Air pollution abatement from Green-Blue-Grey infrastructure

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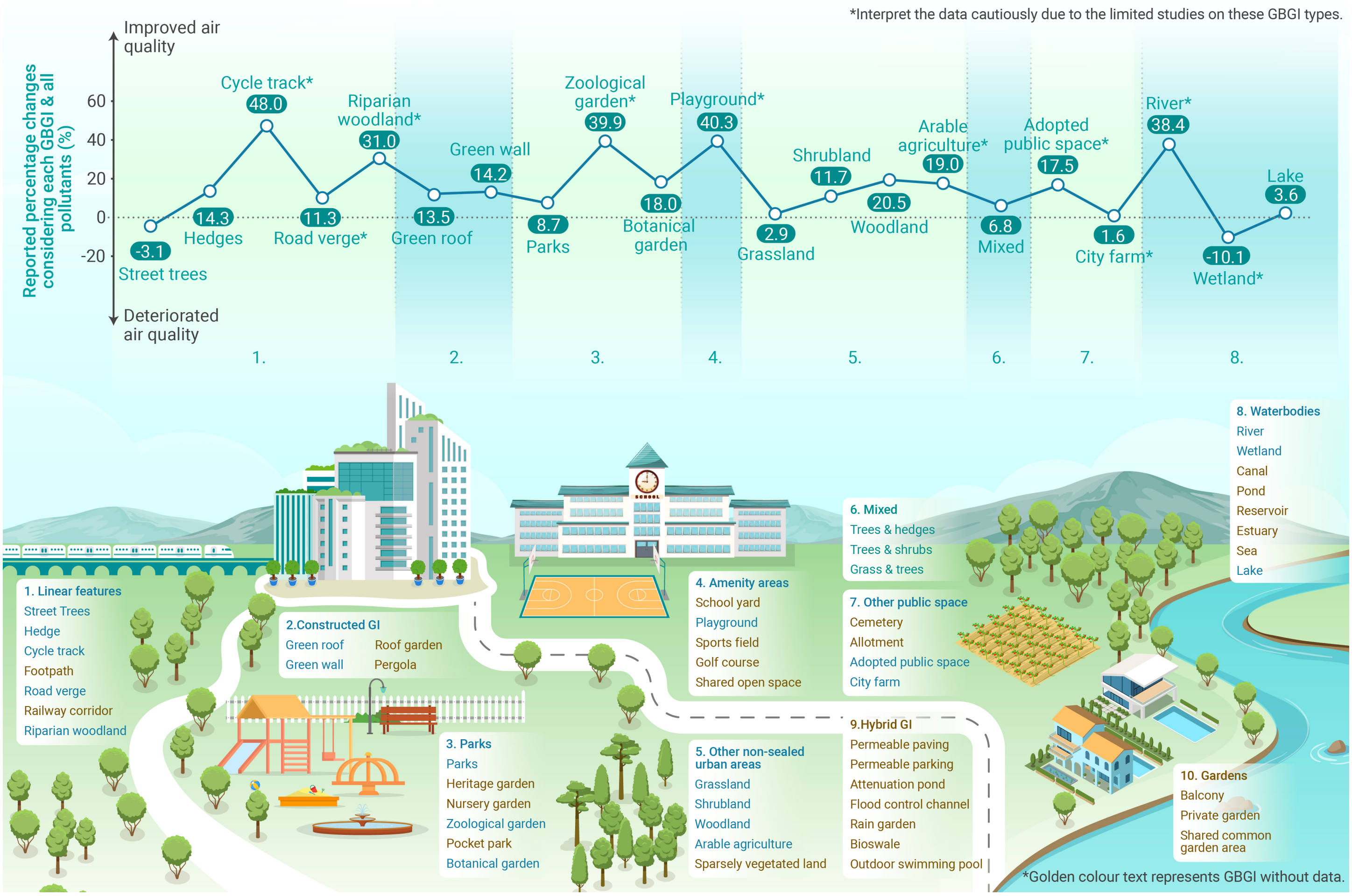
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Review evaluated diverse green-blue-grey infrastructure (GBGI) to abate air pollution.
- Only 22 out of 51 GBGI types assessed provided relevant air pollution efficacy data.
- Street trees are the most studied GBGI: 61% in street canyons, 18% in open roads, and 21% elsewhere.
- GBGI mitigation is dominated by deposition at the city-scale and dispersion along roads.
- Meta-analysis highlighted inconsistent reporting of results to enable direct comparisons.

REVIEW

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Prashant Kumar,[1,2,3,4,*] Karina Corada,[5] Sisay E. Debele,[1] Ana Paula Mendes Emygdio,[1] KV Abhijith,[1] Hala Hassan,[6] Parya Broomandi,[7,8] Richard Baldauf,[9,10] Nerea Calvillo,[11] Shi-Jie Cao,[1,4] Sylvane Desrivières,[12] Zhuangbo Feng,[4] John Gallagher,[3,13] Thomas Rodding Kjeldsen,[14] Anwar Ali Khan,[15] Mukesh Khare,[16] Sri Harsha Kota,[16] Baizhan Li,[17] Shelagh K Malham,[18] Aonghus McNabola,[1,3] Anil Namdeo,[19] Arvind Kumar Nema,[16] Stefan Reis,[20] Shiva Nagendra SM,[21] Abhishek Tiwary,[22] Sotiris Vardoulakis,[23] Jannis Wenk,[14] Fang Wang,[24,25] Junqi Wang,[4] Darren Woolf,[26] Runming Yao,[17,27] and Laurence Jones[28,29]

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Green-blue-grey infrastructure (GBGI) offers environmental benefits in urban areas, yet its impact on air pollution is under-researched, and the literature fragmented. This review evaluates quantitative studies on GBGI's capability to mitigate air pollution, compares their specific pollutant removal processes, and identifies areas for further investigation. Of the 51 GBGI types reviewed, only 22 provided quantitative pollution reduction data. Street trees and mixed-GBGI are the most studied GBGIs, with efficacy influenced by wind, GBGI type vegetation characteristics, and urban morphology. Negative percentages denote worsening air quality, while positive reflect improvement. The 22 different GBGI grouped into eight main categories provide an average (± s.d.) reduction in air pollution of 16 ± 21%, with substantial reduction shown by linear features (23 ± 21%), parks (22 ± 34%), constructed GI (14 ± 25%), and other non-sealed urban areas (14 ± 20%). Other individual GBGI reducing air pollutants include woodlands (21 ± 38%), hedges (14 ± 25%), green walls (14 ± 27%), shrubland (12 ± 20%), green roofs (13 ± 23%), parks (9±36%), and mixed-GBGI (7 ± 23 %). On average, GBGI reduced PM_1, $PM_{2.5}$, PM_{10}, UFP and BC by 13 ± 21%, 1 ± 25%, 7 ± 42%, 27 ± 27%, and 16 ± 41%, respectively. GBGI also lowered gaseous pollutants CO, O_3 and NO_x by 10 ± 21%, 7 ± 21%, and 12 ± 36%, on average, respectively. Linear (e.g., street trees and hedges) and constructed (e.g., green walls) features can impact local air quality, positively or negatively, based on the configuration and density of the built environment. Street trees generally showed adverse effects in street canyons and beneficial outcomes in open-road conditions. Climate change could worsen air pollution problems and impact GBGI effectiveness by shifting climate zones. In Europe and China, climate shifts are anticipated to affect 8 of the 22 GBGIs, with the rest expected to remain resilient. Despite GBGI's potential to enhance air quality, the meta-analysis highlights the need for a standardised reporting structure or to enable meaningful comparisons and effectively integrate findings into urban pollution and climate strategies.

INTRODUCTION

By 2050, 70% of the world's population is expected to live in urban areas.[1] This would aggravate the role of air pollution as a health concern, which already causes 8.8 million premature deaths annually.[2] The World Health Organization (WHO) has set guidelines for particulate matter (PM) and gaseous pollutants, which were recently updated due to the urban air quality crisis.[3] These guidelines have influenced national and city-specific policies, such as London's congestion charge and ultra-low emission zone.[4]

Green and blue infrastructure, recognised as nature-based solutions are crucial for sustainable and resilient urban planning.[5-7] They can reduce air pollution and offer co-benefits, such as mitigation of urban heat islands and flood risks, noise reduction, enhancement of aesthetics and biodiversity and improvement of health and well-being.[8-16] Supplementary Information (SI) Section S1 provides further details about the urgency of addressing urban air pollution and the potential use of GBGI to help reduce exposure.

The European Union Green Infrastructure Strategy defines GI as a network of green or blue spaces providing diverse ecosystem services.[17] GI encompasses a fusion of green and blue infrastructure, and when integrated with

Table 1. Summary of relevant review papers from 2015 onwards discussing air pollution reduction potential of various GBGI types. Reviews on other benefits and services of GBGIs are not included.

Focus and key findings	GBGI type	Review
Assessed five methods that evaluate the effectiveness of the particle air pollution removal by urban vegetation, regarding their suitability, quality and sustainability. Provided the groundwork for a standardised approach to quantify this ecosystem service.	Urban vegetation	Vigevani *et al.*[34]
Analysed the influence of different vegetation characteristics to identify the key factors affecting the removal of urban pollutants.	Vegetation (trees, hedges, herb, liana)	Lindén *et al.*[35]
Performed bibliometric analysis on the research structure dealing with microclimate and air quality, mainly focusing on modelling studies, and provided trends and significant research focus areas.	Greening systems	Ernst *et al.*[31]
Focused on particulate matter (PM) removal by green wall and factors affecting the PM capture. The leaf hairiness, size and roughness enhanced PM capture in green walls.	Green wall, living wall system	Hellebaut *et al.*[33]
Assessing air pollution impacts on vegetation, noting a bias towards certain crop species while emphasising the need for diverse experimental setups and plant health parameters. It discusses GI role in mitigating pollution, highlighting its potential to address air quality issues in urban areas.	Vegetation (climbers, shrubs, and trees)	Pratibha Anand *et al.*[36]
Analysed PM mitigation of green walls in neighbourhood and street canyon scales. PM removal potential of the green wall depended on species type, pollution concentration, residence time and rainfall.	Living wall system, Green façade	Ysebaert *et al*[29]
Reviewed three main PM mitigation mechanisms of green spaces in urban areas. The PM removal potential of green spaces differs by scale, context and vegetation characteristics, and these factors must be considered while designing public green spaces.	Green space	Diener and Mudu[30]
Discussed the impact of various GI types on air quality in street canyons, focusing on removal mechanisms and measurement methods. Quantified air pollution reduction by various GI types in street canyon environments and identified the limited research on GI, such as green walls and roofs.	Green walls, green screens, trees, hedges, green roof	Tomson *et al.*[23]
Assessed the association of leaf trait features on PM capture and compared different GI types. Recommended considering GI characteristics (type, species, leaf traits), meteorological conditions, and built environment configurations to maximise PM removal.	Street trees Green wall Green roof	Corada *et al.*[37]
Provided key recommendations for effective vegetation barrier design by considering the GI influence in spatial scales, built environment configurations, and species-specific plant morphological features. Listed recommendations on GI for improving air quality and plant selection system for UK urban system.	Vegetation barriers	Barwise and Kumar[19]
Examined PM removal by urban forests. The PM removal by urban forests and trees varies at spatial scales. Morphological features of leaves and built environment configurations influenced PM removal.	Urban Forest Single tree, tree stands	Han *et al.*[32]
Investigated air quality enhancement of trees, urban parks and urban forests on different scales. Indicated the complexity of air quality and GI interaction in different scales and key mechanisms of air pollution removal.	Urban parks, Street trees, Urban Forest	Xing and Brimblecombe.[38]
Evaluated PM reduction by various GI types and quantified retention, resuspension and wash-off from plant leaves. Suggested a standardised evaluation system for PM removal based on retained PM wash-off mass.	Tree, shrub, herbs, grass, living wall, green roof	Xu *et al.*[39]
Investigated hedges' environmental benefits and disbenefits in an urban built environment. Hedge species positively impact air quality, pollution capture, biodiversity, noise mitigation, urban water management, and health and wellbeing.	Hedge	Blanusa *et al.*[40]
Quantified the O_3 removal capacity of trees, shrubs, and green roofs and ranked plant species based on the ability to improve air quality. Recommended proper species selection, planning and cost-benefit analysis for maximising GI benefits.	Urban Trees, Urban forests, Green roofs	Sicard *et al.*[41]
Evaluated air pollution reduction potentials of various GI in urban built environments and listed factors affecting urban air quality such as urban morphology, meteorological conditions, and vegetation characteristic. The study recommended vegetation design considerations based on a quantitative assessment of GIs.	Trees, hedges, green wall, green roof, vegetation barriers, solid wall/vegetation barriers.	Abhijith *et al.*[42]
Assessed the limitations and strength of trees and vegetation in improving and deteriorating urban air quality. A combination of tree characteristics, built environment configuration and meteorological conditions determined the improvement in air quality.	Trees and vegetation	Gallagher *et al.*[43]
Provides descriptions of particle pollution deposition and dispersion mechanisms in the presence of GI. Identified key vegetation design considerations to improve air quality.	Vegetation (trees and hedges), parks	Janhäll.[44]

built grey components (such as green walls or canals), it is termed green-blue-grey infrastructure (GBGI). In the context of this review, our focus lies on the integration of traditional grey infrastructure within the broader context of green-blue infrastructure. In the subsequent text, the terms GI and BI are used when specifically referring to green or blue infrastructure to distinguish them from the overarching term GBGI.

Urban GI examples include street trees, hedges, bushes, gardens, parks, grasslands, green roofs, green walls, vegetation/solid wall combinations, vertical green, and other vegetation arrangements with green-blue-grey infrastructure.[18-20] Blue infrastructure includes rivers, lakes, canals, ponds, fountains, wetlands, rain gardens, bioswales, and other water bodies.[20,21]

Several studies using experimental monitoring and modelling methods have evidenced the effectiveness of GBGIs in improving air quality, from micro-scale (open-road and street canyons) to macro-scale (cities and large

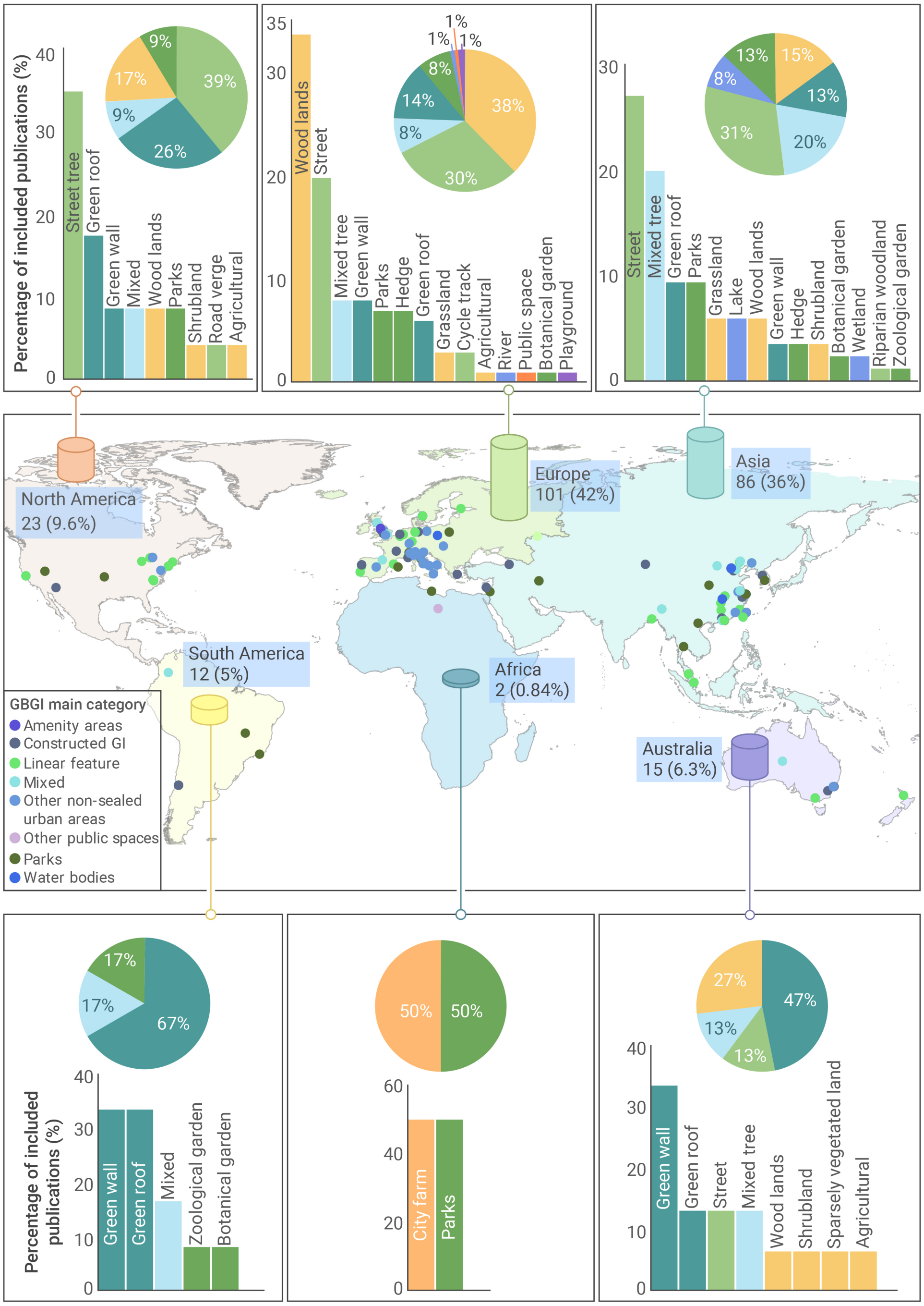

Figure 1. Geographical overview of studies on air quality effects of GBGI, showing the distribution of 242 data represented by 160 studies (one study may report multiple GBGI or locations). The breakdown includes Europe, Asia, North America, South America, Australia, and Africa, represented in both absolute numbers and percentages. The bar plots represent the percentage of GBG subtypes, whereas the pie charts show the percentage of main GBGI types.

parks) assessments, Table 1.[22-24] These studies demonstrate both qualitative and quantitative pollution reduction by different GBGIs, consolidating knowledge on removal mechanisms and factors like meteorological conditions and GBGI-specific characteristics. Detailed reviews have condensed these findings, extending insights into each GBGI type's efficacy and helping to formulate general implementation recommendations.[25-28]

Past reviews consolidated a few GBGI types in specific urban environments, i.e., street canyons or open road conditions.[19,23,29] Moreover, reviews have classified GBGIs using umbrella terms, such as vegetation, vegetation barriers, GI, green space, and urban forest, among others.[30,31] These reviews focused on GBGI's impact in reducing a specific pollutant, mainly PM[32,33] and providing qualitative information on air quality improvement but only limited quantitative evidence. Prior reviews lacked a systematic assessment of diverse GBGIs, pollutants, scales, and study methods for air quality effects. To fill this gap, this review provides comprehensive, quantitative evidence on the effectiveness of various GBGI types, highlights previous investigations on their pollution reduction performance, and identifies poorly understood GBGIs and knowledge gaps.

