <li>No correlation was observed between temperature, air humidity or NO<sub>2</sub> concentrations and cell counts or inflammatory mediator concentration.</li> <li>This study measured breath pH pre- and post-exercise for 16 high school athletes where there were atmospheric concentrations of ozone and PM<sub>2.5</sub>.</li> <li>The pH of exhaled breath condensate (EBC) was used as a biomarker for inflammation reflecting the acid-base balance of the airways.</li> <li>This study found no significant association between ambient ozone or particulate matter and post-exercise breath pH.</li> <li>It did not observe an acute effect of air pollution exposure during exercise on breath pH.</li> <li>The study did find that breath pH was low in this sample compared to 14 sedentary healthy adults possibly indicating that repetitive vigorous exercise may induce airway acidification.</li> </ul>
Ferdinands et al. 2008 (Ferdinands et al., 2008)	Atlanta, United States of America	Prospective observational study	16 <sup>th</sup> to 31 <sup>st</sup> August 2004 (peak smog season in this location)	N = 30 16 high school athletes and 14 healthy sedentary adults (control)	Mean (SD) of pollutants: PM <sub>2.5</sub> (µg/m <sup>3</sup> ) 27.2 (11.9) O <sub>3</sub> (ppb) 71 (Guo & Fu, 2019)	

(Continued)

Table 1. (Continued).

Study	Location/ Source of data	Study design	Study period	Population	Pollutants Data	Main findings
<b>Competition data studies</b>						
Hodgson et al. 2021 (J. R. Hodgson et al., 2021)	Diamond league data from cities: London, Birmingham, Paris, Zurich, Oslo, Doha, Shanghai, Stockholm, Lausanne	Data analysis of meteorological data, air quality data and race performance metrics.	Events from 2010 to 2018	Elite athletes (N not mentioned)	Pollutants studied: NO <sub>2</sub> , O <sub>3</sub> , PM <sub>10</sub> and PM <sub>2.5</sub> (Varied by city)	<ul style="list-style-type: none"> <li>Higher temperatures and wind speed led to slower times while higher relative humidity saw quicker times.</li> <li>O<sub>3</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> were associated with female athletes to producing slower finishing times but the same results were not seen for men, and it is not clear why.</li> <li>Temperature was the biggest factor to affect athletic performance.</li> <li>Birmingham was the slowest event in the Diamond league potentially owing to higher O<sub>3</sub> levels and windier conditions.</li> <li>Higher levels of NO<sub>2</sub> and relative humidity were conducive to quicker 5km times.</li> <li>Birmingham showed significant and detrimental relationships with O<sub>3</sub>, PM<sub>10</sub> and PM<sub>2.5</sub>.</li> <li>Paris showed the quickest finishing times with lowest O<sub>3</sub> levels and the second highest NO<sub>2</sub> levels.</li> <li>Data analysis indicated that as wet bulb globe temperature (WBGT) and PM<sub>10</sub> increase, the marathon performances of men and women become slower.</li> <li>There was a significant relationship between PM<sub>10</sub> and the performance in women (<math>r^2 = 0.33, p &lt; 0.05</math>) but not in men: for every 10-<math>\mu\text{g}\cdot\text{m}^{-3}</math> increase in PM<sub>10</sub>, performance can be expected to decrease by 1.4%.</li> <li>Men's and women's performances were not significantly correlated with any other pollutant.</li> <li>four environmental factors were gathered for each of the 60 races: temperature (°C), humidity (%), dew point (°C), and the atmospheric pressure at sea level (hPa); as well as the concentrations of four atmospheric pollutants: NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub> and PM<sub>10</sub> (<math>\mu\text{g}\cdot\text{m}^{-3}</math>)</li> <li>The environmental factor that affects marathon performance the most was air temperature followed by humidity.</li> <li>Out of pollutants, NO<sub>2</sub> and O<sub>3</sub> had the greatest effect on decreasing marathon performances.</li> <li>It is not isolated to these pollutants but their combination with other parameters like temperature, humidity and dew point.</li> </ul>
Marr and Ely 2010 (Marr & Ely, 2010)	United States: Data from 7 US Marathons weather data, & air pollution concentrations	Retrospective data analysis of 7 marathons	Data from 8–28 years prior to 2007	Competitive athletes (N unclear)	Mean (SD) 7 marathons: CO (ppm) 0.97 (1.05) O <sub>3</sub> (ppm) 0.02 (0.01) PM <sub>10</sub> ( $\mu\text{g}/\text{m}^3$ ) 22.3 (11.5) PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ ) 13.8 (11.8) NO <sub>2</sub> (ppm) 0.02 (0.01) SO <sub>2</sub> (ppm) 0.01 (0.01)	
El Helou et al. 2012 (El Helou et al., 2012)	Paris, London, Berlin, Boston, Chicago and New York.	Retrospective data analysis of six marathons from 2001–2010 (60 races)	2001–2010	N = 1,791,972	Ranges of means: NO <sub>2</sub> ( $\mu\text{g}/\text{m}^3$ ) 26.5–55.1 SO <sub>2</sub> ( $\mu\text{g}/\text{m}^3$ ) 4.5–19.7 PM <sub>10</sub> ( $\mu\text{g}/\text{m}^3$ ) 5.0–37.9 O <sub>3</sub> ( $\mu\text{g}/\text{m}^3$ ) 32.6–73.5	

(Continued)



Table 1. (Continued).

Study	Location/ Source of data	Study design	Study period	Population	Pollutants Data	Main findings
Zoladz and Niecekarz (2021)	Kraków, Poland Annual marathon data	Data analysis and estimation study	28 <sup>th</sup> April 2019	Unclear	Mean value: PM <sub>10</sub> 22 µg/m <sup>3</sup> No similar values for PM <sub>1</sub> and PM <sub>2.5</sub>	<ul style="list-style-type: none"> <li>This study considered the effect of PM<sub>1</sub>, PM<sub>2.5</sub>, PM<sub>10</sub> on runners in the Kraków marathon on 28<sup>th</sup> April 2019.</li> <li>Running a marathon increased the inhalation of PM<sub>10</sub> compared to someone at rest: breathing air containing 50 µg m<sup>-3</sup> PM<sub>10</sub> at minute ventilation (VE) equal to 8 L min<sup>-1</sup> when at rest, resulted in PM<sub>10</sub> deposition rate of approximately 9 µg h<sup>-1</sup>, but a marathon run of an average marathon runner with the VE = 62 L min<sup>-1</sup> increased the deposition rate up to 45 µg h<sup>-1</sup>. The elite marathon runners with the VE = 115 L min<sup>-1</sup> increased PM<sub>10</sub> deposition rate to 83 µg h<sup>-1</sup>.</li> <li>Breathing the air containing 50 µg m<sup>-3</sup> of PM<sub>10</sub> at the VE = 115 L min<sup>-1</sup> by the elite marathon runner during the race resulted in the same PM<sub>10</sub> deposition rate as the breathing highly polluted air containing as much as 466 µg m<sup>-3</sup> of PM<sub>10</sub> when at rest.</li> <li>The total PM<sub>10</sub> deposition was 22% greater in average runners compared to elite runners.</li> <li>Air pollution can increase a marathon time by 2.94–7.95% depending on how polluted the air is on a given day.</li> <li>Air pollution affects the top 10% (fastest runners) three times as much as it does the lowest 10% (slowest runners).</li> </ul>
Guo and Fu (2019)	China	Retrospective data analysis from 56 marathons	2014–2015	N=0.3 million marathon runners	Mean (SD) air quality and pollutant concentration (µg/m <sup>3</sup> ) during race hours: PM <sub>2.5</sub> 73.89 (60.89) PM <sub>10</sub> 104.79 (77.98) SO <sub>2</sub> 21.83 (15.57) NO <sub>2</sub> 45.34 (24.70) O <sub>3</sub> 54.42 (31.75) CO 1.20 (0.61)	<ul style="list-style-type: none"> <li>Use of WHO data also used. Used both data from volunteers and WHO data in combination to see how much PM would be inhaled in the cleanest and dirtiest cities.</li> <li>The inhaled dose of PM<sub>2.5</sub> and PM<sub>10</sub> were significantly higher in the dirtiest cities compared to the cleanest cities at rest and exercise, and significantly higher during exercise compared to the rest in the dirtiest cities.</li> <li>The relative risk of all-cause mortality analysis showed that, while exercise in the cleanest cities improved health benefits throughout up to 90 min, there were no further health benefits after 15 min of exercise in the dirtiest cities, and the air pollution health risks surpassed the exercise benefits after 75 min.</li> <li>Exercise performed in the dirtiest cities might lead to about 37–66 times higher inhaled pollutants than in the cleanest cities, which could suppress the health benefits provided by aerobic exercise.</li> <li>10 male athletes took part in an 8 km run in 4 different conditions testing ozone concentration, temperature and humidity.</li> <li>O<sub>3</sub> had a minimal impact on athletic performance; heat had the greatest impact on athletic performance.</li> <li>It was hypothesised by the author that the cocktail of pollutants of sulphur dioxide, particulate matter (PM<sub>10</sub>), nitrogen oxides (NO<sub>x</sub>), in addition to ozone, that hinder athletic performance.</li> </ul>
<b>Laboratory Controlled studies</b>						
Pasqua et al. (2018)	São Paulo, Brazil.	Experimental design. Use of healthy volunteers to analyse inhaled PM during rest and exercises.	Not mentioned	N=116 healthy male adults ages 25±4 years	Controlled temperature room (20–24 degree Celsius) It simulated PM <sub>10</sub> and PM <sub>2.5</sub> conditions from the most and least polluted cities in the world. Lowest to highest values for different cities: PM <sub>10</sub> (4–594 ppb) PM <sub>2.5</sub> (1.6–149 ppb)	<ul style="list-style-type: none"> <li>Use of WHO data also used. Used both data from volunteers and WHO data in combination to see how much PM would be inhaled in the cleanest and dirtiest cities.</li> <li>The inhaled dose of PM<sub>2.5</sub> and PM<sub>10</sub> were significantly higher in the dirtiest cities compared to the cleanest cities at rest and exercise, and significantly higher during exercise compared to the rest in the dirtiest cities.</li> <li>The relative risk of all-cause mortality analysis showed that, while exercise in the cleanest cities improved health benefits throughout up to 90 min, there were no further health benefits after 15 min of exercise in the dirtiest cities, and the air pollution health risks surpassed the exercise benefits after 75 min.</li> <li>Exercise performed in the dirtiest cities might lead to about 37–66 times higher inhaled pollutants than in the cleanest cities, which could suppress the health benefits provided by aerobic exercise.</li> <li>10 male athletes took part in an 8 km run in 4 different conditions testing ozone concentration, temperature and humidity.</li> <li>O<sub>3</sub> had a minimal impact on athletic performance; heat had the greatest impact on athletic performance.</li> <li>It was hypothesised by the author that the cocktail of pollutants of sulphur dioxide, particulate matter (PM<sub>10</sub>), nitrogen oxides (NO<sub>x</sub>), in addition to ozone, that hinder athletic performance.</li> </ul>
Gomes et al. (2010)	Study location unclear; study based from Edinburgh, UK	Crossover randomised design	Unclear	N = 10 male competitive runners	Either the air was filtered or 0.1 O <sub>3</sub> ppm with varying temperatures or levels of humidity	<ul style="list-style-type: none"> <li>Use of WHO data also used. Used both data from volunteers and WHO data in combination to see how much PM would be inhaled in the cleanest and dirtiest cities.</li> <li>The inhaled dose of PM<sub>2.5</sub> and PM<sub>10</sub> were significantly higher in the dirtiest cities compared to the cleanest cities at rest and exercise, and significantly higher during exercise compared to the rest in the dirtiest cities.</li> <li>The relative risk of all-cause mortality analysis showed that, while exercise in the cleanest cities improved health benefits throughout up to 90 min, there were no further health benefits after 15 min of exercise in the dirtiest cities, and the air pollution health risks surpassed the exercise benefits after 75 min.</li> <li>Exercise performed in the dirtiest cities might lead to about 37–66 times higher inhaled pollutants than in the cleanest cities, which could suppress the health benefits provided by aerobic exercise.</li> <li>10 male athletes took part in an 8 km run in 4 different conditions testing ozone concentration, temperature and humidity.</li> <li>O<sub>3</sub> had a minimal impact on athletic performance; heat had the greatest impact on athletic performance.</li> <li>It was hypothesised by the author that the cocktail of pollutants of sulphur dioxide, particulate matter (PM<sub>10</sub>), nitrogen oxides (NO<sub>x</sub>), in addition to ozone, that hinder athletic performance.</li> </ul>

(Continued)

Table 1. (Continued).