This work aims to develop a comparative assessment of GBGI's air pollution reduction potential and quantify relative air quality improvements. The objectives are to (i) systematically review studies on GBGI's pollution abatement, (ii) explain GBGI's pollution reduction mechanisms, (iii) assess evaluation complexities considering urban scale, meteorology, and GBGI characteristics, and (iv) identify knowledge gaps and provide implementation recommendations for urban air quality improvement.

Scope and outline

To avoid inconsistencies, this review uses a feature-based typology,[16,20] aggregating 51 GBGI types into ten broad categories. This classification applies to temperate and humid tropical urban systems alike.[16] A new 'mixed-GBGI' category accommodates studies on combined GBGI air quality impacts (e.g., trees and hedges/shrubs/grass)[42]. Definitions of main and subcategories are in Supplementary Information (SI) Table S1.

The scope of this study is limited to existing scientific articles investigating the air pollution reduction potentials of GBGI. The primary consideration is given to various sizes of PM (PM_{10}, $PM_{2.5}$, PM_1) and ultrafine particles (UFP, $PM_{0.1}$), along with black/elemental carbon (BC/EC), nitrogen oxides (NO, NO_2, NO_x), ozone (O_3), sulphur dioxide (SO_2) and carbon monoxide (CO). Other services provided by the GBGI, such as urban overheating, biodiversity, carbon sequestration, stormwater runoff reduction, and mental well-being, as well as the detailed analysis of individual pollutants, including predictions of the performance of GBGI case studies under different climate scenarios, are beyond the scope of this review. Figure S1 shows the procedure for selecting the literature. Figure 1 provides the geographical location of the studies. The available studies under each of the 10 GBGI sub-categories are provided in Figure 2.

This review in Section 3 outlines the systematic literature review (SLR) and meta-analysis methodologies. Section 4 explains removal mechanisms and links GBGI characteristics with air quality improvements. Section 5 discusses complexities in quantifying and comparing the air pollution reduction potentials of various GBGIs. Sections 6 and 7 provide a comprehensive synthesis and meta-analysis of reviewed article subsets. Section 8 discusses climate change' s impact on air pollution and the effectiveness of current GBGI, suggesting future GBGIs for shifting climate conditions. Section 9 highlights knowledge gaps, followed by conclusions and recommendations in Section 10.

MATERIALS AND METHOD

Search criteria and data acquisition

This study followed the PRISMA (Preferred Reporting Items for Systematic

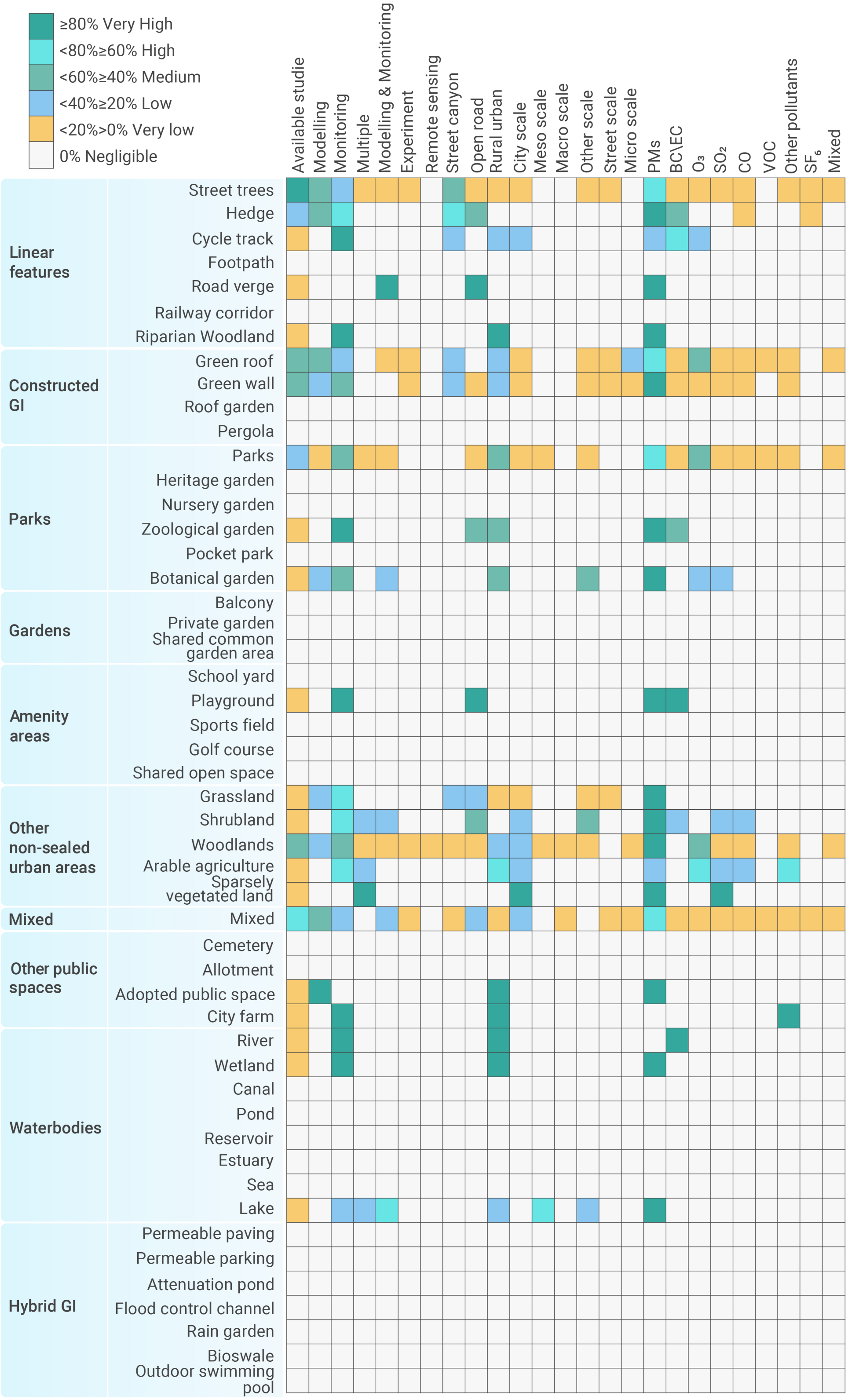

Figure 2. Availability of studies in each of the 51 GBGI categories is represented using a six-point classification scale[16] to colour-coded the percentage of studies examining the impact of GBGI on various air pollutants.

Reviews and Meta-Analysis) methodology to ensure comprehensiveness and achieve its objectives.[45] A four-stage selection process was performed for reviewing and extracting relevant information (Figure S1).

1) *Identification:* Search terms were developed based on the study's aims, GBGI classifications, and relevant scientific terms (Table S2). We systematically searched the Web of Science for pertinent peer-reviewed studies published between 2010 and 2023. This database allowed for accurate search term combinations and effective screening. The search identified 18,108 relevant publications (Figure S1).

2) *Screening and exclusion:* Titles and abstracts were screened to exclude misclassified articles or those lacking relevant quantitative data. Further screening removed duplicates and inaccessible full texts, leaving 722 papers (Figure S1). Non-English articles, those lacking specific GBGI details for any 51 types and studies outside real-world urban settings or without comparators were also excluded. Rapid full-text reading excluded an additional 508 articles.

3) *Eligibility and inclusion:* During the final screening of 214 articles, we eliminated those that did not (i) provide quantitative data on the impact of GBGI on air pollution in relative percentage values or absolute concentrations, (ii) compare the effect of at least one GBGI on air quality with its absence or prior condition, and (iii) describe and characterise the investigated GBGI. This left 160 articles (0.88% of the initially identified papers) for analysis and discussion.

4) *Data extraction:* Data extraction from the included publications covered (i) study location, city and country, site environmental conditions, (ii) GBGI details, including dimensions, physical features, and vegetation species, (iii) methodology of investigation (e.g. study type, unit of measurement, street layouts), (iv) air pollutant details, absolute concentrations, and relative changes with GBGI presence, and (v) key messages and gaps identified by individual studies. Two independent reviewers conducted the data extraction to ensure methodological rigour.[46]

GBGI studies were categorised into three types: monitoring, modelling, and multiple (integrating more than one type, such as modelling and monitoring or remote sensing and experimentation). The data were categorised into four measurement types: concentration, deposition, other (clean air delivery rate, ventilation rates, and filtering efficiencies), and combined. 'Concentration' includes studies reporting airborne pollutant concentrations via direct ambient air measurements, often representing dispersion. 'Deposition' encompasses studies reporting pollutant deposition on leaves, GBGI surfaces, and total pollutant removal (uptake). 'Other' represents studies reporting values, like clean air delivery rate, ventilation rates, and filtering efficiencies. 'Combined' refers to studies reporting concentration and deposition values combined.

To compare studies, we used the percentage change (%) in air pollution in the presence of GBGI. Studies have used different measurement methods and reference points to calculate percentage differences (Sections 5.2 and 5.3). This involves comparing pollutant concentrations behind GBGI to those in front or to a reference area, and in modelling studies comparing scenarios with and without GBGI. The percentage change was either reported directly, or the paper provided a comparator (without GBGI) for which calculations could be conducted to derive the percentage change (%) = $((C_{ref} - C_{GBGI}) / C_{ref})$

x 100. Where C_{ref} is the pollution concentration without intervention of GBGI (comparator value), C_{GBGI} is the pollution concentration with intervention of GBGI (GBGI value). Negative values indicate deterioration (increase in pollutant concentration) and positive values indicate improvement (decrease in pollutant concentration). This convention is used consistently throughout the manuscript. Variation in estimates is expressed as ±s.d. (standard deviation). We also considered the range of percentage changes (minimum and maximum values) alongside averages and standard deviations to understand the full spectrum of GBGI's influence on pollutants. This approach allowed for the comparison of studies with different site-specific characteristics and methodologies (Section 6). We categorised GBGI implementation into four main Köppen climate zones: temperate, continental, dry, and tropical, along with 30 sub-climate types (Figure S2). Additionally, we analysed the migration of GBGI systems between different Köppen-Geiger zones under present and future climate conditions (Section 8), using the largest emission scenario (RCP8.5), for the periods 2041–2070 and 2071–2100.[47]

Data analysis

A bibliometric analysis was performed using VOSviewer software version 1.6.19[48] for quantitative and qualitative analysis to identify trends from the selected papers.[49] Keywords were extracted via VOSviewer and a matrix created based on their frequency, co-occurrence and similarity.[50] Keywords with high similarity and co-occurrence were grouped closely together, while less similar ones were spaced further apart.[48]

A meta-analysis consolidated results from diverse GBGI studies, providing a comprehensive overview of their impact on air pollution mitigation. This analysis quantified effect sizes and identified factors influencing the effectiveness of abatement strategies.[51,52] Stringent inclusion criteria required at least three studies per GBGI category for each pollutant, along with statistics, including mean, standard deviation, and sample size.[51,52] Studies on deposition did not meet the meta-analysis criteria, which focused instead on ambient air pollution concentration. More details are in Section S2.

Both fixed and random effects models were initially used to account for variability among studies using meta-analysis software (version 4.0) for each GBGI type. Heterogeneity was assessed with I^2 statistics, with values over 40% indicating significant heterogeneity.[53-55] The random-effects model was chosen for GBGI with fewer than five studies or notable diversity.[51] Forest plots visualised effect estimates and 95% confidence intervals (CIs) for both pooled results and individual studies.[51,56,57] Statistical significance was determined by a p-value <0.05. Publication bias was evaluated using funnel plots and Egger's regression tests, with the trim-and-fill method employed as needed.[52] When publication bias was detected, only imputed estimates were reported, urging careful interpretation due to potential study variation.[58,59]

RESULTS

Mechanisms of air pollution removal by GBGI

Pollutant removal by green infrastructure. The mechanisms of air pollutants removal by GI are generally grouped into two main processes: dispersion and deposition.[30,35,44] The term dispersion (also known as aerodynamic effect, or aerodynamic dispersion) refers to the advection, diversion, and diffusion of air pollutants, mainly for PM.[44,60] Dispersion is influenced by both atmospheric (irregular, large scale random air motions, air motions characterised by winds that vary in speed and direction) and mechanical (friction between air and surface roughness of GI features) turbulence. Deposition involves PM transferring from the air to (plant) surfaces, either settling or penetrating cell membranes, sometimes absorbed through stomata.[44] Dry deposition is influenced by pollutant and leaf (surface) characteristics, represented by the leaf area index (LAI; leaf area/ground area in $m^2\ m^{-2}$) or leaf area density (LAD; leaf area/unit volume in $m^2\ m^{-3}$).

Modelling studies integrate GI characteristics and various atmospheric processes into simulations, varying by model complexity and application scale.[22] At the macroscale (city level), GI-induced turbulence is understudied, but preliminary work suggests it increases surface roughness, reducing ground-level pollutant concentrations in the atmospheric boundary layer.[22] Deposition schemes in air transport models use empirical equations to estimate accumulated pollutants on (leaf) surfaces.[44] GI simulations consider aerodynamic effects, pollutant deposition, and surface roughness impacting turbulence.

At the microscale, roadside GIs barriers like hedges significantly reduce personal exposure.[61] At the macroscale, urban forests, parks, gardens, and hedges collectively enhance atmospheric dispersion and act as sinks for particles through dry deposition on leaves. Most field studies do not clearly distinguish between dispersion and deposition, but understanding their relative contributions is essential for effective GI implementation in air pollution mitigation. Identifying specific contributions require carefully designed experiments.

Due to the ambiguity in the literature regarding whether dispersion or deposition is reported, we categorised the identified papers into 'concentration,' 'deposition,' 'combined,' and 'other' groups (Section 3.1). Of the studies reviewed, 73% studied concentration, 18% focused on deposition, 8% reported both and (1%) presented 'other' measurements (Figure 3 &Table S3).

(1) Deposition effects

GBGI studies on deposition mechanism focus on calculating mass removal and settling velocities on leaf surfaces.[44,62-64] These studies quantify deposition by measuring PM retention on leaf samples using imaging[65-67], sampling at different distances from vegetation and source[68,69], characterising particles[70] and using deposition models with species-specific parameters.[71-73] Key vegetation attributes describe include LAI or LAD.[44] High vegetation density provides a larger surface area for direct deposition[74], but it can also deflect air, preventing pollutant transport to leaf surfaces.[42,44,75,76] Proximity to pollution sources increases vegetation exposure and deposition rates.[29,75,77,78] Particle capture and retention are extensively researched commonly using LAI and LAD methodologies.

The most studied GBGI for deposition are green walls, woodland, street trees, and green roofs. Deposition is a size-dependent removal process for the PM.[39,44,79] Large particles >20 μm are removed by gravitational sedimentation, while smaller particles (1-20μm) are deposited through interception and impaction.[23,35] Research predominantly focuses on particle capture and retention dominates the deposition dialogue[65,67,68,80-82], with fewer studies on deposition of sub-micron particles (PM_1) and gaseous pollutants absorption.[41,68,83-85] Recent studies show that leaf micro-structures (size, folds, uneven surface, grids, pores/stomata) influence particle retention.[67]

However, leaf traits aiding PM retention are still under study. Traits like roughness and hairiness, typically considered beneficial for PM removal, may actually hinder the net removal over time. A recent study found that roughness has a minor influence on plant-specific PM reduction, with stomatal features playing a more significant role.[86] Positive correlations between PM deposition and feathery leaf shape as well as the leaf wax content were shown.[65] PM capture rate varies significantly among plant species based on leaf size, orientation, and size fraction.[39,87] Studies on green walls reveal species with small leaves and high LAI have higher PM capturing capacity, mainly on the adaxial leaf surface.[87-89] Leaf shape also influences PM capture capability.[86,90] For instance, roadside plant species with needle leaves (e.g., *Taxus baccata*) retain more PM than broad leaves under high traffic emission,[91] likely due to the thin boundary layer created by narrow, long needles.[92]

The removal of gaseous pollutants (e.g., O_3 and NO_x) by GI has been investigated using various modelling tools (e.g., iTree Eco, WRF-Chem, CFD models, ENVI-met, EMEP)[36,93-98] and air quality sensors.[93-98] Weather conditions significantly influence the efficacy of GI in reducing gaseous pollutants.[91,101-105] The density of leaf stomata controls the absorption or release of gaseous pollutants.[106] There is insufficient evidence on the absorption process through stomata across different plant species, indicating substantial research gaps for future studies.

(2) Dispersion effects

The impact of GI on dispersion depends on wind conditions, GI features (vegetation species, porosity, and dimensions), and street layouts.[76,103,107,108] Some studies used real-time measurements to detect pollutant reduction downwind of green spaces[109,110], but most employed modelling approaches with various vegetation configurations and land cover scenarios to simulate pollutant dispersion.[111] These investigations primarily focus on local scales, with few evaluating a neighbourhood scale. Models typically assess the effect of vegetation on the dispersion of traffic emissions in street canyons and open-road sections.[112] The dispersion of air pollutants is influenced by street geometry and meteorological conditions, which can either enhance or hinder

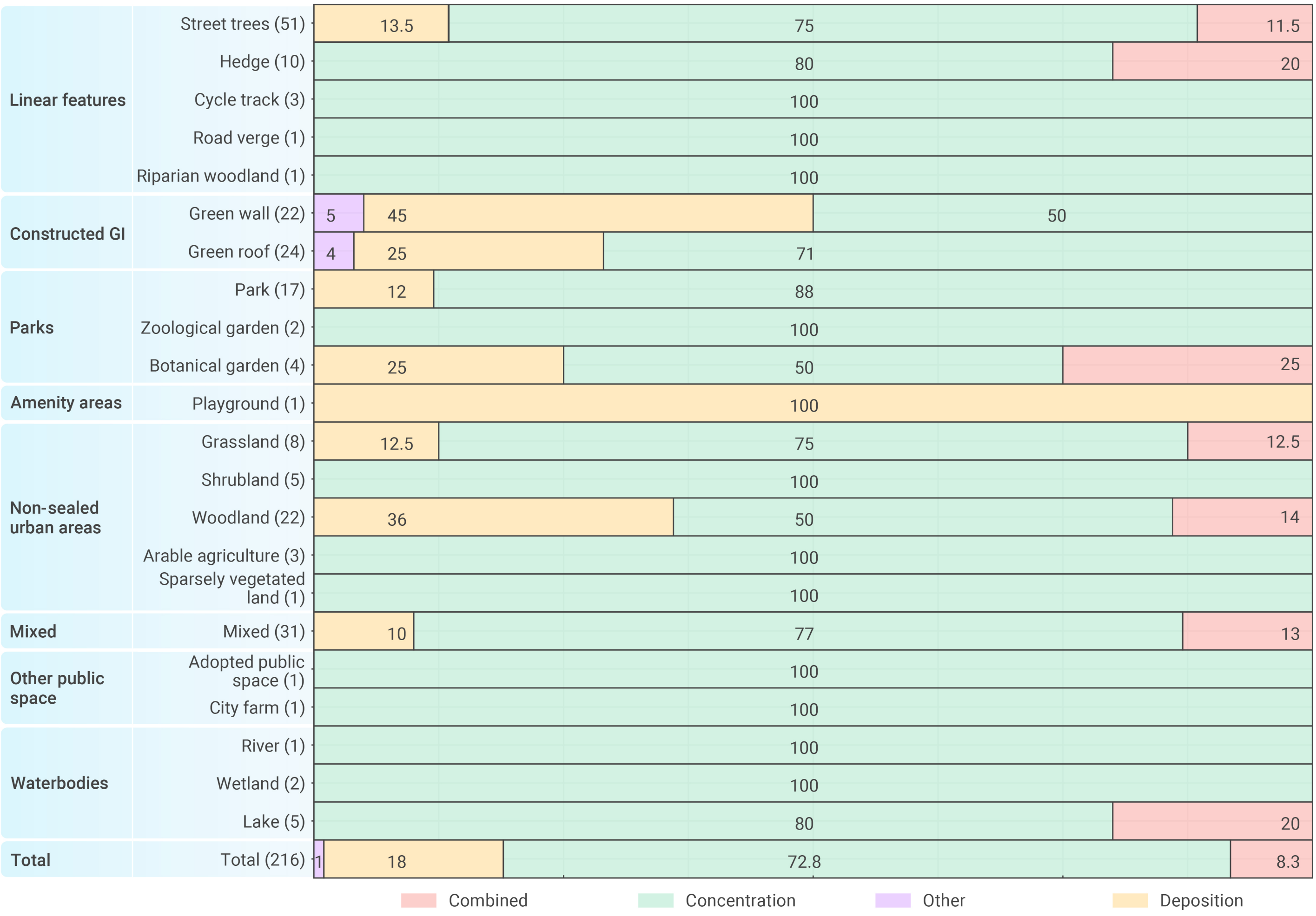

Figure 3. Percentage of studies showing the removal mechanism used for different GBGI categories. The number in the parenthesis next to GBGI feature types provides total studies available for classification. The details of studies are given in Table S3.

pollutant dispersion. [98,103,113-117] The physical features of open roads, such as topography and local weather, also impact air quality.[112]

Street trees and mixed-GBGI are most studied in relation to dispersion, followed by green roofs, parks, green walls and woodlands. Studies of street canyons show that green barriers reduce wind speeds, preventing traffic emissions from reaching pavements.[107,108] Trees increase PM concentrations upwind due to reduced mixing in the street canyons[25,103,118-120] but decrease downwind concentrations of smaller particles with high deposition velocity.[83] On open roads, vehicle turbulence and built structures improve mixing, alleviating concerns about elevated PM concentrations near trees. Wind speed affects gaseous pollutant absorption; at speeds below 2 m s^{-1}, trees can reduce the CO$_2$ concentrations 2.5%, although tree resistance can limit gas dispersion.[121] Tree placement along roads significantly influences wind patterns and dispersion capacity, especially under parallel wind conditions.[122]

Three common wind directions in street canyons are parallel (0°), perpendicular (90°), and oblique (45°)[111,122,123], with the least pollution reduction under oblique winds. [61,114,124] Green roofs reduce PM$_{2.5}$ during parallel winds,[125] while green screens were effective only below 2 m on the pavement.[125] The impact of GI along open roads is ambiguous; as mixed-GBGI, parks, street trees, and hedges can either worsen[18,61,77,101,126-129] or improve[18,74,77,109,127] air quality depending on wind direction and vegetation characteristics like height, thickness, density, and leaf maturity.[18,127] Indeed, recent studies have identified factors, such as LAD, and tree height influenced the concentration on the windward side under perpendicular and oblique wind directions, while LAD and crown diameter affected the concentration on the leeward side of the street.[98,103,104,130] The impact on the leeward footpath is closely linked to specific wind speeds and tree spacing.[103]

Hedges reduce pedestrian-side pollutant concentrations by allowing air passage and being closer to emission sources.[108] A CFD study on UK hedges showed porous hedges are better at removing "coarse" particles (10–20 μm), while denser hedges are more effective for "fine" particles (0.5–3.5 μm).[131] Conifer trees increase turbulent flow and provide more surface for deposition compared to deciduous trees or grassland.[60,74] Using different vegetation heights in roadside barriers can prevent airflow blockage and reduce pavement pollutant concentrations.[108,132]

In parks, dispersion is the dominant mechanism for reducing traffic emissions, especially when background concentrations are disregarded.[95,133,134] When modelling includes background concentrations, deposition effects are amplified for pollutants with high deposition velocity (e.g., 0.64 m s^{-1} for PM$_{10}$ and 0.3 m s^{-1} for VOC), while dispersion remains the dominant mechanism for pollutants with low deposition velocity (e.g., 0.00003-0.00034 m s^{-1} for CO and 0.03 m s^{-1} for NO$_x$).[95,135] Benefits of urban parks diminish with distance as air mixes with additional emissions.[133,136]

Pollutants removal by blue infrastructure. Limited studies explore the impact of blue infrastructure on air pollution reduction, focusing mainly on PM patterns around urban lakes and wetlands, with few details on removal dynamics.[137-139] Evidence suggests that lakes reduce PM concentrations.[83,141,144] For example, Zhou et al.[139] used a WRF-UCM model to find negative correlations between PM$_{2.5}$ concentrations and water surface area, varying by lake location and size. In downtown areas PM$_{2.5}$ levels decreased with more water surface, while in suburban areas, lakes larger than 60 km^2 showed a 6-13% higher PM$_{2.5}$ concentration compared to land surfaces, indicating a blocking effect on particles import from outside the city. In downtown areas, PM$_{2.5}$ levels decreased with more water surfaces, while in suburban areas, lakes larger than 60 km^2 showed a 6-13% higher PM$_{2.5}$ concentration compared to land surfaces, indicating a blocking effect on particles

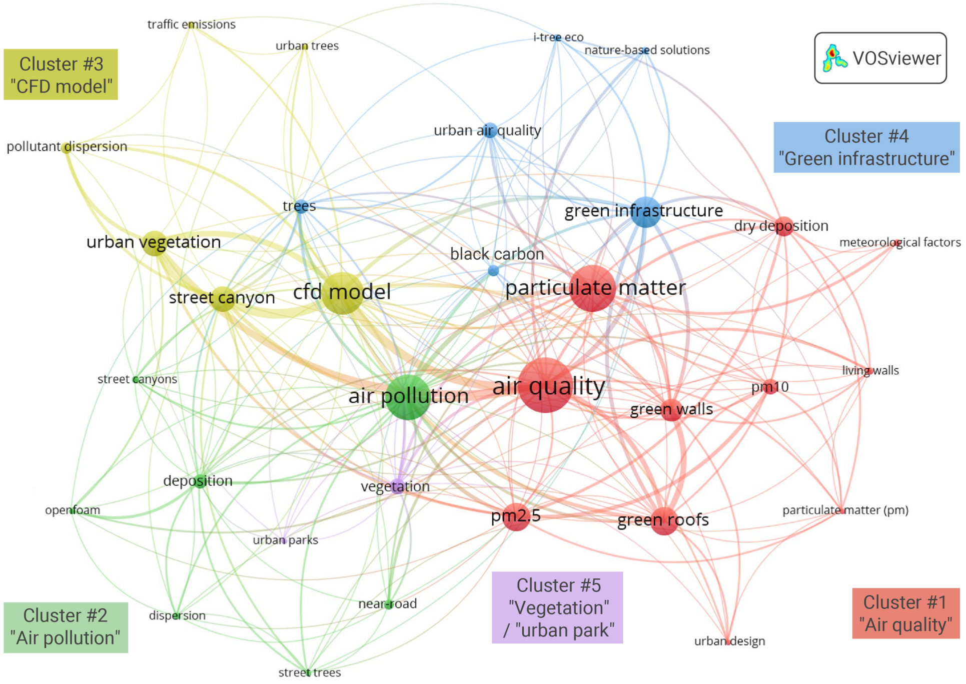

Figure 4. Mapping co-occurrence keyword network. The main keywords that appear most frequently in the studied have been grouped into five clusters: Cluster #1 (with main key word "Air quality"), Cluster #2 ("Air pollution"), Cluster #3 ("CFD model"), Cluster #4 ("Black carbon"), and Cluster #5 ("vegetation" / "urban park").

imported from outside the city. This blocking effect is caused by the lake breeze circulation, which transfers the particles from the surface of the surrounding land to accumulate right above the water surface, a phenomenon that has been reported by other studies for gaseous pollutants such as ozone.[141] For lakes smaller than 50 km^2, the correlation was weaker.[139] This study also noted that water bodies increase the planetary boundary layer height at night, aiding PM$_{2.5}$ dispersion.

Wetlands can reduce airborne PM concentrations due to increased relative humidity.[142] Monitoring studies, such as those at 16 urban lake wetlands in Wuhan, show PM reductions with increased green space and humidity.[137] At high humidities, PM undergoes hygroscopic growth, making the size of particles larger, thus settling more easily. Deposition velocity is a key parameter in particle transport models. Atmospheric dispersion models like the Community Multiscale Air Quality Model (CMAQ), the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem), and the Urban Airshed Model (UAM) consider hygroscopic growth and adjust deposition velocity.[143] However, dedicated studies on GBGI modelling in this context are still scarce.

Green spaces around and alongside rivers or lakes can potentially reduce PM. The PM$_{2.5}$/PM$_{10}$ ratio was found to be significantly lower at 1 m from a river compared to 6 m and 11 m due to the hygroscopic growth of PM$_{2.5}$ and particle coagulation.[129] Changes in lake breeze circulation affect the pollutant distribution near lakes.[144] The strength of the lake breeze is influenced by temperature differences, water body size, and background wind, with larger water bodies creating stronger cold and wet island effects and more pronounced PM blocking effects.[140,144]

A key challenge with blue infrastructure is distinguishing between pollutant removal mechanisms and the naturally lower air pollution levels due to reduced transport emissions and more open spaces, which enhance natural wind dispersion. Further studies are needed to understand how blue infrastructure specifically removes air pollution.

Grey Infrastructure. Grey infrastructure such as low-boundary walls, noise barriers, and street ventilation systems primarily affect air quality through enhanced dispersion and mixing of pollutants.[145-149] For example, sound walls located along roadways have been shown to decrease downwind air pollutant concentrations by as much as 50%, depending on the pollutant.[150-153] Grey infrastructure can also be implemented as passive techniques to improve air quality through the use of low boundary walls in urban street canyons, location and type of building designs, and even street parking designs.[43] Key considerations for the use of grey infrastructure are heights of structures and locations relative to where people are exposed to air pollution. Some pollutant deposition can also occur on certain types of grey infrastructure surfaces either naturally or through coatings, such as TiO$_2$[154,155] although research continues to fully understand the effectiveness of such coatings. A complete review is beyond the scope of this paper.

Navigating complexities: Challenges in assessing the relationship between GBGI and air pollution reduction

Several studies have examined the complex relationship between GBGI and air pollution reduction, considering physicochemical processes, meteorological conditions and built environments.[30,35,156,157] Nineteen of the analysed papers discuss this relationship extensively. [60,73,75,79,81,115,116,138,158-168] Urban pollutants can be absorbed, adsorbed, dispersed or released around GBGI and biogenic volatile organic compounds (bVOCs) from vegetation add complexity by contributing to ground-level ozone and secondary organic aerosols (SOA). bVOC emissions are species-specific and increase at temperatures between 35°C and 40°C, posing a challenge under climate change scenarios.[19] Nine studies analysed bVOC emissions, often viewing them as potential disservice. [41,71,84,95,100,125,166,169,170] Selecting plant species with low bVOC emissions is suggested to avoid secondary pollutants.[100,171] Analysing the impact of bVOC emissions, pollen and other bioaerosols by urban trees[19,172-174] is beyond the scope of this work.

To understand the relationships and prevalent topics in the reviewed studies, a co-occurrence map of 471 keywords (with at least four occurrences each) was created and organised into five clusters (Figure 4). Cluster #1 (11 items) centred on "air quality" linked with "dry deposition", "green roofs", "green walls", "living walls", "meteorological factors", "particulate matter (PM)", "PM$_{10}$" and "PM$_{2.5}$". In Cluster #2 (7 items), focused on "air pollution" and related terms like "deposition", "dispersion", "near-road", "OpenFOAM", "street canyons", and "street trees". Cluster #3 (6 items) associated with modelling techniques, particularly "CFD model". Cluster #4 (6 items) centred on "black carbon", "green infrastructure", and "nature-based solutions". Cluster #5 (2 items) included "urban parks" and "vegetation". The map indicates that research on GBGI primarily focuses on air pollution in urban areas, particularly air quality using GI and modelling techniques, with PM as the main pollutant studied. Other pollutants (e.g., NO$_x$, SO$_2$, O$_3$) were not prominent in the clusters due to their absence as keywords, highlighting the limited number of studies on these pollutants.

Further research is needed on air pollution removal mechanisms through GBGI, and studies on common GIs like trees, green walls, and roofs. No link has been found between blue and grey infrastructures and 'air quality', likely due to limited studies.

The bibliographical analysis highlighted three main challenges in data extraction due to the variability of GBGI in size, vegetation composition, characteristics, and temporal-spatial context: (1) Variety of GBGI types, (2) Scale of the studies, and (3) Methods to assess GBGI effectiveness (Figure 4).

Differentiating across GBGI types. Approximately 95.4% of studies focused on five GBGI types (Figure 1): linear features (28.5%), other non-sealed urban areas (24.7%), constructed GI on grey infrastructure (19.2%), mixed-GBGI (13.0%), and parks (10.0%). The remaining 5.6% of studies focused on water bodies (3.3%), other public spaces (0.8%), and amenity areas (0.4%).