Study	Location/ Source of data	Study design	Study period	Population	Pollutants Data	Main findings
<b>Miscellaneous observational studies</b>						
Santos et al. 2019 (Santos et al., 2019)	São Paulo, Brazil. Primary data from volunteers and data from the Environmental Company of São Paulo State	Comparison of data between runners and sedentary people in one location	15 weeks (time unclear)	N = 40 volunteers (20 street runners and 20 sedentary people)	Mean values ranges: (approximate figures) PM <sub>2.5</sub> (7–45 µg/m <sup>3</sup> ) PM <sub>10</sub> (10–70 µg/m <sup>3</sup> ) O <sub>3</sub> (1–50 µg/m <sup>3</sup> )	<ul style="list-style-type: none"> <li>Higher levels of immunological agents can be found in physically active people leading to greater protection, which decreases the incidence of upper respiratory tract infections.</li> <li>The association between chronic particulate matter exposure and the particle accumulation in the airways was able to elicit an immunological response, improving the mucosal airway protection, albeit only in runners.</li> <li>The practice of outdoor aerobic exercise was able to modulate the airways' immune/inflammatory responses in different ways than in sedentary people.</li> <li>Long-standing regular practice of outdoor endurance exercise might improve the immunological and inflammatory status in the airways after both acute and chronic particulate matter exposure differently from that observed in the sedentary lifestyle of people in the same community.</li> <li>The highest (statistically significant) CO concentrations were found in motorcyclists.</li> <li>The runner had a significantly lower exposure to CO compared to the car and bus commuters when there was a dedicated pedestrian/cycleway available on their route to work but not significantly different when the runner just found a less congested route.</li> <li>While the runner experienced a significantly lower exposure compared to the car and bus commuters, their dose of CO was significantly higher (reflected by the higher ventilation and the longer commute time).</li> <li>The inhalation dose of CO (Carbon Monoxide) increased by 78% and PM<sub>2.5</sub> by 28.4% when a person switched from walking to running.</li> </ul>
Dirks et al. 2012 (Dirks et al., 2012)	Auckland, New Zealand	Comparison experimental study: compared people who commute to work via bus, car, train, motorbike, and run.	8 November to 17 December 2010	N unclear (data of 88 commutes collected, 4–10 per mode per route)	CO levels are given the 4 different modes of transport. CO levels were reported to be 0.4 ppm for runners	
Kaur, Singla and Bansal 2017 (Kaur et al., 2017)	Chandigarh City, India	Data collected via an app	Not mentioned	N=5	CO and PM <sub>2.5</sub> identified but ambient air levels not specified. The mean CO inhalation recorded was 1.64 µg/min and the mean recorded inhalation of PM <sub>2.5</sub> was 0.011 µg/min	

UK). Two studies were based on locations from a myriad of locations across the world (El Helou et al., 2012; J. R. Hodgson et al., 2021).

The majority of the studies included used primary data from their respective studies. There were five exceptions, in which the studies used secondary data in their analysis (El Helou et al., 2012; Guo & Fu, 2019; J. R. Hodgson et al., 2021; Marr & Ely, 2010; Zoladz & Nieckarz, 2021). These five studies used data from running competitions along with environmental data to study how environmental factors can impact running performance (El Helou et al., 2012; Guo & Fu, 2019; J. R. Hodgson et al., 2021; Marr & Ely, 2010; Zoladz & Nieckarz, 2021). Hodgson et al. (J. R. Hodgson et al., 2021). used competition data (race performance metrics) from the Diamond League events in London, Birmingham, Paris, Zurich, Oslo, Doha, Shanghai, Stockholm, and Lausanne from 2010 to 2018 along with air quality data and race performance metrics. Marr and Ely (Marr & Ely, 2010) did a similar retrospective study using marathon data from seven cities in the United States over many years prior to 2007. Likewise, Zoladz and Nieckarz (Zoladz & Nieckarz, 2021) studied the results of the 2019 Kraków marathon to study the effect that particulate matter had on runners. El Helou (El Helou et al., 2012) used retrospective data from six marathons (60 races) from 2001–2010 along with data on humidity, dew point, temperature and pollution to see their effects on athletes. The cities chosen for this study were Paris, London, Berlin, Boston, Chicago and New York. Guo and Fu (Guo & Fu, 2019) used retrospective data from 56 marathons in China. In each of these five studies, race performance metrics were used to study how pollution, temperature and other factors can affect running performance.

The remaining 14 out of 19 studies used primary data. The biggest group of these were the seven studies (Aydın et al., 2014; Bos et al., 2013; De Sá M et al., 2016; Laurino et al., 2021; Pun & K-F, 2019; Rundell et al., 2008; Wagner & Brandley, 2020) that used a crossover design where participants ran in areas with high and low ambient air pollution, usually with a washout period in between. Two studies compared runners before and after running in areas with ambient air pollution (Chimenti et al., 2009; Ferdinands et al., 2008). Two studies (Gomes et al., 2010; Pasqua et al., 2018) were based in laboratory-controlled conditions to study the effect that one particular pollutant had on runners. One of these, namely by Gomes et al. (Gomes et al., 2010), was also a crossover study but was put in a different category to the other seven crossover studies due to it being in controlled conditions. Santos et al. (Santos et al., 2019). compared runners versus sedentary people

who inhaled ambient air pollution. The study by Dirks et al. compared people who commute to work via bus, car, train, motorbike, and by running (Dirks et al., 2012). Kaur, Singla and Bansal used an app to monitor their participants as they switched from walking to running in different environmental conditions (Kaur et al., 2017).

### 3.2. Quality of the studies

The full results of the quality assessment can be viewed in the supplementary material. For the most part, the included studies tended to have small sample sizes. Any large sample sizes were mainly from the studies that used data from running competitions. The majority (10 out of 19) studies used a sample size of 30 or less.