Out of 22 GBGI categories, seven were most studied, comprising 83.7% of the total: street trees (22.2%), woodland (17.6%), mixed-GBGI (13.0%), green roofs (10.0%), green walls (9.2%), parks (7.5%), and hedges (4.2%). The least studied 15 categories made up 16.3%, including shrubland and botanical gardens.

The majority of studies were from Europe (42.0%), followed by Asia (36.0%), focusing mainly on woodland, street trees, and mixed-GBGI. North America (9.6%) primarily studied street trees and green roofs, while South America (5.0%) and Asia (6.3%) focused on green walls and green roofs. Africa (0.84%) had studies on city farms and parks (Figure 1).

This distribution is influenced by several key factors: Europe and Asia (78.0%) show heightened awareness and commitment to addressing air pollution. These regions have been facing significant urbanisation and industrialisation, driving the need for GBGI research and implementation.[175,176] Government policies in Europe and Asia prioritise improving air quality through GBGI development.[175,177] Regions like Europe and China, with greater resources, can conduct comprehensive GBGI research, while the United States also has significant resources and programmes, such as the EPA Green Infrastructure Program and the Department of Transportation's Transportation Alternatives Program to support GBGI efforts.[178]

In Europe, GBGI strategies like integrating GI into urban areas, river restoration projects, sustainable agriculture practices, and biodiversity conservation align with EU environmental goals, including Horizon 2020 and the European Green Deal. The European Commission has launched special programs for GBGI to further support its adoption in rural and urban areas.[179,180]

Similarly, the extensive development of GBGI in Asia addresses challenges arising from rapid urbanisation and population growth. Cultural preferences for green community spaces and environmental goals focused on biodiversity conservation and air quality also drive GBGI initiatives. Government policies prioritising large park creation as part of urban planning and environmental strategies highlight a comprehensive approach to urban development challenges.[181]

The effectiveness of GBGI in reducing air pollution exposure varies based on factors like vegetation density, height, canopy, mix of species, location, meteorological conditions, and proximity to pollution sources. Linear features like street trees and hedges can significantly reduce pedestrian exposure to air pollutants locally[66,83,109,124,182-184] while larger urban parks impact broader areas.[170,185] The variability in GBGI dimensions presents challenges for general conclusions, as different studies focus on various factors such as canopy size, particle deposition, and aerodynamic effects. Green walls, for example, primarily address pollutant absorption or deposition in a two-dimensional context, whereas urban parks improve air quality over larger areas (Table 1). Blue infrastructure, such as wetlands and lakes, enhances air quality by increasing humidity and facilitating fine particle aggregation, reducing PM_{10} and $PM_{2.5}$ concentrations.[137,142]

Comparing GBGI studies was challenging due to inconsistent definitions. For instance, small trees were sometimes classified as shrubs, complicating comparisons of linear features. Similar issues arose with varying types of vegetation, such as shrubland, grassland and wetlands. Only urban parks had a clear definition, being designated natural or human-made green areas within an urban or metropolitan area ranging from 0.28 to 20,275 ha.[169,186]

Scale of the studies. The diversity of GBGI has prompted studies at different scales to measure air quality impacts. At the microscale (local or street level), pollution can be directly deposited onto or absorbed by street trees, hedges, road verges and green walls, reducing nearby concentrations.[66,77,83,109,124,126,182-184,187,188] However, in some cases, street trees can worsen air quality by reducing local ventilation and increasing pollutant concentrations on the road-facing side.[108,118,121,170,189,190] This highlights that GBGI effects on air quality are spatially and scale-dependent, influenced by meteorological conditions and street configurations.[103,119,122 126,129,191]

At the local scale, dispersion is the dominant mechanism for pollution reduction, compared to microscale deposition (Section 4).[113,132,192] In contrast, larger GBGI like parks, forests, wetlands, grasslands, woodlands and gardens can improve air quality at the city or neighbourhood level (mesoscale) (Table 2).[98,140,164,169,193-195]

Different GBGI studies use diverse methodologies and measurement units, complicating direct comparisons. For example, some studies express air quality by pollutant concentrations (e.g., μg m^{-3}), while others use metrics like PM deposition on leaf surfaces per unit time (e.g., μg cm^{-2} h^{-1}) (see Section 6). This data heterogeneity presents statistical challenges to be addressed for effective comparison.

Methods assessing the effectiveness of GBGI. There are three main methods to quantify air pollution removal by GBGI: monitoring (field measurements), controlled experiments (e.g., wind tunnel), and mathematical modelling (e.g., CFD models) (Table 2). Monitoring involves ground-level air quality measurements near and within GBGI features, with variations often due to sensor placement, number of sensors, and background pollutant concentrations (Table 2). Study designs differ greatly, with variations in selection criteria, study durations from days to years, sample sizes and plant species studied under varying conditions. Experimental studies typically focus on single plants or parts of a plant (e.g., a branch) under controlled pollutant exposure in chambers or wind tunnels.[157,229] This diversity in methodologies and conditions complicates consistent inter-study comparisons of GBGI.

Modelling studies offer broader spatial and temporal assessments and can predict outcomes under various urban and GBGI conditions. However, results depend on model parameters and incorporated processes. Different modelling methods, such as CFD models, operational dispersion models (e.g., ADMS-Urban, EMEP), and tools like i-Tree/UFORE, require varied inputs.[22,257]

CFD models need detailed data to simulate fluid flow, heat transfer, and mass transport in 3D spaces[107,108,118,241] and are used in atmospheric chemistry models like EMEP or WRF-CHEM at larger scales. CFD modelling primarily assesses air pollution impact on GI in street canyons and neighbourhoods (Table S4). Conversely, i-Tree/UFORE relies on field measurements, tree inventories, and environmental data to estimate the GBGI impact.[258] Comparing modelling studies is challenging due to these varied inputs.

The representation of GBGI in computational models introduces disparities that impede direct comparisons across studies. CFD models often simplify GBGI attributes, using geometric figures defined by specific dimensions and properties. Most models use a momentum sink equation with LAD/LAI and deposition velocity as main inputs, assuming uniform LAD. In reality, GI (e.g., trees, hedges) have complex structures affecting their environmental impact.

Deposition velocities vary with wind speed, particle size and species type[259,260]; but models like OpenFOAM and CiTTy-Street often use a standard deposition velocity of 0.64 cm s^{-1} regardless of species or particle size.[75,124,227] For blue infrastructure, deposition velocities depend on wind speed, particle diameter and relative humidity, with the latter being crucial at wind speed below 2 m s^{-1}.[79,137] These simplifications may not fully capture real-life complexities.

To overcome these challenges, collaborative efforts are essential, emphasising the standardisation, consistent methodologies, and transparent reporting practices. Establishing common metrics or frameworks for evaluating and reporting air quality improvements from GBGI could enhance comparability and facilitate meaningful cross-study analyses.

Air pollution removal potential of GBGIs

Figures 5-6 illustrate the range of percentage changes in pollutant levels across various GBGI types. Figure S3 & Table S4 summarise the pollutant assessments across different study types (modelling, monitoring, multiple) and methodologies (concentration, deposition, and others). These different study types and methodologies, and their combinations (Section 5) led to staggering 48 types of quantification units (μg/m^3, cm^{-3}, ppb, ng/m^3, μg/cm^2, particles/cm^3, μg/m^2, mg/m^3, %, normalised, dimensionless pollutant concentration, μg/m^3, mg/g^1, g/ha/year, particles/mm^2, t/ha/y, kg/m^2/y, g/m^2/y, t/y, kg/ha/y, g/m^2, PMAC (particulate matter attenuation coefficient), mg/m^3, ppm, particles/m^3, kt/year, mg/m^2, particles, particles/mm^2, kg/year, mm^2, μg/cm^2/h, particles/cm^2, mg/cm^2/day, μg/cm^2, mg/cm^2, m^3/h/m^2, ppbv, ppmv, t/ha, kg/ha, kg/acre, μg, g/y, tonnes, Mg/y, Mg, pphm). Although many of these units can be converted to a common unit (e.g., concentration), multiple metrics remain difficult to reconcile or compare. Non-GBGI sites (comparator) were often used for determining background concentration, as reference or control site, such as locations with overall lower pollutant concentrations (due to fewer sources - farther from the source or higher heights). However, the comparison with these sites may not accurately reflect GBG effectiveness in reducing pollutant concentration. In this case, the reduction values were not considered for this section analysis. Deposition

Table 2. Overview of methodological parameters across the selected articles in this literature review. This table summarises key methodological parameters extracted for each GBGI analysed. The parameters are: (1) Study type: Monitoring (Mn), Modelling (Md). Both (Mn and Md) and other (e.g., GIS spatial analysis, land-use cover, and mapping). The number of studies is presented in parenthesis; (2) Dimensions of GBGI represent the appearance of studied GBGI, including areas or stand-alone elements; 3) Species commonly studied; (4) Sampling height, which represents the common height from which air pollution data was extracted; (5) Monitoring methods applied in each study, indicating where or how the sampling was undertaken; (6) Consider the concentrations at the sampling site, which represents the number of studies that mentioned concentrations during the sampling period at the sample site, and (7) Sampling period, which indicate the sampling range that can be found for each GBGI. The number of studies per GBGI type is shown in parentheses.

GBGI	Study type	Dimensions of GBGI	Species commonly studied	Sampling height(*)	Monitoring method(s)	Consider the concentration at the sampling site	Sampling period
Botanical garden	Mn (4)[a] Md (1)[b]	0.07-400 ha	Evergreen and deciduous trees and shrubs	2-3 m	Leaf collection or stationary monitoring	Yes (3)	1 month to 1 year
City farm	Mn (2)[c]	~0.4 ha	NI	NI	Stationary monitoring	No (2)	1 week to 4 months
Cycle track	Mn (2)[d]	Cycle routes (50 m to 9.8 km)	NI	NI	Portable monitors and stationary monitoring	Yes (1)	2 weeks to 2 months
Grassland	Mn (5)[e] Md (6)[f] Both (2)[g] Other (2)[h]	Tree H between 6-20 m. Forest up to 9000 ha	Grass, forest, shrubs, deciduous trees	0.5-6 m	Stationary monitoring; Remote sensing imagery	Yes (5)	Up to 2 months
Green roof	Mn (10)[i] Md (15)[j]	0.4ha, 27.87 ha to 262 ha And building simulations between 3 to 35 m in height and, at the top of a green roof	Extensive, intensive and semi-intensive green roof with herbaceous and shrub species. Common Species planted in different substrate thickness	1.2 m (1)	Stationary monitoring on the roof	Yes (6)	2 days (1 week, 6 months), and 1 year
Green wall	Mn (13)[k] Md (6)[l]	4.5-325 m^2 Or plots based on 200 m × 200 m grid	Common indoor or outdoor species	1.25-6.5 m	Stationary monitoring inside or around the green wall (before and after the green wall installation) or analysis of PM deposition on leaves	Yes (8)	1 day to 6 months
Hedge	Mn (7)[m] Md (4)[n]	1 m × 1.2 m // 1.2 m × 2.2 m; up to 4m (hedges) 4 m × 2.5 m // 9 m × 7 m // 10 m × 6.5 m; up to 18 m (trees) 3.5-4 m (trees+hedges)	Continuous and discontinuous trees, hedges and a combination of trees-hedges/shrubs	0.6-1.7 m	Stationary monitoring (behind and in front of the hedge) and mobile measurement	Yes (7)	6 days to 1 month
Lake	Mn (1)[o] Both (4)[p]	0.5 to 2,000 km^2	Lakes	1.5 m	Stationary monitoring	No	1 to 3 months
Park	Mn (8)[q] Md (3)[r] Both (4)[s] Other (1)[t]	2.8-29,000 ha	Evergreen and deciduous trees	1.5 m	At the edge of the park, or stationary monitoring at different distances from a road	Yes (6)	1 to 5 months
Playground	Mn (1)[u]	NI	'tredges'	NI	Portable optical particle spectrometers at roadside and playground at 1 m and ~ 5 m behind the tredges	Yes (1)	*~5 months*
Riparian woodland	Mn (2)[v]	30-40 m wide	Woodland and wetlands, trees, shrubs, and grass layers	1.5-4.0 m	Portable sensors and stationary monitoring at different distance from the river edge	Yes (1)	1 month
Road verge	Mn (2)[w] Both (1)[x]	~50 m	Mosses, herbaceous plants, shrubs, and trees	1.5 m	Stationary monitoring	Yes (1)	~1 month
Shrubland	Mn (3)[y] Both (1)[z] Other (1)[aa]	~ 600 ha and trees	Evergreen broad-leaved forests, Deciduous and conifer species, shrubs, and herbaceous plants	1.5 m (3)	Stationary monitoring (at different distances from the edge of the road)	Yes (1)	2 days to 4 months
Street trees	Mn (19)[bb] Md (22)[cc] Both (4)[dd]	Individual species. Tree H=3-18 m Canopy = -18 m	Evergreen and deciduous common planted trees	~1.5 m and at different distance from the road	Stationary, portable, and static monitoring	Yes (6)	From 2 days to 2 years (most common 2 months)

Table 2. *(Continued)*

GBGI	Study type	Dimensions of GBGI	Species commonly studied	Sampling height[(*)]	Monitoring method(s)	Consider the concentration at the sampling site	Sampling period
Woodland	Mn (11)[ee] Md (4)[ff] Other (2)[gg]	0.04 km^2, to 7.42 ×10^5 ha	Mixed deciduous and pine woods; shrubland and grassland; beech woods	1.5 m	Satellite images; stationary monitoring	Yes (3)	From days during different seasons to 1 year
Wetland	Mn (2)[hh]	68-1724 ha	Water body (e.g., lake wetlands with few trees)	1.5 m (2)	Remote sensing satellite images; Stationary monitoring at 50 m to 500 m from the lake wetland	Yes (1)	1 year
Zoological garden	Mn (2)[ii]	20-140 ha	Endemic flora and trees	1.6 m (1)	Stationary monitoring	Yes (2)	6 months and dry and rainy periods

Note: [a]Chen et al.[193]; Liang et al.[196]; Hrotko et al.[197]; [b]Junior et al[198]; [c]Skop et al.[199]; Tong et al.[200]; [d]Mohamed et al.[201]; Lonati et al.[202], [e]Kaminska et al.[203] ; Nguyen et al.[158]; Chen et al.[204]; Cai et al.[164]; Wang et al.[129]; [f]Dai et al.[205] ;Selmi et al.[206]; Rui et al.[207]; Tiwari & Kumar[60]; de la Paz et al.[166]; Zhai et al.[73]; Wang et al.[140]; [g] Zafra et al.[208]; [h]Baraldi et al.[209]; Chen et la.[210]; [i]Muresan et al.[211]; Luo et al.[212]; Tong et al.[200]; Jayasooriya et al.[213]; Sicard et al.[41]; Viecco et al.[81]; Anderson and Gough[99]; Barmparesos et al.[214]; Vera et al.[215]; Arbid et al.[106]; [j]Irga et al.[100] ; Yang et al.[216]; Baik et al.[217]; Park et al.[93]; Moradpour et al.[218]; Qin et al.[188]; Rafael et al.[161]; Arghavani et al.[162]; Rafael et l.[219]; Viecco et al.[220]; Zhong et al.[96]; Rafael et al.[221]; Hosseinzadeh et al.[97]; Saxena and Yaghoobian[222]; Wang et al.[116c; a-] [k]Li et al.[171]; Ottelé et al.[88]; Sternberg et al.[223]; Weerakkody et al.[87]; Weerakkody et al.[82]; Ghazalli et al.[2241] He et al.[91]; Paull et al.[225]; Paull et al.[89]; Anderson and Gough[99]; Donateo et al.[85]; Pettit et al.[226]; [l]Vera et al.[215]; Pugh et al.[227]; Vos et al.[108]; Jayasooriya et al.[213]; Qin et al.[228;] Viecco et al.[220]; [m]Li et al.[171]; Gromke et al.[229]; Abhijith and Kumar[61]; Ottosen and Kumar[127]; Abhijith and Kumar[68]; Chen et al.[167]; Kumar, et al.[230]; [n]Tran et al.[231]; Wania et al.[107]; Vos et al.[108]; Gromke et al.[229]; [o]Li et al.[171]; [p]Liu et al.[79]; Zhu and Zeng1[40]; Zhu and Zhou[138]; Zhao et al.[195]; [q]Zhou et al.[139]; Yin et al.[136]; Cohen et al.[186]; Bonn et al.[169]; Klingberg et al.[194]; Gomez-Moreno et al.[232]; Kim and Hong[185]; Su et al.[233]; [r]Niu et al.[168]; Fares et al.[170]; Nemitz et al.[84]; [s]Moradpour and Hosseini[95]; Qin et al.[228]; Xing and Brimblecombe[133]; Zhou et al.[234]; Benedict et al.[235]; [t]Heshani et al.[236]; Keiser et al.[237]; [v]Maher et al.[69]; Wang et al.[129], [w]Sou et al.[238]; Przybysz et al.[65x]; Popek et al.[66]; [y]Deshmukh et al.[18]; Nguyen et al.[158]; Niu et al.[168]; [z]Dai et al.[205]; [aa]Deshmukh et al.[244]; [bb]Douglas et al.[239]; Harris and Manning[240]; Buccolieri et al.[241]; Hagler et al.[182]; Gromke and Ruck[140]; Islam et al.[187]; Salmond et al.[242]; Al-Dabbous and Kumar[183]; Brantley et al.[126]; Jin et al.[243]; Lin et al.[109]; Klingberg et al.[194]; Abhijith and Kumar[61]; Wang et al.[110]; Anderson and Gough[99]; He et al.[244]; Miao et al.[245]; Tan et al.[67]; [cc]Liu et al.[246]; Buccolieri et al.[241]; Salim et al.[189]; Wania et al.[107]; Vos et al.[108]; Gromke and Blocken[247]; Abhijith and Gokhale[123]; Vranckx et al.[119]; Moradpour et al.[218]; Morakinyo and Lam[77]; Tong et al.[200]; Morakinyo and Lam[77]; Jeanjean et al.[75]; Jayasooriya et al.[213]; Buccolieri et al.[124]; Baro et al.[71]; Karttunen et al.[132]; Lin et al.[113]; Li et al.[120]; Liu et al.[246]; Santiago et al.[115]; Jung and Yoon[248]; [dd]Li et al.[125]; Zhou et al.[234]; Liu et al.[246]; Liu et al.[249]; [ee]Wang et al.[250]; Grundström and Pleijel[251]; Nguyen et al.[158]; Blanusa et al.[80]; Bonn et al.[169]; Liu et al.[79]; Klingberg et al.[194]; Anderson and Gough[99]; Cai et al.[164]; Cong et al.[142]; Hrotko et al.[197]; [ff]Popek et al.[66]; Tallis et al.[252]; Hirabayashi et al.[262]; Manes et al.[254]; [gg]Nemitz et al.[84]; Fusaro et al.[160]; [hh]Douglas et al.[239]; Przybysz et al.[65]; [ii]Popek et al.[66]; Phan et al.[255]; Maia et al.[256]. [(*)]Height of the monitor, in parentheses the number of selected studies that provide the information. N/A: Not Applicable; NI: No Information.

studies lacked non-GBGI comparisons, making percentage reduction derivation infeasible. Only 30% of deposition studies (Section 4) reported percentage reduction values. Consequently, limiting their representation of the overall scenario.