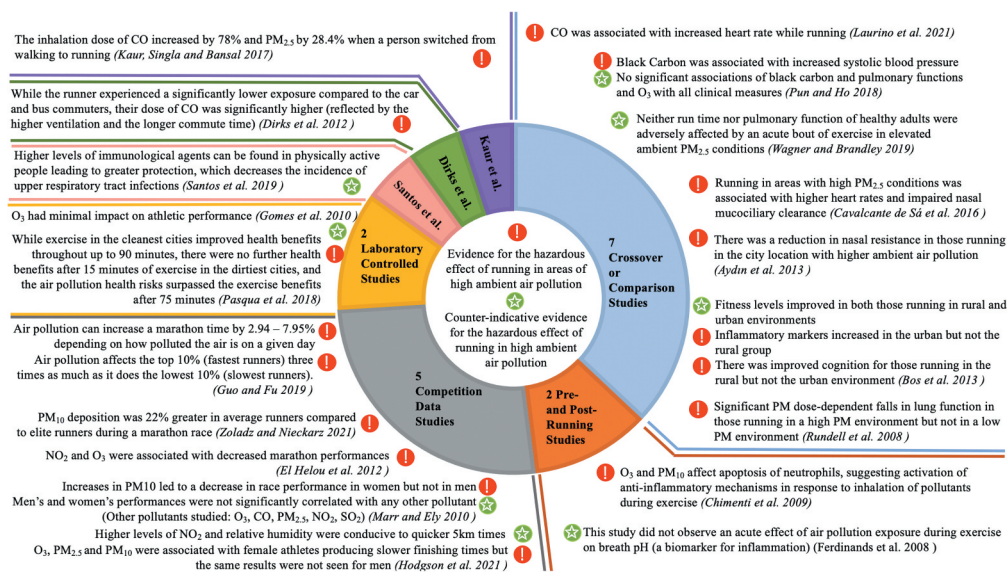
Most of the studies used robust scientific methods for measuring levels of pollution inhaled or absorbed in the blood stream, such as using blood tests, spirometry or gas analysers. There were also some methods in which the methodology was questionable such as the use of an app in the Kaur, Singla and Bansal study (Kaur et al., 2017) or the Zoladz and Nieckarz study (Zoladz & Nieckarz, 2021), whereby some calculations were based on assumptions and modelling rather than laboratory-based methods.

Controlling for confounding is very difficult for these types of studies since there are many parameters such as temperature, the participants' health or fitness status etc. that can be confounders when trying to assess how ambient air pollution affects health or running performance. Some studies, such as the Chimenti et al. study (Chimenti et al., 2009), did make an effort to control these confounders (in this case temperature) by conducting their study at different times of the year, whereas other studies (Laurino et al., 2021; Wagner & Brandley, 2020) conducted their study at one time of the year.

While the two laboratory-based studies (Gomes et al., 2010; Pasqua et al., 2018) were able to control for conditions, such as temperature, these two studies had poor external validity since they are not fully reflective of ambient air pollution. Some studies had good external validity since their participants covered a wide range of ages and fitness ability (Laurino et al., 2021; Santos et al., 2019) but others only used male runners (Aydın et al., 2014) or elite runners (J. R. Hodgson et al., 2021).

### 3.3. Pollution exposure for runners in areas of high ambient air pollution

Some main results from the included studies are presented in Figure 2. Each study either has evidence for



**Figure 2.** Key evidence and counter-indicative evidence for the hazardous effect of running in areas of high ambient air pollution.

the hazardous effect of running in areas of high ambient air pollution, counter-indicative evidence, or a mixture of both. The legend for the type of evidence is marked in the centre of the diagram and the studies are grouped according to the type of study included in this review.

Kaur, Singla and Bansal found that the inhalation dose of CO increased by 78% and PM<sub>2.5</sub> by 28% when a person switched from walking to running in a highly polluted setting (Kaur et al., 2017). The Dirks et al. study compared different commuters (car, bus, runner, etc.) and found that runners often can have a lower exposure to toxins than the car or bus commuters, owing to their choice of a less polluted route (Dirks et al., 2012). However, the runners' dose of CO was significantly higher, reflected by the higher ventilation and the longer commute time (Dirks et al., 2012). Zoladz and Nieckarz (Zoladz & Nieckarz, 2021) found that the deposition of PM<sub>10</sub> into the lungs was statistically more significant in someone running compared to someone at rest and, moreover, that the total PM<sub>10</sub> deposition was 22% greater in average runners compared to elite runners. Pasqua et al. found that the inhaled dose of PM<sub>2.5</sub> and PM<sub>10</sub> were significantly higher in the dirtiest cities compared to the cleanest cities at rest and exercise, and significantly higher during exercise compared to the rest in the dirtiest cities (Pasqua et al., 2018). Moreover, this study concluded that exercise performed in the dirtiest cities might lead to about 37–66 times higher inhaled pollutants than in the cleanest cities (Pasqua et al., 2018).

### 3.4. Effects of ambient air pollution on respiratory health in runners

While there are mixed results on the hazardous effect of running in high ambient air pollution, most of the evidence indicates that it is hazardous for respiratory health. Pasqua et al. concluded that while exercise in the cleanest cities improved health benefits throughout up to 90 minutes, there were no further health benefits after 15 minutes of exercise in the dirtiest cities, and the air pollution health risks surpassed the exercise benefits after 75 minutes (Pasqua et al., 2018). Rundell et al. found significant PM dose-dependent falls in lung function in those running in a high PM environment but not in a low PM environment (Rundell et al., 2008). Chimenti et al. found that O<sub>3</sub> and PM<sub>10</sub> affect apoptosis of neutrophils, suggesting activation of anti-inflammatory mechanisms in response to inhalation of pollutants during exercise (Chimenti et al., 2009). Similarly, Bos et al. found that inflammatory markers increased in those running in urban areas but not in those running in rural areas (Bos et al., 2013). Moreover, Aydın et al. found that there was a reduction in nasal resistance in those running in the city location with higher ambient air pollution in their study (Aydın et al., 2014). Cavalcante de Sá et al. reported that running in areas with high PM<sub>2.5</sub> conditions was associated with higher heart rates and impaired nasal mucociliary clearance (De Sá M et al., 2016).

There was also some counter-indicative evidence to suggest that running in areas of high ambient air

pollution does not affect respiratory health. For example, Santos et al. mention that higher levels of immunological agents can be found in physically active people leading to greater protection, which decreases the incidence of upper respiratory tract infections (Santos et al., 2019). Pun and Ho found no significant associations of black carbon and pulmonary functions and O<sub>3</sub> with all clinical measures (Pun & K-F, 2019). Wagner and Brandley reported that neither run time nor pulmonary function of healthy adults was adversely affected by an acute bout of exercise in elevated ambient PM<sub>2.5</sub> conditions (Wagner & Brandley, 2020). Contrary to the Bos et al. study, the Ferdinands et al. study did not observe an acute effect of air pollution exposure during exercise on breath pH (a biomarker for inflammation) (Ferdinands et al., 2008).

### **3.5. Effects of ambient air pollution on general health in runners**

Whilst the focus of this review was primarily on respiratory issues, other health issues were also noted. For example, Laurino et al. found that CO was associated with increased heart rate while running (Laurino et al., 2021). Pun and Ho reported a significant adverse association between increased systolic blood pressure and black carbon, which was only observed in the polluted route (Pun & K-F, 2019). In the Bos et al. study, runners in both urban and rural areas saw their fitness improve but there was improved cognition for those running in the rural area but not the urban environment (Bos et al., 2013).

### **3.6. Effects of ambient air pollution on running performance**

The five studies that used competition data showed similar results (El Helou et al., 2012; Guo & Fu, 2019; J. R. Hodgson et al., 2021; Marr & Ely, 2010; Zoladz & Nieckarz, 2021). These studies found some associations between air pollution and longer marathon times (being a proxy measure of lung function) while controlling for confounders like temperature and humidity. Marr and Ely, Hodgson et al. and El Helou et al. all found that higher temperature was the factor that was most associated with participants having slower times upon racing (El Helou et al., 2012; J. R. Hodgson et al., 2021; Marr & Ely, 2010). Interestingly, Hodgson et al. (J. R. Hodgson et al., 2021). found that O<sub>3</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> appeared to be associated with female athletes producing slower finishing times but the same results were not seen for men (the results were not statistically significant). Marr and Ely also found a significant relationship

between PM<sub>10</sub> and the performance of women but not the performance of men (Marr & Ely, 2010). However, this latter study (Marr & Ely, 2010) did not find a significant correlation between the performances of men or women with other pollutants. Moreover, Hodgson et al. found that higher levels of NO<sub>2</sub> and relative humidity were conducive to quicker 5 km times (J. R. Hodgson et al., 2021). El Helou et al. also found a significant correlation with both NO<sub>2</sub> and O<sub>3</sub> and with running performance (El Helou et al., 2012). The latter author contended that the hindering or helping of running performance is not isolated to these pollutants but it is their combination with other parameters like temperature, humidity and dew point (El Helou et al., 2012). Guo and Fu concluded that air pollution affects the top 10% (fastest runners) three times as much as it does the lowest 10% (slowest runners) (Guo & Fu, 2019). This study also found that air pollution can increase a marathon time by approximately 3–8 % depending on how polluted the air is on a given day and can cause decreased lung function, irregular heartbeat, increased respiratory problems, nonfatal heart attacks, angina and even lower cognitive ability (Guo & Fu, 2019).

## **4. Discussion**

It appears to be well established that running in conditions with ambient air pollution results in an increased dose compared to moderate exercise, like walking, or being at rest (Kaur et al., 2017; Pasqua et al., 2018; Zoladz & Nieckarz, 2021). This can vary significantly depending on the dose of ambient air pollution between different locations (Pasqua et al., 2018). What is not so clear, however, is whether the effect of this extra dose of ambient air pollution has a significant effect on the respiratory health of runners. The results are generally mixed but more studies (Aydın et al., 2014; Bos et al., 2013; Chimenti et al., 2009; De Sá M et al., 2016; Pasqua et al., 2018; Rundell et al., 2008) in this review have indicated that the effect of running in high ambient air pollution has a significant effect on respiratory health than studies (Ferdinands et al., 2008; Pun & K-F, 2019; Santos et al., 2019; Wagner & Brandley, 2020) that found that the same effect was not significant. In particular, at least two studies (Bos et al., 2013; Chimenti et al., 2009) illustrated that there were significant inflammatory responses associated with high ambient air pollution. In contrast, there were at least two other studies (Ferdinands et al., 2008; Wagner & Brandley, 2020) that found no evidence of inflammatory responses associated with running in high ambient air pollution.

It can be difficult to compare the studies since they had different designs or they studied different pollutants or measured the pollutants with different units of measurement. However, we can compare two of the studies that made different conclusions yet both had a crossover design with areas of 'high' and 'low' ambient air pollution. Wagner and Brandley (Wagner & Brandley, 2020) had a low and high PM<sub>2.5</sub> trial and concluded that neither run time nor pulmonary function of healthy adults was adversely affected by an acute bout of exercise in elevated ambient PM<sub>2.5</sub> conditions, equivalent to yellow or orange on the air quality index. On the other hand, Cavalcante de Sá et al. (De Sá M et al., 2016) compared runners in a street and a forest with 'high' and 'low' ambient air pollution, respectively. This study concluded that street running was associated with higher heart rates and impaired nasal mucociliary clearance (De Sá M et al., 2016). If we compare the two 'high' dose pollution areas, the PM<sub>2.5</sub> level is reported to be  $37.7 \pm 7.9 \mu\text{g}/\text{m}^3$  in the Wagner and Brandley (Wagner & Brandley, 2020), whereas the PM<sub>2.5</sub> level is reported to be  $65.1 \pm 39.1 \mu\text{g}/\text{m}^3$  in the street ('high' dose) area in the Cavalcante de Sá et al. study (De Sá M et al., 2016). The study with the higher PM<sub>2.5</sub> level found a significant effect on respiratory health, whereas the study with the lower PM<sub>2.5</sub> level did not. Hence, it may be the case that respiratory health is affected in runners but only if the levels of pollution are sufficiently high. It was not in the parameters of this scoping review, however, to determine that level or threshold.

In addition to the studies (Aydın et al., 2014; Bos et al., 2013; Chimenti et al., 2009; De Sá M et al., 2016; Pasqua et al., 2018; Rundell et al., 2008) that found evidence for the significant effects of running in ambient air pollution on respiratory health, there were also the studies (Bos et al., 2013; Laurino et al., 2021; Pun & K-F, 2019) that found evidence to suggest that running in ambient air pollution impairs the cardiovascular system and cognition. These were secondary outcomes of this review. It is most likely that all of these connected systems are affected simultaneously. When taken altogether, these studies indicate that a majority of studies from this review indicate that running in areas of high ambient air pollution can be in some way hazardous to health. Indeed, most of the keynotes in the Figure 2 indicate evidence for a hazardous effect of ambient air pollution on runners.

Furthermore, all of the studies that examined competition data (El Helou et al., 2012; Guo & Fu, 2019; J. R. Hodgson et al., 2021; Marr & Ely, 2010; Zoladz & Nieckarz, 2021) unanimously concluded that ambient air pollution was associated with slower times in athletes (either just in female athletes or both). This may not

necessarily be a direct cause of some form of impaired health due to air pollution. There is a myriad of confounders that need to be considered. The climate in which the study takes place and the season or time of year is one potentially crucial confounding variable. Other environmental factors like temperature, humidity, precipitation, etc., can be confounders in any study that involves ambient air pollution and human health. Nevertheless, all of these studies did find an association between reduced running performance and air pollution. It may be that reduced running performance may be a proxy measure for impaired respiratory health or impaired health in general due to the effects of a high ambient air pollution dose. Moreover, these five studies (El Helou et al., 2012; Guo & Fu, 2019; J. R. Hodgson et al., 2021; Marr & Ely, 2010; Zoladz & Nieckarz, 2021) studying competition data showed significant results despite the fact that city marathons, in particular, tend to occur during weekends and bank holidays when city traffic (and other sources of ambient air pollution) may be below usual levels. Hence, these five studies may actually have under-reported the effects of running in cities during busier rush-hour or business periods.