Linear features. Available evidence on the air pollution reduction potential of GBGIs varies (Figure 3). The most studied GBGIs include linear features (e.g., street trees and hedges), constructed GIs (e.g., green roofs and green walls), followed by other non-sealed urban areas (e.g., woodland, grassland) and mixed GBGIs (Figure 2). GBGIs reduce air pollution by about 16 ± 21% (average ± s.d.). Street trees have been the primary focus, particularly along busy urban streets. Among 51 studies on street trees, 61% examined their effects in street canyons, 18% on open roads, and 21% on other urban areas. Most street tree modelling studies used CFD (84.4%) followed by i-Tree (6.2%) and others such as Solow's neoclassical, dry deposition and system dynamics models (9.4%). In street canyons, 58% of studies used modelling (CFD, RANS, OpenFOAM, and ENVI-met), 23% used monitoring and 19% used multiple methods. For open road conditions, 67% of studies used monitoring, 22% used modelling, and 11% used a mixed approach for street tree evaluation (Figure 2).

The overall average percentage change in pollutant concentration due to street trees was −3±32%. In *street canyons*, factors like aspect ratio, LAD/LAI of trees, wind direction and wind speed, and seasonal variations significantly influence pollutant concentration changes. Depending on species characteristics and climate conditions, street trees can either worsen air quality (negative values) or improve it (positive values).

Modelling studies on trees in idealised street canyons mainly reported an average increase in PM concentration (including all PM types, i.e. ultrafine, fine, coarse and total) −16±51%, ranging from −353% to +23% (Table S5), and mixed results for gaseous pollutants like CO, showing a range of −36% to +53% (Figure 6). Modelling studies indicate pollutant deposition on vegetation surfaces can slightly improve air quality depending on the extent and characteristics of GI.[41,71,75,124,246]

Monitoring studies, however, showed a lesser increase in pollutants, with an average change of −7±27% ranging from −219% to +12% for PM. The high concentrations of −353% and −219% were reported by a CFD study and a laboratory experiment for PM_{10} comparing high-density tree planting with a tree-free case in a street canyon with a 45° wind direction.[241]

The discrepancy between modelling and monitoring results could be due to the simplification of real-world settings in models and assumptions about dispersion and deposition mechanisms.[18,103,110,190,243] In contrast, simpler environmental dynamics and pollution dispersion mechanisms on open roads might facilitate more accurate model representations.

In *open-road conditions*, trees generally improve air quality in contrast to street canyons. Studies have documented reductions in PM with an overall average of +23±29% (ranging from −15% to +77%). Notably, monitoring studies have shown reductions in freshly emitted traffic pollutants, such as UFP (+38% to +63%) and CO (+21% to +56%) in the presence of trees along open busy streets (Table S5).

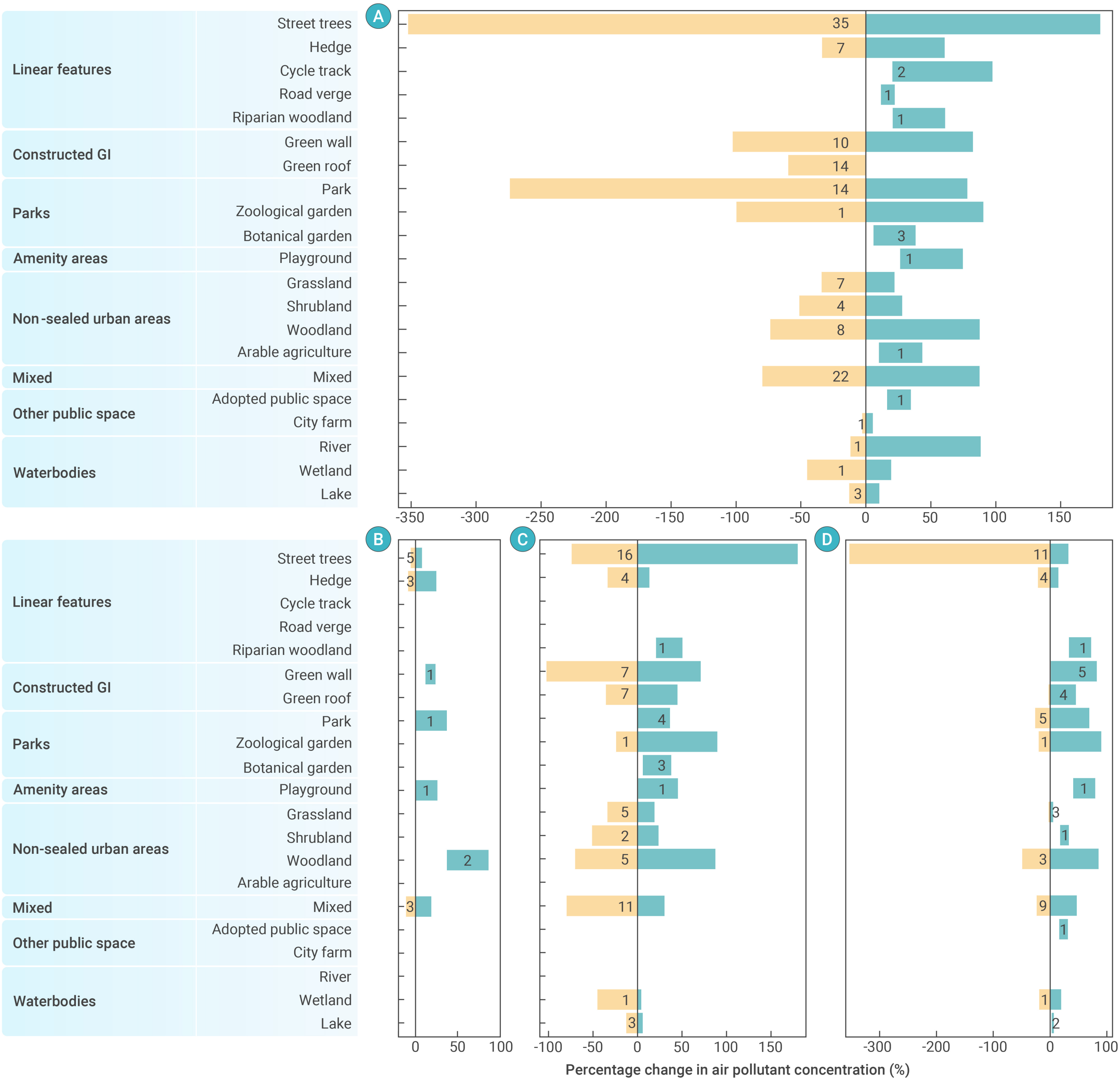

Figure 5. Extracted percentage changes (ambient concentration and deposition) considering different GBGI types in studies (A) Across all pollutants, (B) PM_1, (C) $PM_{2.5}$, and (D) PM_{10}. The numbers printed on the bars represent the number of studies available that provide the percentage change under each GBGI, shown in Table S4. Negative values represent deterioration of air quality, while positive values represent improvement in air quality.

Similar to street canyons, factors like height, width, foliage or leaf canopy of the street tree (LAI/LAD), wind direction, and speed influence pollutant reduction in open roads. However, gaps between trees, significant clearance from ground to tree canopy, and low tree stand porosity in open-road conditions can compromise their effectiveness.[61,132,182,261] Some studies also explored the influence of poorly maintained street trees combined with other GBGIs, such as grass, hedges or bushes, categorising them closer to mixed-GBGI studies.[61]

The second most studied linear feature GBGI, hedges, was the focus of ten studies. Of these, 60% used monitoring techniques, 30% employed modelling and 10% combined both approaches (Figure 2). Nearly half of the studies assessed hedges in street canyons (60%), mainly through modelling (50%), showing a percentage change ranging from −34% to +61% (Figure 5). In contrast, in open-road conditions, mainly assessed via monitoring, air quality changes from −22% to +59% across all pollutants (Table S5). For instance, hedges significantly reduced UFP concentrations by up to +59% on open roads, highlighting their efficiency in mitigating freshly emitted traffic pollutants near the source.[231] The efficacy of hedges in improving air quality is influenced by factors such as their dimensions, LAI, wind speed and direction, and seasonal changes.

Other linear features like cycle tracks, road verges, and riparian woodlands were less studied. Cycle tracks with adjacent low-growing vegetation improved UFP concentrations by +33% to +54% for UFP (Figure 6A) and BC by +20 to +78% (Figure 6B). Only one study focused on riparian woodlands, reporting a PM concentration decrease of +20% to +41%, affected by leaf presence and meteorological conditions.[238]

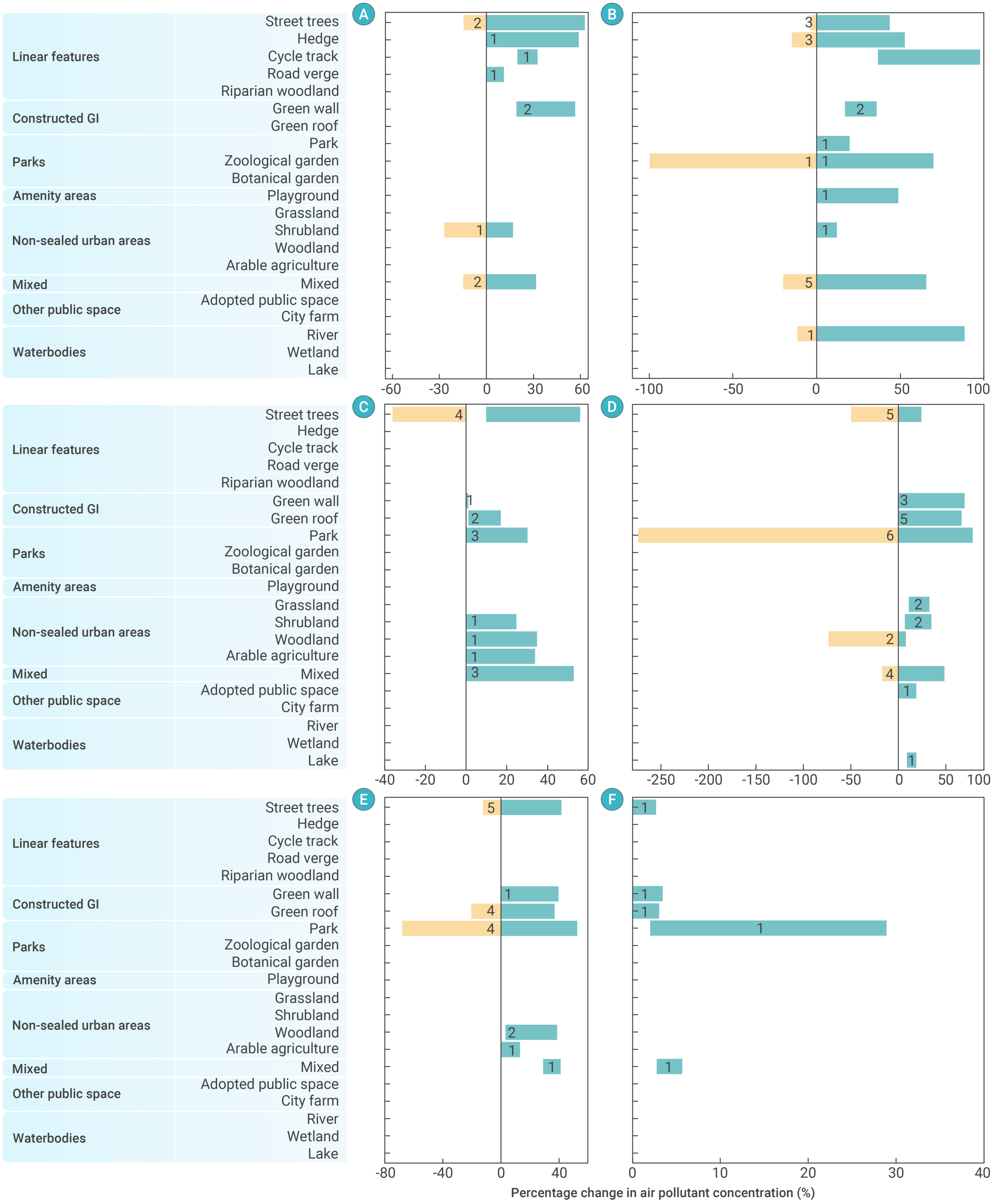

Figure 6. Extracted percentage changes (ambient concentration and deposition) considering different GBGI categories in studies (A) UFP, (B) BC/EC, (C) CO, (D) NO- NO_2-NO_x (E) O_3, and (F) SO_2. The number printed on the bars provides studies used under each GBGI, shown in Table S4. Negative values represent deterioration of air quality, while positive values represent improvement in air quality.

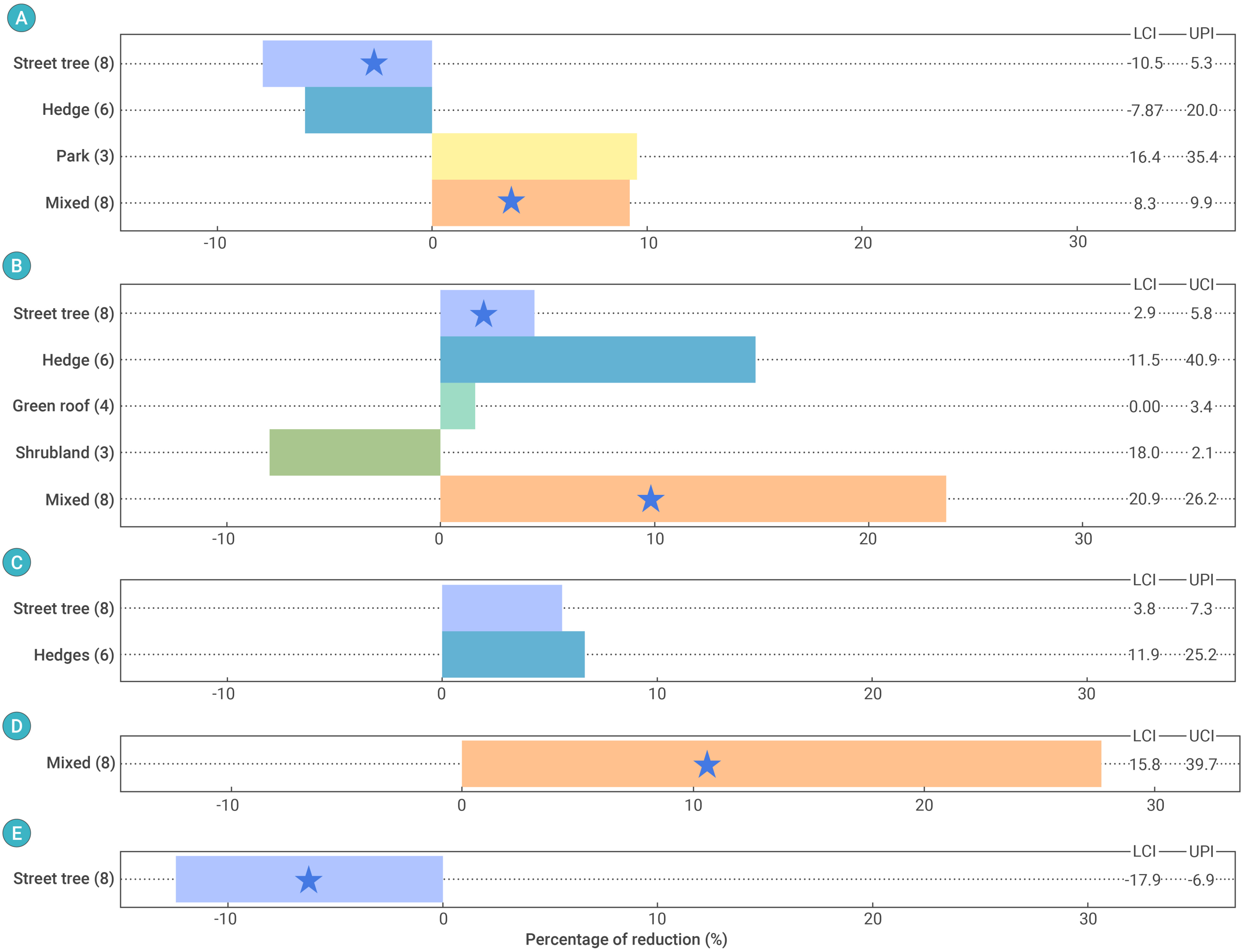

Figure 7. Percent change showing the removal potential of different GBGI types for mean (A) PM_{10}, (B) $PM_{2.5}$, (C) PM_1, (D) BC, and (E) TSP. Numbers in parentheses on the y-axis indicate the number of publications qualified the meta-analysis criteria and included in computing the potential removal. Bars with ★ indicate statistically significant values. Negative and positive values represent deterioration and improvement in air quality, respectively. The details of these studies are available in SI Tables S6 and S7.