Altogether, it seems likely that running in areas of high ambient air pollution does affect runners' health in some way, and perhaps in different ways, depending on the person. Furthermore, this has been seen to apply to runners across the entire spectrum of athletic fitness, from casual runners to elite athletes. The effects on the upper end of the fitness spectrum were indicated by five studies that used competition and environmental data (El Helou et al., 2012; Guo & Fu, 2019; J. R. Hodgson et al., 2021; Marr & Ely, 2010; Zoladz & Nieckarz, 2021) and on the lower end of the fitness spectrum by studies like the Pasqua et al. study (Pasqua et al., 2018).

#### 4.1. Implications

Running is a cheap and convenient way of keeping fit and has been shown to reduce NCDs and increase life expectancy (Pun & K-F, 2019). Due to the low level of skill required and the minimal amount of equipment needed for this sport, it should be promoted as an easily accessible means of staying fit and healthy. It is imperative, however, that city planners should be mindful of the environmental impacts that air pollution could have on its inhabitants. More greenways and parks should be provided for runners and commuters in towns and cities to mitigate against the effects that airborne pollutants could have on human health. Public health officials in cities with higher air pollution may need to advocate that people who use running as a form of exercise should try to limit their exposure by exercising during

non-rush-hour periods or by designating ‘safe zones’ (if lower pollution areas exist) for exercise in those cities. It is important that public health officials simultaneously promote the health benefits of running (or indeed any form of exercise), whilst advising people about the potential harms of doing so in high ambient air pollution conditions. This indeed may be a tricky task and is worth further exploration.

The use of face masks may also mitigate against the effects of air pollution while running. The COVID-19 crisis greatly increased the demand for, and awareness of, facemasks for public use (Smart et al., 2020). Advocating the use of facemasks for running, however, could be a significant challenge. The Smart et al. study, albeit focused solely on children and not necessarily whilst they were exercising, showed that by making face masks more appealing, breathable, cooler, and improving their fit, then wearability of these face masks may be improved (Smart et al., 2020). Educating people on the use of masks and wearing the correct mask is important: wearing a loosely fitting mask could allow contamination of pollution into the airways, for example (Laumbach & Cromar, 2022).

#### 4.2. Limitations

The primary focus of this review was on how air pollution affects respiratory health in runners. As the review unfolded, it became apparent that other health systems, such as cardiovascular health, could also be impinged greatly by pollutants. These were reported as secondary outcomes but it is possible that the search strategy did not pick up articles related to runners, pollution and other non-respiratory health issues. Any further studies on this topic should consider any health issues since it is likely they are interconnected.

The quality assessment carried out in this review was also somewhat subjective. Due to the nature of the scoping review, there was a wide variation in the types of studies included in this review. Hence, using a specific type of quality assessment instrument for all the studies was not appropriate. Any future systematic review or meta-analysis would need to examine similar types of studies (crossover studies, for example) and use an appropriate quality assessment instrument.

This review also included two laboratory-based studies that are not entirely reflective of ambient air pollution (Gomes et al., 2010; Pasqua et al., 2018). We deemed that these two studies should remain in the review, however, so that if a systematic review or meta-analysis is undertaken following this article, the relevant research has been pre-identified. Moreover, these studies utilised laboratory-based conditions to

study the effects of specific air pollutants that occur in ambient air pollution but are difficult to study in isolation in ambient air pollution conditions, which usually contain a cocktail of different toxins. Thus, while the results of these two studies should be caveated as not being completely applicable to the conditions for the aim of this review, it is important that they are reported since they both inform of us of the potential effects of the specific pollutants and will inform future research.

Many of the studies in this review were subject to the participants’ performance bias. Blinding participants to the air quality in which they exercise was an issue for most of the studies included in this review and is an issue that cannot be easily solved in future research studies on this topic, especially in the case of randomised controlled trials. Even in the case of participants exercising in laboratory conditions, where the environmental conditions of low and high ambient air pollution are imitated, blinding of any sort may still be impossible to achieve here.

Another area that many studies were deemed to have low quality and that studies in the future will need to consider carefully, is in the realm of external validity. Some studies like Aydın et al. and Gomes et al., only recruited male participants (Aydın et al., 2014; Gomes et al., 2010). The Hodgson et al. study was specific to elite athletes only (J. R. Hodgson et al., 2021). Any future study in this area should consider runners from both genders, from all ages and from a range of individuals on the running fitness spectrum. It would be interesting to gain further insights into the different effects that airborne pollutants can have on subgroups within running populations: recreational versus elite or competitive runners; male and female runners; or, younger versus older runners.

#### 4.3. Further research

Further research is needed in this area to understand both the short- and long-term effects that running in a polluted atmosphere can have on human health. In fact, most of the studies included in this review did not use randomisation to choose its participants and so this should be incorporated into any future studies in this area. In particular, carefully planned randomised control trials should be used to study the short- and medium-term effects of exercising in ambient air pollution conditions, such as pulmonary inflammation. It is also worth investigating if a certain pollution-level threshold exists as to when respiratory and other health systems are impaired when running.

The results from this review indicate that most of the effects of air pollution on runners were in the short- or

medium-term. More studies need to be conducted to study the long-term effects of running in ambient air pollution, since for many people, running is a lifelong activity. Indeed, longitudinal cohort studies should incorporate questions in their questionnaires to study the long-term effects of running in cities with ambient air pollution. More specific questions like ‘does regular running in conditions with high ambient air pollution cause lung cancer in the long term?’ could be addressed using such longitudinal cohort studies. A recent study led by Charles Swanton found new evidence to show that air pollution contributes significantly to the development of lung cancer (Gourd, 2022). In particular, they found that  $PM_{2.5}$  triggers an alarm response in the lungs, causing an inflammation and activation of dormant cells carrying cancer-causing mutations (Gourd, 2022). This is concerning since this review found evidence that runners in urban areas with high PM were particularly at risk of inflammation (Bos et al., 2013; Chimenti et al., 2009). Given the popularity of running as a means to keep fit and as a hobby, as mentioned earlier, and the large populations in urban areas living in close proximity to industrial and busy traffic centres, there should be adequate statistical power to support such investigations in the future. Many of the studies included in this review had small sample sizes, reducing their statistical power. Larger numbers of participants recruited into future studies is therefore needed.

There are many confounders that can affect such a study. The climate in which the study takes place and the season or time of year is one potentially crucial confounding variable. Other environmental factors like temperature, humidity, precipitation, etc., can be confounders in any study that involves ambient air pollution and human health. Therefore, the utmost care needs to be taken by any researchers conducting studies like those included in this review to control for confounding variables. Hence, various locations and climates should be used in a study and the study should be conducted at various times during the year to account for different seasons. Moreover, various levels of what is deemed to be ‘high’ or ‘low’ ambient air pollution need to be accounted for also. Depending on the country or region, what is considered ‘low’ pollution in one region may very well be considered ‘high’ pollution in another. Furthermore, controls need to be taken for the participants themselves—many of the studies included were successful in their application here. Only healthy participants with no underlying medical conditions, like asthma, should participate in the studies. Furthermore, controls for

what medications, how much sleep, and what food or drink is consumed by the individuals need to be measured prospectively so that the participants can be properly compared. On the other hand, a certain degree of error is to be expected from any future study; that is, to totally control for all possible confounders is realistically going to be impossible.

A myriad of different scientific techniques and types of measurement instruments were used in the different studies included in this review. Further research is needed in itself to determine the optimal measurement systems and instruments in areas like spirometry, rhinoscopy, and others relevant to such studies. For the most part, the studies in this review appeared to use robust scientific methods but given the variety of methods used, it is important that future studies can rely on the most scientifically sound techniques.

## 5. Conclusion

Running is a cheap and convenient way for people to stay fit, active and healthy and it should be promoted as a means for reducing NCDs. However, more greenways and parks should be provided for runners and commuters in towns and cities to mitigate against the effects that airborne pollutants can have on human health both in the short- and long-term. Other potential measures could include using facemasks, avoiding running during rush hour traffic or exercising in designated safe zones with lower ambient air pollution. Further research needs to be undertaken to examine the effects of running in ambient air pollution using larger sample sizes that randomise its participants. Moreover, shorter term studies such as randomised control trials should be utilised as well as longitudinal cohort studies to study this important topic.

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## Abbreviations

AQI air quality index;  $CO_x$  carbon oxides; HC hydrocarbon;  $NO_x$  nitrogen oxides; NCD non-communicable diseases;  $O_3$  ozone; PM fine particulate matter;  $SO_x$  sulphur oxides; UFP ultrafine particles; WHO World Health Organisation.

## Author contributions

Conception and design: DMcE, CB; Planning: DMcE, CB; Conduct: DMcE; Acquisition of data: DMcE; Analysis and interpretation of data: DMcE, CB; Reporting: DMcE, CB

## Disclosure statement

No potential conflict of interest was reported by the authors.

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## References

- Aydin, S., Ulusoy, S., Cingi, C., San, T., & Orhan, İ. (2014). The effects of air pollutants on nasal functions of outdoor runners. *European Archives of Oto-Rhino-Laryngology*, 271(4), 713–717. <https://doi.org/10.1007/s00405-013-2610-1>
- Bennett, W. D., Zeman, K. L., & Jarabek, A. M. (2003). Nasal contribution to breathing with exercise: Effect of race and gender. *Journal of Applied Physiology*, 95(2), 497–503. <https://doi.org/10.1152/jappphysiol.00718.2002>
- Bos, I., De Boever, P., Vanparijs, J., Pattyn, N., Panis, L., & Meeusen, R. (2013). Subclinical effects of aerobic training in urban environment. *Medicine & Science in Sports & Exercise*, 45(3), 439–447. <https://doi.org/10.1249/MSS.0b013e31827767fc>
- Chimenti, L., Morici, G., Paterno, A., Bonanno, A., Vultaggio, M., Bellia, V., & Bonsignore, M. R. (2009). Environmental conditions, air pollutants, and airway cells in runners: A longitudinal field study. *Journal of Sports Sciences*, 27(9), 925–935. <https://doi.org/10.1080/02640410902946493>
- Cutrufello, P. T., Smoliga, J. M., & Rundell, K. W. (2012). Small things make a big difference: Particulate matter and exercise. *Sports Medicine*, 42(12), 1041–1058. <https://doi.org/10.1007/BF03262311>
- Davies, M., Hungenberg, E., & Aicher, T. (2018). The relationship between runner environmental paradigm and their motives to participate in an urban or rural marathon. *International Journal of Event and Festival Management*, 10(1), 48–66. <https://doi.org/10.1108/IJEFM-02-2018-0013>
- De Sá M, C., Nakagawa, N. K., De André Cd, S., Carvalho-Oliveira, R., De Santana Carvalho, T., Nicola, M. L., de André, P. A., Nascimento Saldiva, P. H., & Vaisberg, M. (2016). Aerobic exercise in polluted urban environments: Effects on airway defense mechanisms in young healthy amateur runners. *Journal of Breath Research*, 10(4), 046018. <https://doi.org/10.1088/1752-7163/10/4/046018>
- Dirks, K. N., Sharma, P., Salmond, J., & Costello, S. B. (2012). Personal exposure to air pollution for various modes of transport in auckland, New Zealand. *The Open Atmospheric Science Journal*, 6(1), 84–92. <https://doi.org/10.2174/1874282301206010084>
- El Helou, N., Tafflet, M., Berthelot, G., Tolaini, J., Marc, A., Guillaume, M., Hausswirth, C., & Toussaint, J. -F. (2012). Impact of environmental parameters on marathon running performance. *Plos One*, 7(5), e37407. <https://doi.org/10.1371/journal.pone.0037407>
- Ferdinands, J. M., Crawford, C. A. G., Greenwald, R., Van Sickle, D., Hunter, E., & Teague, W. G. (2008). Breath acidification in adolescent runners exposed to atmospheric pollution: A prospective, repeated measures observational study. *Environmental Health: A Global Access Science Source*, 7(1), 10. <https://doi.org/10.1186/1476-069X-7-10>
- Gomes, E. C., Stone, V., & Florida-James, G. (2010). Investigating performance and lung function in a hot, humid and ozone-polluted environment. *European Journal of Applied Physiology*, 110(1), 199–205. <https://doi.org/10.1007/s00421-010-1485-8>
- Gourd, E. (2022). New evidence that air pollution contributes substantially to lung cancer. *The Lancet Oncology*, 23(10), e448. [https://doi.org/10.1016/S1470-2045\(22\)00569-1](https://doi.org/10.1016/S1470-2045(22)00569-1)
- Guo, M., & Fu, S. (2019). Running with a mask? The effect of air pollution on marathon runners' performance. *Journal of Sports Economics*, 20(7), 903–928. <https://doi.org/10.1177/1527002518822701>
- Hodgson, J. R., Chapman, L., & Pope, F. D. (2021). The Diamond League athletic series: Does the air quality sparkle? *International Journal of Biometeorology*, 65(8), 1427–1442. <https://doi.org/10.1007/s00484-021-02114-z>
- Hodgson, A., & Hitchings, R. (2018). Urban air pollution perception through the experience of social practices: Talking about breathing with recreational runners in London. *Health & Place*, 53, 26–33. <https://doi.org/10.1016/j.healthplace.2018.07.009>
- Kaur, A., Singla, S., Bansal, D. (2017). Quantifying personal exposure to spatio-temporally distributed air pollutants using mobile sensors. *Proceedings of the First ACM Workshop on Mobile Crowdsensing Systems and Applications*, Delft, Netherlands.
- Laumbach, R. J., & Cromar, K. R. (2022). Personal interventions to reduce exposure to outdoor air pollution. *Annual Review of Public Health* 43(1), 293–309. <https://doi.org/10.1146/annurev-publhealth-052120-103607>
- Laurino, M., Lomonaco, T., Bellagambi, F. G., Ghimenti, S., Messeri, A., Morabito, M., Marrucci, E., Pratali, L., & Trivella, M. G. (2021). Sport in town: The smart healthy ENV project, a pilot study of physical activity with multi-parametric monitoring. *International Journal of Environmental Research and Public Health*, 18(5), 2432. <https://doi.org/10.3390/ijerph18052432>
- Lv, G., Lv, G., Ms, K., & Ms, K. (2014). The health effects of exercising in air pollution. *Sports Medicine*, 44(2), 223–249. <https://doi.org/10.1007/s40279-013-0108-z>
- Marr, L. C., & Ely, M. R. (2010). Effect of air pollution on marathon running performance. *Medicine and Science in Sports and Exercise*, 42(3), 585–591. <https://doi.org/10.1249/MSS.0b013e3181b84a85>
- Nielsen Sports. Recreational running: Consumer research study: Nielsen sports; 2021 [cited 20/11/2022]. Available from: <https://assets.aws.worldathletics.org/document/60b741d388549ceda6759894.pdf>.
- Ouzzani, M., Hammady, H., Fedorowicz, Z., & Elmagarmid, A. (2016). Rayyan - a web and mobile app for systematic reviews. *Systematic Reviews*, 5(1), 210. <https://doi.org/10.1186/s13643-016-0384-4>
- Pasqua, L. A., Damasceno, M. V., Cruz, R., Matsuda, M., Garcia Martins, M., Lima-Silva, A. E., Marquezini, M., Saldiva, P., & Bertuzzi, R. (2018). Exercising in air pollution: The cleanest versus dirtiest cities challenge. *International Journal of Environmental Research and Public Health*, 15(7), 1502. <https://doi.org/10.3390/ijerph15071502>