Constructed GBGI. Most studies on constructed GBGI, specifically green walls and roofs, reported a decrease in pollutant concentrations, with an average pollutant reduction of 14±25%. Green wall studies primarily used field campaign monitoring (54%), while green roof studies predominantly employed modelling (58%).

For green walls PM concentration ranged from −103% to +60% in modelling studies and from +11% to +38% in monitoring studies. Deposition studies on leaves showed a PM reduction ranging from +1% to +83%, with monitoring indicating +49% to +83% and modelling +1% to +42% (Figure S3). Higher PM accumulation on leaves (e.g., +83%) compared to a situation without leaves (no GBGI) was attributed to the installation of green walls in indoor environments, implying a lack of washing off.[224] Gaseous pollutants, such as NO_2, SO_2, CO, and O_3 showed percentage changes ranging from 0% to +70% in both modelling and monitoring studies (Figures 6-7).

For green roofs modelling and monitoring studies reported PM concentration reductions of −36% and improvements of +38% (modelling from −36% to +17% and monitoring from +10% to +38%) (Figure 5). Similarly, concentration changes in gaseous pollutants (CO, NO, NO_2, NO_x, O_3) and VOC have ranged from −21% to +67% (modelling −21% to +60% and monitoring 6% to +67%) (Figure 6). PM deposition on green roofs ranges from +1% to 46% for monitoring (+45%) and multiple studies (+1% to +46%).

A study noted a significant increase in NO_2 concentration (e.g., −91%) when comparing a green roof to a conventional roof; attributed to a nearby construction site rather than actual influence of the GBGI.[100] This highlights the complexity of the data and the challenges faced in field work when assessing the impact of GBGI on air pollution reduction.

Linear features and constructed GIs are generally effective in reducing local air pollution in open-road environments, where dispersion helps redistribute pollution. However, their impact in street canyons varies significantly, influenced by factors such as aspect ratio, wind direction, and speed.[103,104] Green walls' effectiveness on air quality is affected by building height, surrounding urban infrastructure, vegetation cover, and the type of pollutants studied.[220,220]

Monitoring studies suggest pollutant reductions could be more pronounced within street canyons compared to rooftop level or annual removal metrics, likely due to site-specific characteristics.[100] Elevated pollutant capture is often attributed to leaf deposition rather than changes in airborne concentrations, highlights the importance of leaf micro and macro morphology, and the LAI of the GI in understanding the full impact of green roofs and walls on air quality.[100,188,200,212,216]

Parks. Parks, zoological and botanical gardens show typically lower air pollution concentrations than surrounding urban areas, serving as pollutant sinks. Factors such as tree canopy density, size, and seasonal changes affect pollution reduction[101,262], with parks showing an average pollutant reduction of 22±34%.

Specifically, parks can change PM concentrations from −27% to +70% (modelling from +1% to +37%, monitoring from −27% to +70%), while botanical gardens reported improvements in air quality from +11% and +33% in monitoring studies (Figure 5A). Canopy density, tree coverage percentage,

Table 3. A comparison summary indicating the meta-analysis results relative to the range reported by the collective pool of studies for each GBGI and pollutant type. Normal, bold, and italic values represent meta-analysis results within the overall concentration range found in Section 6 studies, and those above the range, respectively. Normal, bold, and italic values represent meta-analysis results within the overall concentration range found in Section 6 studies, and those above the range, respectively. *refer to the statistically significant values (in bold) for different GBGI. The original studies from where the data below is extracted is available inTable S6. Percentage values are estimated using the equation available in "Search criteria and data acquisition" Section. The negative percentage values indicate the deterioration of air quality (i.e., increase in pollutant concentration) and positive percentage values indicate an improvement in air quality (i.e., decrease in pollutant concentration).

GBGI type	Pollutants	From meta-analysis (Figure 7) for pollutants showing *statistically significant values for different GBGI; 95% CI are given in [ ]	Overall concentration range from SLR studies (from Figures 5 & 6)
Green Roofs	$PM_{2.5}$	1.6% [0.00, 3.4]	−36 to 38%
	PM_1	6.7% [12, 25]	−9 to 25%
Hedge	$PM_{2.5}$	*14.7% [11, 41]*	*−34 to 14%*
	PM_{10}	−5.6% [-8, 20]	−22 to 15%
Mixed	**$PM_{2.5}$**	**23.6% [21, 26]***	**−80 to 20%**
	PM_{10}	**9.1% [8, 10]***	**−25 to 43%**
	BC	**27.7% [16, 40]***	**−20 to 66%**
Park	PM_{10}	9.5% [16, 35]	−27 to 70%
Shrubland	$PM_{2.5}$	−7.9% [-18, 2]	−52 to 24%
	PM_{10}	**−7.9% [-5, -10]***	**−353 to 12%**
Street trees	**$PM_{2.5}$**	**4.3% [3, 6]***	**−74 to 39%**
	PM_1	**5.6% [4, 7]***	**−6 to 8%**
	TSP	**-12.4% [-18, -7.0]***	**−26 to 66%**

tree size, and seasonal changes[134] in leaf presence significantly influence pollution reduction.

However, one study reported a deterioration in air quality in parks due to increased PM_{10} compared to an urban square during low summer concentrations, attributed to dust re-suspension from human outdoor activities. Interestingly, the same study noted the most significant PM reduction during winter compared to a street canyon area.[186]

Amenity areas, other public spaces and other non-sealed urban areas. City farms and playgrounds with GI have shown changes in air pollution ranging from −3% to +6% and +26% to +49%, respectively (Figure 5). Other non-sealed urban areas, including grasslands, shrublands and woodlands, presented an average air pollution reduction of 14±20%. These areas have demonstrated effectiveness in reducing air pollution with reductions reaching up to +22% for grassland, +28% for shrublands and +88% for woodlands (Figure 5).

High reduction values were found for woodland in a monitoring study (up to +88% for $PM_{2.5}$) when comparing a location just behind the forest edge with a location 5 metres from the road.[70] Grasslands alone showed the lowest maximum concentration reduction (Figure 5), but combining them with other GIs like trees, hedges, and shrubs enhances their effectiveness, especially in smaller areas.[73,208,263]

Mixed-GBGI. Mixed GIs are more effective in improving air quality than individual GIs. In monitoring studies, mixed GIs (e.g., hedge plus trees) showed changes in pollutant concentration ranging from −19% to +88% (Table S4). Negative values were linked to mild wind reducing PM removal efficiency in arbor-grass setups[129], while higher reductions were observed for $PM_{2.5\text{-}10}$ with high-density planted vegetation in an experimental study[157] and for BC in a monitoring study.[61]

Water bodies. Research on the impact of water bodies, including rivers, wetlands, and lakes, on PM concentrations is limited. Available literature reports PM changes ranging from −45% to +89% for rivers (-12% to +89%), lakes (−13% to +6%) and wetlands (−45% to +20%) (Figure 5). The reduction of PM near lakes and wetlands is likely due to their hygroscopic influence and subsequent deposition on nearby vegetated surfaces.[142] GBGI can increase humidity and generate local turbulence, promoting PM deposition and diffusion. However, high relative humidity during cloudy and hazy conditions can slow PM diffusion, leading to PM accumulation in wetlands due to hygroscopic growth and particle agglomeration. Conversely, on sunny days, solar heating induces convection that enhances atmospheric turbulence and mixing, reducing PM concentration near wetlands.[264] Although relative humidity is crucial for studying PM deposition in water bodies, modelling studies often neglect changes in deposition rates.

In summary, while linear features, constructed GI, and parks have been extensively studied for their air pollution reduction capabilities, further research is needed for other GBGIs and gaseous pollutants, to fully understand their potential in improving air quality. Interpreting percentage changes in air pollutants for these less-studied GBGI should be approached with caution due to the limited number of confirmatory studies.

GI can exacerbate local air pollution when the vegetation is not sufficiently dense or lacks full coverage from the ground to the top of the canopy.[18,25,42] or installed in deep street canyons due to reduced dispersion.[10,27,75] Gaps or highly porous vegetation can allow air pollution to funnel and concentrate through these gaps. Additionally, vegetation can reduce wind speeds, leading to air stagnation and pollution buildup.[18] In addition, grey infrastructure can also contribute to air pollution buildup by blocking airflow, leading to elevated concentrations in front of the structure.[153] When solid walls or fencing are used along roadways and other air pollution sources, higher air pollution concentrations can be experienced at the edges of the walls as pollution wraps around the edge of the wall.[139] To mitigate these effects, care must be taken on where GBGIs are located relative to where populations will be exposed to air. Additionally, designing and using other green, blue, or grey infrastructure can help mitigate these impacts.[44] Properly planned and executed GBGI, with attention to vegetation density, coverage, and strategic placement of grey infrastructure, can significantly enhance air quality and reduce the risk of exacerbating pollution levels. Therefore, optimal solutions that strike a balance between benefits and drawbacks are necessary to prevent unintended negative consequences.

Limitations. Some GBGI, like street trees, are well-researched (Table S10). Others like parks (9% of studies), green roofs (13%), green walls (14%) or hedges (14%) have a moderate number of studies (*n*>7). However, many GBGIs have limited studies, including cycle tracks (48% average reduction, n = 2), zoological gardens (40%; n = 1), playgrounds (40%, n =1), road verge (11%, n = 1), adopted public spaces (18%, n = 1), city farms (1.6%, n = 1), riparian woodlands (31%, n = 1), wetland (−10%, n = 1), arable agriculture (19%, n = 1) and rivers (38%, n = 1).

High values in some GBGIs are attributed to specific characteristics. For example, playgrounds showed higher reductions due to the efficacy of western red cedar hedges in removing traffic-sourced PM and BC.[69] In zoological

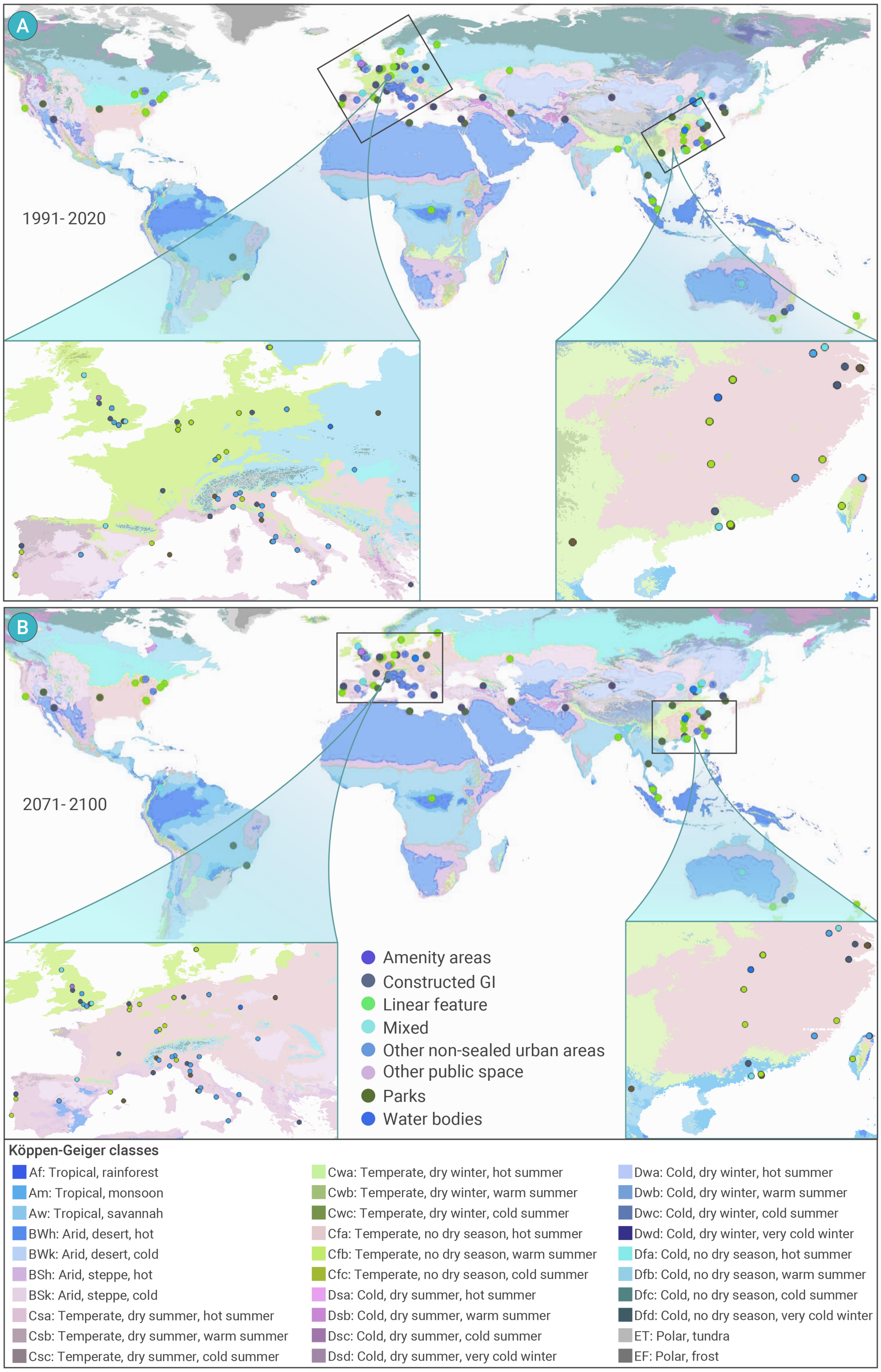

Figure 8. Base maps are Köppen-Geiger classifications, and the points are locations of eight GBGI categories: (A) shows the present-day map (1991–2020), and the (B) future map (2071–2100) under the RCP8.5 high-emissions scenario. The zoomed rectangular areas represent Europe and Asia to show the climate shift in more detail, along with the location of the implemented GBGI main types.

gardens, lower PM levels were observed compared to urban areas due to the dense tree canopy, reduced traffic and other human activities.[255] Cycle tracks near greenery significantly reduced UFP and BC compared to city centre cycle lanes adjacent to main roads.[202,203] River paths had lower BC levels due to better ventilation compared to high-traffic urban routes.[203]

While these data highlight the impact of GBGI on air quality, the true impact may be overestimated or underestimated due to a shortage of confirmatory studies and variations in urban morphology, climate and other local factors. Therefore, the above results should be interpreted with caution.

Quantification of GBGI efficacy based on meta-analysis

Figure 7 and Table 3 shows the results of the meta-analysis, with detailed statistics in Table S6. Among the considered GBGI, 26 studies met the criteria, assessing the efficacy of six GBGI (street tree, hedge, green roof, park, shrubland, and mixed) in influencing five types of PM pollutants (PM$_1$, PM$_{2.5}$, PM$_{10}$, BC, and TSP). PM$_{2.5}$ was the most commonly assessed pollutant by five GBGI types (street trees, hedge, green roof, shrubland, and mixed), followed by PM$_{10}$ by four (hedge, mixed, park, and street trees) and PM$_1$ by two (hedge and street trees) (Table S6). BC and TSP were only studied for mixed GBGI.

Among these six GBGI, only mixed-GBGI and street trees showed significant results for all five pollutants. None of the studies on gaseous pollutants met the meta-analysis criteria (minimum of three studies reporting mean and standard deviation). For PM$_{2.5}$, statistically significant results ($p<0.05$) were observed in mixed GBGI and street trees, showing reductions of +24% and +4%, respectively (Figure 8). These results were outside the average PM$_{2.5}$ change range for mixed-GBGI (−80% to +20%) but within the range for street trees (−74% to +39%, Figure 5B & Table 3).

Conversely, green roofs, shrublands and hedges showed non-significant results ($p>0.05$) despite having five qualified studies each, mainly due to high data variability. Erroneous assumptions about the relative benefits of different GBGI can occur if values reported in the literature are not appropriately presented. This is crucial as the effectiveness of GBGI can vary depending on the built environment (e.g. open road vs street canyon), where they may either reduce or exacerbate pollutants (Section 6). Consequently, averaging overall results or reporting them without a comprehensive understanding of the data may lead to misleading conclusions.