- Pun, V. C., & K-F, H. (2019). Blood pressure and pulmonary health effects of ozone and black carbon exposure in young adult runners. *The Science of the Total Environment*, 657, 1–6. <https://doi.org/10.1016/j.scitotenv.2018.11.465>
- Qin, F., Yang, Y., Wang, S. T., Dong, Y. N., Xu, M. X., Wang, Z. W., & Zhao, J. -X. (2019). Exercise and air pollutants exposure: A systematic review and meta-analysis. *Life Sciences*, 218, 153–164. <https://doi.org/10.1016/j.lfs.2018.12.036>
- Research NIO H. PROSPERO International prospective register of systematic reviews York: Centre for reviews and dissemination, University of York; 2022 [cited 20/02/2022]. Available from: <https://www.crd.york.ac.uk/prospero/>.
- Rundell, K. W., Slee, J. B., Caviston, R., & Hollenbach, A. M. (2008). Decreased lung function after inhalation of ultrafine and fine particulate matter during exercise is related to decreased total nitrate in exhaled breath condensate. *Inhalation Toxicology*, 20(1), 1–9. <https://doi.org/10.1080/08958370701758593>
- Santos, J., Foster, R., Jonckheere, A. C., Rossi, M., Luna Junior, L. A., Katekaru, C. M., de Sá, M. C., Pagani, L. G., Almeida, F. M. D., Amaral, J. D. B., Vieira, R. D. P., Bachi, A. L. L., Bullens, D. M. A., & Vaisberg, M. (2019). Outdoor endurance training with air pollutant exposure versus sedentary lifestyle: A comparison of airway immune responses. *International Journal of Environmental Research and Public Health*, 16(22), 4418. <https://doi.org/10.3390/ijerph16224418>
- Smart, N. R., Horwell, C. J., Smart, T. S., & Galea, K. S. (2020). Assessment of the wearability of facemasks against air pollution in primary school-aged children in London. *International Journal of Environmental Research and Public Health*, 17(11), 3935. <https://doi.org/10.3390/ijerph17113935>
- Tainio, M., Jovanovic Andersen, Z., Nieuwenhuijsen, M. J., Hu, L., de Nazelle, A., An, R., Garcia, L. M. T., Goenka, S., Zapata Diomedi, B., Bull, F., & Sá, T. H. D. (2021). Air pollution, physical activity and health: A mapping review of the evidence. *Environment International*, 147, 105954. <https://doi.org/10.1016/j.envint.2020.105954>
- Tricco, A. C., Lillie, E., Zarin, W., O'brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C. . . . Straus, S. E. (2018). PRISMA extension for scoping reviews (PRISMA-Scr): Checklist and explanation. *Annals of Internal Medicine*, 169(7), 467–473. <https://doi.org/10.7326/M18-0850>
- UK Air Pollution Information System. UK air pollution information system. 2022 [cited 24/11/2022]. Available from: <https://www.apis.ac.uk>.
- United Nations. 68% of the world population projected to live in urban areas by 2050, says UN; 2018 [cited 12/02/2020]. Available from: <https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html>.
- Wagner, D. R., & Brandley, D. C. (2020). Exercise in thermal inversions: PM(2.5) air pollution effects on pulmonary function and aerobic performance. *Wilderness & Environmental Medicine*, 31(1), 16–22. <https://doi.org/10.1016/j.wem.2019.10.005>
- World Health Organisation. Billions of people still breathe unhealthy air: New WHO data 2022 [cited 13/12/2022]. Available from: <https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data>.
- Zoladz, J. A., & Nieckarz, Z. (2021). Marathon race performance increases the amount of particulate matter deposited in the respiratory system of runners: An incentive for “clean air marathon runs”. *Peer Journal: Life and Environment*, 9, e11562. <https://doi.org/10.7717/peerj.11562>