Regarding PM$_{10}$, statistically significant results ($p<0.05$) were observed in only two out of the four GBGI categories: mixed-GBGI and street trees, with PM$_{10}$ changes of 9% and −8%, respectively. Most eligible studies on street trees for PM$_{10}$ were conducted in street canyons (60%), where negative values highlighted the adverse impact of trees in moderate and deep street canyons (Table S7). These significant changes fell within the PM$_{10}$ concentration change range of −25% to +43% for mixed-GBGI and −353% to +12% for street trees (Figure 5B & Table 3).

For PM$_1$, street trees showed statistically significant results ($p<0.05$), with a net 6% decrease in pollutant concentrations, within the range of −6% to +8% (Section 6). Mixed GBGI demonstrated statistically significant results ($p<0.05$) for BC, with an improvement of +28% (Table S6), falling within the range of −20% to +66% for all study types (Figure 6B & Table 3).

The meta-analysis revealed several key findings: (1) Only mixed-GBGI and street trees out of six GBGI types demonstrated statistically significant improvements in air quality for the five particulate pollutants investigated. However, street trees exhibited deterioration for PM_{10} and TSP but improvement for $PM_{2.5}$ and PM_1 (Table S6); (2) in most cases, the mean values from the meta-analysis fell within the ranges reported in Section 6 (Figures 5-6); (3) the meta-analysis provides a better estimate of GBGI performance than values simply derived from literature, which might overestimate performance, or fail to distinguish between high and low-performing GBGI. However, interpreting mean values of the overall meta-analysis without proper context may lead to a misunderstanding of the true impact of GBGI on air pollution; (4) reductions were most pronounced for mixed-GBGI, reaching up to +28%, followed by the street trees (up to +6%); (5) The meta-analysis was limited by a maximum of eight studies for each GBGI and pollutant type (Figure 7 & Table 3). Consequently, comprehensive studies are needed to assess other GBGI types and present detailed statistics to facilitate reliable meta-analyses and conclusions on GBGI performance.

GBGI for air pollution abatement in the changing climate

Climate change can significantly impact air pollution globally.[244,265] Higher temperatures increase the formation of ground-level O_3 from reactions of NO_x and VOC precursors with sunlight.[266] Additionally, more frequent and intense heatwaves, droughts, and wildfires release more PM into the atmosphere, exacerbating respiratory and cardiovascular diseases (Table S8).

Wildfires affect air quality over vast regions, even those far from the fires.[267] Beyond these large-scale trends, climate change impacts air quality at regional and urban scales due to changes in local weather parameters such as wind, cloud cover, solar radiation, temperature, and precipitation. For example, future projections for London predict significant changes in larger scale pollution patterns affecting urban air quality, e.g., changes in local NO_2, O_3 and PM concentrations.[268]

While GBGIs can significantly reduce air pollutants through various mechanisms (Section 4), their future performance will be influenced by shifts in global climate zones (Figure 8, with higher resolution for Europe and China). Changes in temperature and precipitation patterns, along with large-scale and local-scale air pollution changes, may exacerbate existing air pollution issues and introduce new challenges to the effectiveness of both existing and future GBGI solutions.

Strategic thinking and innovative approaches, such as retrofitting climate-proof and human-friendly GBGI, are essential for sustainable urban planning and adaptation.[16] Addressing climate change and air pollution through GBGI requires a proactive and integrated approach from urban planners and policymakers. Tailoring GBGI to current and future climate conditions can help abate air pollution and foster a healthier urban environment as climate change intensifies. Furthermore, uneven climate changes will cause some regions to experience more significant alterations than others. Therefore, it is crucial to quantify the effects of climate change on GBGI across different regions under present and future conditions. To investigate these impacts, we analysed the migration of different GBGI sub-categories across climate zones under the largest emission scenario of RCP 8.5 (Figure S2). These shifts are likely to impact ecology, water systems, food supply chains, and the functionality of GBGI and their co-benefits. Due to these changes, reorganising the distribution of GBGI may affect biodiversity and ecosystem services, including air pollution removal efficacy.

Different GBGIs may respond variably to climate change, affecting their functionality and effectiveness. Table S9 outlines the impact of current and future climate on air pollution and the role of GBGI in managing it under future scenarios for European regions and China. For example, in western Europe, oceanic temperate subclimates (Cfb) are projected to transition to hot summers (Cfa) and dry winters (Cwa) with more frequent and intense heatwaves and extreme precipitation events. These changes could increase ground-level O_3 formation and pollutant volatilisation raising air pollution levels. Figure 8 suggests that linear features (street trees and hedges), constructed GI (green roofs and walls), parks, mixed-GBGI, non-sealed urban areas (woodlands and grasslands), and waterbodies (lakes) could be effective GBGI solutions to counteract these climate and pollution changes.

Constructed GI (green roofs and walls) can enhance climate resilience, particularly in regions such as southern Europe transitioning from a dry, hot and warm summer temperate climate (Csa and Csb) to a fully desert and hot arid (BWh and BWk) climate (Figure 8). Southern Europe is likely to experience altered precipitation patterns and more extreme weather events. Heatwaves and reduced summer precipitation worsen air pollution, impacting existing GBGI interventions. This combination amplifies photochemical reactions, leading to increased gaseous pollutants (e.g., NO_2, SOA, O_3), particularly in urban areas during hot, sunny weather.[269] Additionally, drier conditions resulting from reduced precipitation enhance the accumulation of particulate matter, further deteriorating air quality. The lack of water availability affects the functionality of GBGI, exacerbating health impacts due to elevated concentrations of PM_{10} and $PM_{2.5}$.

In temperate zones (Cfb), such as northern Europe, expected climate changes pose significant challenges. Projected increases in temperatures, more frequent heatwaves, and warmer winters will raise both daytime and nighttime temperatures. Variable precipitation patterns will alter the timing, intensity, and distribution of rainfall. Additionally, temperature changes may increase instances of rain instead of snow in winter, exacerbating air pollution by intensifying the release of pollutants. Adaptive solutions, such as street trees and woodlands, can effectively respond to these projected shifts toward an arid climate zone (Dfb) (Figure 8).

In the cold climate zones (Dwa and Dwb) like China, future projections suggest a shift towards temperate sub-climates with dry winters and hot to warm summers (Cwa, CwbCfa, Cfb). This transition requires more adaptive GBGI measures. Effective current GBGI solutions like shrubland, street trees, and mixed-GBGI should be complemented with additional GBGI such as parks, green roofs, and zoological gardens to address future climate shifts and improve air quality, biodiversity, and other associated benefits. Approximately 71% of urban parks in Northeast China and the North China Plain, currently in the Dwa and Dwb sub-climate zones, are projected to transition to the Cwa sub-climate zone by 2071-2100 under the RCP8.5 scenario.[270]

Adapting to climate change impacts on air pollution demands a multifaceted approach that integrates current GBGI solutions with future measures capable of withstanding extreme temperatures, weather events and water availability issues. Investing in GBGI and exploring innovative solutions allows policymakers to mitigate climate change effects on air quality and promote sustainable development.

DISCUSSION

Knowledge gaps

This review shows significant progress in understanding the role of GBGI in urban air quality improvement, but several knowledge gaps remain. More long-term monitoring is needed to assess the sustained impact of these infrastructures, including how vegetation evolves and adapts in cities in a changing climate. Understanding GBGI interactions with other urban elements, such as traffic, street layouts, and micro-meteorological conditions, is crucial. Considering spatial and temporal variation as well as rainfall wash-off will lead to a more accurate assessment. Future research should include these factors to better understand GBGI's role in air quality control, standardise impact quantification and enable more effective design, and inform decision-making and optimal placement of GBGI elements in cities.

Understanding air pollution removal mechanisms by GBGI also requires further research. Existing dispersion models often oversimplify mechanisms, neglecting combined effects and the role of deposition across plant species, potentially skewing predictions of the impact of urban vegetation. Most studies focus on PM deposition on plant surfaces by weight and number, often overlooking exposure time and capacity. Literature on detailed removal mechanisms by blue infrastructure is so far limited, especially when considering natural dispersion in areas with lower emission sources.

Most studies in this review evaluated air pollution impacts of linear feature street trees in urban areas. However, evidence on most other GBGIs is lacking, and the reported air pollution reduction potentials may change as evidence emerges. Many studies focused on PM concentration changes with GBGIs, but there is a need to assess other pollutants, including gaseous and biological ones, for a comprehensive understanding of GBGI impacts on air quality. The variety in quantification methods and result reporting makes intercomparison challenging. Furthermore, there is a shortage of holistic multi-scale studies assessing both micro- and macro-scale impacts of GBGIs in urban areas. This is crucial since GBGIs show positive air quality changes on the macro-scale, but some micro-scale environments, such as street canyons, may experience the opposite. Eliminating this uncertainty will enable unambiguous implementation of GBGIs by policy makers and authorities.

This review highlights a geographic skew in studies, with most originating from Europe and Asia (primarily China) and only 1% from Africa (Figure 1B). This underscore limited research in low- and middle-income countries, where urbanisation and air pollution impacts are more severe. Rapidly urbanising regions with high sprawl[150] need studies in diverse environmental and geographical contexts to support urban planning and effective GBGI implementation, enhancing resilience against changing environmental and pollution conditions.

The meta-analysis reveals critical research gaps in understanding the impact of GBGI on air quality. Only 26 studies qualified, investigating six GBGI types, including street trees, hedges, green roofs, parks, shrublands, and mixed-GBGI. In addition, the focus on PM_{10} and $PM_{2.5}$ overlooks other key pollutants like NO_2, bVOCs and O_3, highlighting the need for more comprehensive research on various GBGI types and a broader spectrum of pollutants.

Further research is necessary to investigate the effectiveness of specific GBGI components, such as parks, street trees, green roofs, and green walls, in reducing the impact of climate change on air quality, especially in regions with varying climatic conditions. Additionally, studies should assess the long-term efficiency, scalability and socio-economic implications of GBGI strategies. This information will support evidence-based decisions and promote the widespread adoption of GBGI measures for climate adaptation and air quality improvement.

CONCLUSIONS AND RECOMMENDATIONS

This review synthesises and assesses the air pollution reduction potential for a comprehensive range of GBGI types. A meta-analysis quantitatively compared GBGI effectiveness, identifying key factors influencing air quality enhancement and addressing complexities in GBGI evaluation. Key research gaps and future directions are highlighted. The following conclusions are drawn:

- ***Air quality is affected differently by GBGIs.*** The varied pollutant reduction percentages for hedges, parks, mixed-GBGI, and street trees demonstrate the nuanced effectiveness of different GBGI types. Constructed GIs and linear features significantly improve air quality nearby, especially in open-road conditions. Green walls, assessed mainly by field campaign monitoring and green roofs using modelling techniques, show average PM reductions of 8±24% and 2±11%, respectively. Street trees can either deteriorate air quality in street canyons or improve it on open roads, depending on factors like tree distance, canopy height, tree stand porosity and species. Mixed-GBGI (e.g., trees plus hedges) presented enhanced performance with higher pollution reductions in open-road conditions reaching up to 66%.

- ***Among modelling studies, CFD models are the most commonly used.*** The ENVI-met model stands out as the most used within the domain of CFD models. These models mainly evaluate the impact of street trees. Among the street trees modelling studies, 84% utilised the CFD model, followed by i-Tree (6%) and other models (9%), such as Solow's neoclassical, dry deposition and system dynamics models. These studies highlight that dispersion influences air pollution concentration in linear features and constructed GIs at the microscale. Considering all GBGI, tools such as the i-Tree (or UFORE model) and the Weather Research and Forecasting model were used in 13% and 9% of the research efforts, respectively. The i-Tree model combines field data with local air pollution and meteorological information to assess the environmental, economic, and structural benefits of urban forests. The remaining 21% of studies used various other models, such as the support vector machines (SVM) model, big-leaf dry deposition model, land use regression model (LUR), and gaussian plume model (ADMS-Urban), and EMEP among others. Using integrated modelling approach considering both deposition and aerodynamic effects of GBGI must be prioritised in future research to produce results that are more comprehensive and eliminate the uncertainties caused by oversimplification and often-dismissed factors (e.g., exposure time and deposition capacity for PM).

- ***All the evaluated GBGIs showed potential to improve air quality.*** GBGIs reduce PM as well as gaseous pollutants, highlighting their importance in improving urban air quality. Among the eight primary GBGI categories, four show notable reductions in air pollutants: linear features (23±21%), parks (22±34%), constructed GI (14±25%), and other non-sealed urban areas (14±20%). Additionally, specific GBGI subtypes demonstrate effectiveness in mitigating the adverse effects of air pollutants, such as woodlands (21±38%), hedges (14±25%), and green walls (14±27%). On average, GBGI reduces PM_1, $PM_{2.5}$, PM_{10}, UFP, and BC by 13±21%, 1±25%, 7±42%, 27±27%, and 16±41%, respectively. Similarly, GBGI shows reductions in gaseous pollutants, with average decreases of 10±21% for CO, 7±21% for O_3, and 12±36% for NO-NO_2-NO_x. The majority of the reviewed studies focused on linear features, despite the fact that many GBGIs showed the potential to reduce air pollution. More emphasis should be given to the less assessed GBGIs and understudied pollutants (especially gaseous and biological pollutants) to enhance the current evidence of their impacts and broaden the options for green space interventions.

- ***GBGI and air pollution reduction are climate and urban morphology dependent.*** The complexity arises from the diverse mechanisms through which GBGI functions against pollutants and the varied environmental conditions and urban settings in cities. Additionally, the variety of GBGI types poses challenges in drawing conclusions across different scales, whether individual species or larger areas like parks. Computational models may oversimplify GBGI attributes, not fully capturing real-life complexities. Moreover, understanding potential air quality deterioration associated with street trees, particularly in street canyons, emphasises the importance of considering contextual factors and location-specific characteristics when implementing GBGIs.

- ***The impact of GBGI on air quality is spatially and scale dependent.*** Studies at micro-, macro-, and meso-scales show that GBGI characteristics (e.g., physical dimensions, LAI or porosity, seasonal changes), built environment (e.g. open-road, street canyon) and environmental features (e.g., wind direction and speed, seasonal changes) affect air pollution concentration in urban environments. At the micro-scale, GBGI's impact on air pollution is dominated by dispersion effects. At the macro-scale, parks, and other non-sealed urban areas, such as woodland, effectively improve air quality. The extent of GBGI coverage and seasonal variations also determine air pollution reduction potentials. Further multiscale studies, which examine the GBGI impacts simultaneously at the micro- and macro-scale, could minimise the uncertainties associated with the spatial scales as well as the meteorological and climatic conditions.

- ***Deriving conclusions from GBGI studies poses various challenges.*** The lack of clear definitions, inconsistent dimensions and metrics, variable sampling design and monitoring periods, and divergent parameter choices and GBGI representation in studies hinder conclusive findings. Addressing these challenges requires interdisciplinary collaboration, standardised terminology and methodologies, and GBGI designs aligned with evolving demands in a changing urban climate. These efforts will be crucial in developing a standardised framework to assess the effects of GBGI, and guide planners and policy makers in optimising green space interventions within cities.

- ***The results are relevant for urban planning and policy development.*** Urban planners can strategically incorporate different GBGIs into city landscapes to enhance overall air quality. Policymakers can utilise these findings to formulate targeted policies supporting the establishment and maintenance of green spaces prompting the creation of greener urban environments. Strategic integration of GBGI into urban planning can reduce air pollutants and maximise their benefits for air quality improvement. Policymakers should emphasise the importance of gathering additional evidence on lesser-known types of GBGI, such as cycle tracks, road verges, riparian woodlands, wetlands, rivers, and lakes. Investing in GBGI and integrating climate-responsive approaches into urban planning policies can help mitigate the adverse effects of climate change on air quality and promote sustainable development.

- ***GBGI contributes to climate change mitigation and adaptation efforts.*** Climate change-induced shifts in temperature and precipitation patterns, such as transitions from temperate oceanic to continental climates in Western Europe and from temperate continental to humid subtropical in China, are expected to exacerbate existing air pollution issues and introduce new challenges across various regions. These shifts can lead to increased formation of ground-level O_3 and PM, affecting air quality and public health. Adaptation strategies must prioritise the implementation and expansion of GBGI tailored to current and future climate conditions. Effective GBGI options include street trees, hedges, green roofs, parks, mixed woodlands, lakes, grasslands, green walls, zoological gardens, and botanical gardens. Enhancing air quality and mitigating climate change go hand in hand with the implementation of GBGI.

- ***There is a lack of studies on gaseous pollutants.*** Among the 160 studies examined, 36% addressed gaseous pollutants (e.g., NO_2, NO, CO, CO_2, SO_2, NH_3, O_3), but only 19% reported a percentage change due to GBGI. The available data covered the following GBGI: street trees, park, city farm, adoptable public space, green roof, green wall, lake, woodland, grassland, shrubland, arable agriculture, mixed-GBGI and cycle track. The percentage change in gaseous pollutants ranged widely from −274% to +78%, highlighting the need for more studies to narrow down this range and better elucidate their influence on air pollution.

The above findings allowed us to make the following recommendations:

- ***Prioritise research and data collection on non-linear GBGI features.*** Appreciable amount of information is available on linear GI features, such as street trees and hedges/shrubs, unlike other GBGI types. Insufficient information on rivers, road verges, riparian woodland, playgrounds, city farms, wetlands, adoptable public space, arable agriculture, and zoological gardens can hinder the evidence-based introduction of comprehensive greenery in cities. This gap can lead to implementation without understanding their impacts or causing unintended consequences. Thus, there is a need to develop an understanding of various GBGI types for air pollution reduction under diverse environmental conditions.
- ***Carefully evaluate the environmental context when incorporating GBGI in urban areas.*** Strategic implementation and expansion of GBGI areas should aim for optimal coverage, proximity to pollution sources, and thoughtful placement concerning surrounding structures. In micro-scale environments, linear features and constructed GBGIs are beneficial in open-road urban areas. However, in street canyons, the aspect ratio and prevailing wind directions must be considered to prevent unintended air quality deterioration. Local studies are essential to identify the most appropriate and effective species or vegetation forms of GBGI types in a specific geographical location for air pollution removal through deposition.
- ***Mixed-GBGI can potentially amplify the positive impact on air quality.*** Reductions in air pollution found in the meta-analysis were most pronounced for mixed-GBGI, reaching up to 28% (Table S6). Most GBGI types improve air quality in open-road conditions due to deposition, pollution blocking and redistribution capacities. Mixed GBGI further enhances efficacy in reducing air pollution concentration and increases vegetation species diversity.
- ***Increasing green spaces and water bodies can mitigate air pollution, but additional research is required.*** While the primary strategy should focus on controlling source emissions, augmenting urban green cover with parks and water bodies could significantly reduce air pollution concentrations. Further research on specific GBGI types and vegetation species is necessary to support decision-making.
- ***Prioritise and conduct studies on the effect of GBGI in low-income countries.*** Most GBGI studies on air pollution are from Europe, with limited research from low and middle-income countries, primarily from China. This scarcity undermines decision-making for GBGI application in diverse geographical and climate contexts, emphasising the need for GBGI investigations, particularly in rapidly urbanising regions.
- ***Standardise definitions for each GBGI and adopt consistent methodologies to facilitate comparisons.*** The lack of standardised definitions and varied scales in GBGI pose challenges for drawing generic conclusions. Establishing standardised definitions, consistent assessment methodologies, and transparent reporting practices is essential to enhance comprehension and facilitate comparisons among GBGIs. This is crucial for developing sustainable global strategies to mitigate air pollution exposure whilst making urban areas resilient and sustainable through their co-benefits.
- ***Standardised reporting practices are needed to enhance research comparability across different GBGI and climate zones.*** To allow cross-comparability of diverse GBGI studies, it is important to (1) provide detailed, consistent methodology description, including local weather parameters, data collection procedure and analysis methods; (2) ensure transparency in data presentation with statistical measures, like mean, median, standard deviation, and confidence intervals; and (3) include a control area without GBGIs to evaluate their effectiveness.

Beyond these findings and recommendations, this study highlights a major gap in scientific evidence, revealing that around 29 GBGI types have never been studied for air pollution reduction potential. Implementations are often based on expert judgement, and inconsistent reporting hinders direct comparisons. Further research is crucial to integrate these less studied but possibly effective GBGI types into urban air pollution and climate plans for enhancing urban resilience.

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Prashant Kumar: Conceptualisation, Methods, Supervision, Project Administration, Funding, Data analysis (Figures, Tables), Writing - Original Draft, Writing - reviewing & editing. **Karina Corada, Sisay Debele, Ana Paula Mendes Emygdio, Abhijith Kooloth Valappil, Hala Hassan and Parya Broomandi**: Conceptualisation, Methods, Data extraction, Data analysis (Figures, Tables), Writing - Original Draft, Writing - reviewing & editing. **Richard Baldauf**: Methods, Writing - review & editing. **Nerea Calvillo**: Methods, Funding, Writing - review & editing. **Shi-Jie Cao, Sylvane Desrivières, Zhuangbo Feng and John Gallagher**: Methods, Writing - review & editing. **Thomas Rodding Kjeldsen**: Methods, Funding, Writing - review & editing. **Anwar Ali Khan, Mukesh Khare, Sri Harsha Kota and Baizhan Li**: Methods, Writing - review & editing. **Shelagh K Malham**: Methods, Funding, Writing - review & editing. **Aonghus McNabola, Anil Namdeo, Arvind Kumar Nema, Stefan Reis, Shiva Nagendra SM, Abhishek Tiwary, Sotiris Vardoulakis, Jannis Wenk, Jannis Wenk, Fang Wang, Junqi Wang, Darren Woolf and Runming Yao**: Methods, Writing - review & editing. **Laurence Jones**: Conceptualisation, Funding, Methods, Writing - review & editing. All authors commented on the draft manuscript and assisted in the conceptual development of the text, tables, figures, and the overall cohesiveness and proofreading of the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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Supplemental Information

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SUPPLEMENTAL SECTION

SUPPLEMENTAL FIGURE

multiple approaches) for ambient concentration (the upper panel) and deposition (the lower panel) considering different GBGI. The percentage changes are represented in range and include the minimum and maximum changes. Negative values represent deterioration of air quality, while positive values represent improvement in air quality. The number printed on the y-axis provides studies used under each GBGI, shown in Table S4.

SUPPLEMENTAL TABLE

Table S1. Description of the ten GBGI categories and details of 51 GBGI types under each main category.

Table S2. Description of Search terms for each GBGI type. Searching for each object category carried out by adding searching term(s) to: (urban OR city OR cities OR town*) AND ("air pollution*" OR "air quality*" OR "air pollution exposure*") AND.

Table S3. Classification of GBGI based on removal mechanisms considered in evaluating air pollution change.

Table S4. Reported percentage changes (max, min, mean and sd) in each category type, considering the studies available that provide the percentage change under each GBGI and different pollutants, study and measurement types. Negative values represent deterioration of air quality, while positive values represent improvement of air quality; the studies have employed different measurement methods and reference points to calculate the percentage differences mentioned in Sections 4, 5 and 6. The table includes values only if they were reported in at least one paper.

Table S5. Reported percentage changes (max, min, mean and SD) in each category type, considering the studies available that provide the percentage change under each GBGI and different pollutants and built environment (open road and street canyon). Negative values represent deterioration of air quality, while positive values represent improvement of air quality; the studies have employed different measurement methods and reference points to calculate the percentage differences mentioned in Sections 4, 5 and 6. The table includes values only if they were reported in at least one paper.

Table S6. Overview of meta-analysis results across the different GBGI and pollutants. This table summarises key information extracted from the meta-analysis and includes the rate of change, STD, reduction (%), p-value, 95%CI, prediction interval, I2 and imputed reduction rate.

Table S7. Percentage change in pollutant levels for street trees in street canyon with varied aspect ratio definitions

Table S8. Indicative evolutionary patterns from published literature of the role of different GBGI components on the human health and climate change adaptation initiatives.

Table S9. The impact of current and future climate on air pollution and the role of GBGI in managing air pollution under future climate change scenarios.

Table S10. Average percentage changes and number of studies for each GBGI category considering all pollutants. Negative values represent deterioration of air quality, while positive values represent improvement of air quality; the studies have employed different measurement methods and reference points to calculate the percentage differences mentioned in Sections 4, 5 and 6. The table includes values only if they were reported in at least one paper.

References

S1. GBGI health benefits

In an era characterised by urbanisation and climate change, the need for sustainable solutions to mitigate air pollution and its associated health impacts has become increasingly urgent Although the link between exposure to green/blue spaces and health and well-being has not been definitively proven (Grellier et al, 2017; Kumar et al., 2019a); there are evolutionary patterns that suggest the role of different components of GBGI on health impact and climate change adaptation initiatives (Table S8). A recent review of different nature-based sustainability strategies (Tiwary and Brown, 2024) has found strong evidence for the role of GBGI in developing resilient and healthy/liveable urban landscapes in a changing climate. These studies show the association between public health and natural environments in relation to the following pathways: socio behavioural/cultural Ecosystem Services (e.g., stress and physical activity) and regulating Ecosystem Services (e.g., heat reduction) – or defined health outcomes (e.g, cardiovascular mortality) (van den Bosch and Ode Sang, 2017). The impact of GBGI on health and climate greatly depends on the characteristics of the specific GBGI category, the geographical conditions of the area, and whether it presents direct and indirect effects for local and national conditions. The positive benefits of GBGI on human health range from direct mental health benefits (e.g., White et al., 2021) to promoting physical activity (e.g., Yen et al., 2021) and providing interactive and accessible social spaces (e.g., Mell and Whitten, 2021), whilst also reducing pollution in the air and water (e.g., Nieuwenhuijsen et al., 2021). From a climate perspective, different forms of GBGI infrastructure offer benefits of carbon sequestration (e.g., Liu et al., 2021), reductions of urban heat island (e.g., Antoszeski et al., 2020), energy savings for buildings (e.g., Liu et al., 2021b), and enhancing biodiversity (e.g., Donati et al., 2022). In addition, studies like Javadi and Nasrollahi (2021) have noted the nexus or co-benefits between health and climate that further highlight the value of GBGI in the built environment.

The implementation of GBGI, particularly GI, has significant implications for public health (Nieuwenhuijsen, 2021). GI can impact human health in two primary ways: directly, by influencing human physical and mental health, and indirectly, by influencing human living environments (Dover, 2015; Labib et al., 202; Ying et al., 2021). GBGI, such as parks, urban forests, wetlands, and blue-green corridors, provide opportunities for physical activity, relaxation, and social interaction. It contributes to human health by enhancing urban aesthetics, providing recreational opportunities, and promoting psychological restoration. Access and exposure to these green and blue areas encourage outdoor exercise, positively affecting cardiovascular health, muscular strength, and overall fitness, reducing all-cause mortality and morbidity (Vert et al., 2019). Increased physical activity through recreational walking, cycling, and running can have positive effects on cardiovascular health, neurocognitive development, and general well-being and can reduce sedentary lifestyles (Vert et al., 2019; Stangierska et al., 2023). People who live in the greenest areas engage in 13 to 18% more days of physical activity than people who live in areas lacking greenery (Lachowycz & Jones, 2014). In addition, access and exposure to GBI also reduce stress, anxiety, and depression levels, leading to improved mental well-being (White et al., 2021; Geary et al., 2023). Engaging in “blue-green” outdoor activities has been found to have numerous benefits for individuals, including an increase in self-esteem, positive engagement, improved depressive mood, and reduced anxiety (Coventry et al., 2021; Cardinali et al., 2024). Additionally, being in a green environment has been shown to decrease feelings of loneliness, frustration, worry, confusion, depression, tension, and tiredness (Sandifer et al., 2015; Mygind et al., 2019). Furthermore, nature based stress management intervention has been reported to reduce burnout fatigue and long-term sick leaves, and improve workability among the working age female population in Sweden (Sahlin et al., 2014). GBI indirectly mitigates the urban heat island effect, reducing heat-related illnesses and enhancing thermal comfort for vulnerable populations during extreme temperatures. avoiding greater risk of worsening mood or behaviour disorders, violence, aggression and anxiety disorder (Andreucci et al., 2019; Liu et al., 2021a).

S2. Meta-analysis

Meta-analysis was employed to (i) synthesise findings from diverse GBGI studies, providing a comprehensive overview of their collective impact on air pollution mitigation; (ii) quantify effect sizes for an overall reduction in pollutant concentrations; and (iii) identify factors influencing the effectiveness of air pollution abatement strategies. Meta-analysis software (version 4.0) conducted analyses for each GBGI type, incorporating data meeting specific criteria: (1) at least three studies per GBGI category for each pollutant (Luben et al., 2023; Higgins et al., 2023), and (2) detailed statistics including mean, standard deviation, and sample size.

Initially, models with fixed and/or random effects were considered to address study variability, and the I2 statistic assessed heterogeneity, with values above 40% deemed significant, following Cochrane Handbook guidelines (Higgins et al., 2023). The random-effects model was selected for fewer than five studies or high diversity, assuming related but diverging intervention effects. Forest plots illustrated effect estimates with 95% CIs, considering a p-value <0.05 as statistically significant (Borenstein et al., 2009; Schriger et al., 2010; Higgins et al., 2023). Symbol size in plots indicated the study's relative weight.

Publication bias was evaluated through funnel plots and Egger's regression tests. Trim and fill methods addressed potential bias impact, but adjusted estimates were reported cautiously due to inherent limitations. Trim and fill methods solely rely on a presumption of symmetrical funnel plots, with uncertainty regarding adjusted intervention effects and potential causes for imbalance. Interpretation of corrected predictions should be cautious, especially with substantial variation between studies (Terrin et al., 2003; Peters et al., 2007).

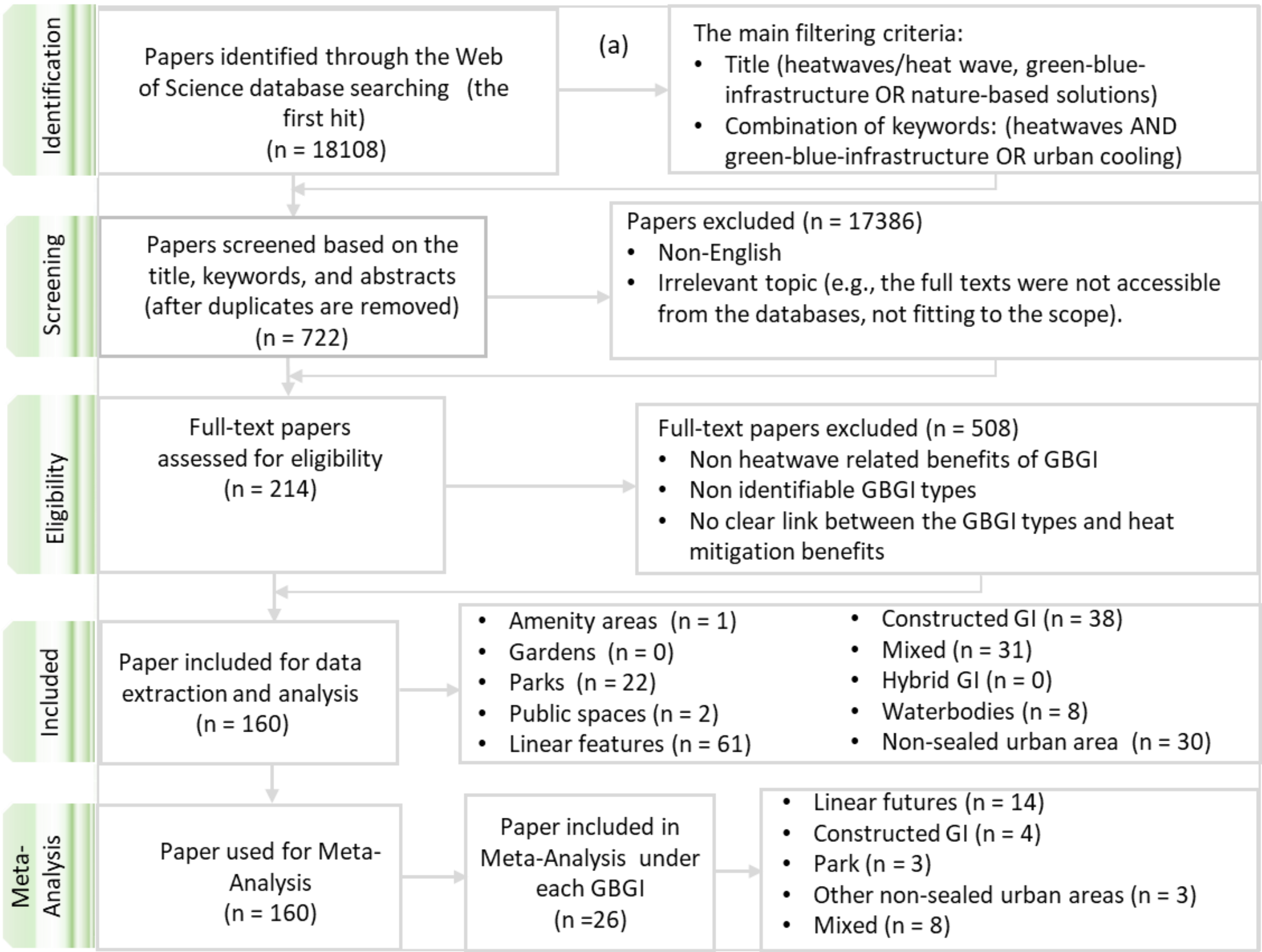

Figure S1. Schematic representation of literature selection procedure. A comprehensive four-stage process was conducted to identify and select relevant scientific articles for review and data extraction. 1) Identification: Using the terms provided by Table S2, it was systematically searched in Web of Science database for peer-reviewed studies published between 2010 and 2023. This gave 18,108 relevant publications. 2) Screening: Of these relevant publications, titles and abstracts were read. Non-English articles, those published before 2010, studies lacking specific details on GBGI types, and those not conducted in real-world urban settings or without comparators were excluded, resulting in 722 papers. 3) Eligibility: further full-text screening. Applied criteria to ensure articles provided quantitative data on GBGI impact, comparisons, and detailed descriptions, reduced to 214 articles. 4) Included: The selected papers were read again, selecting at the end 160 articles for this literature review (0.88% of the initial search). This final number of selected articles were used for meta-analysis.

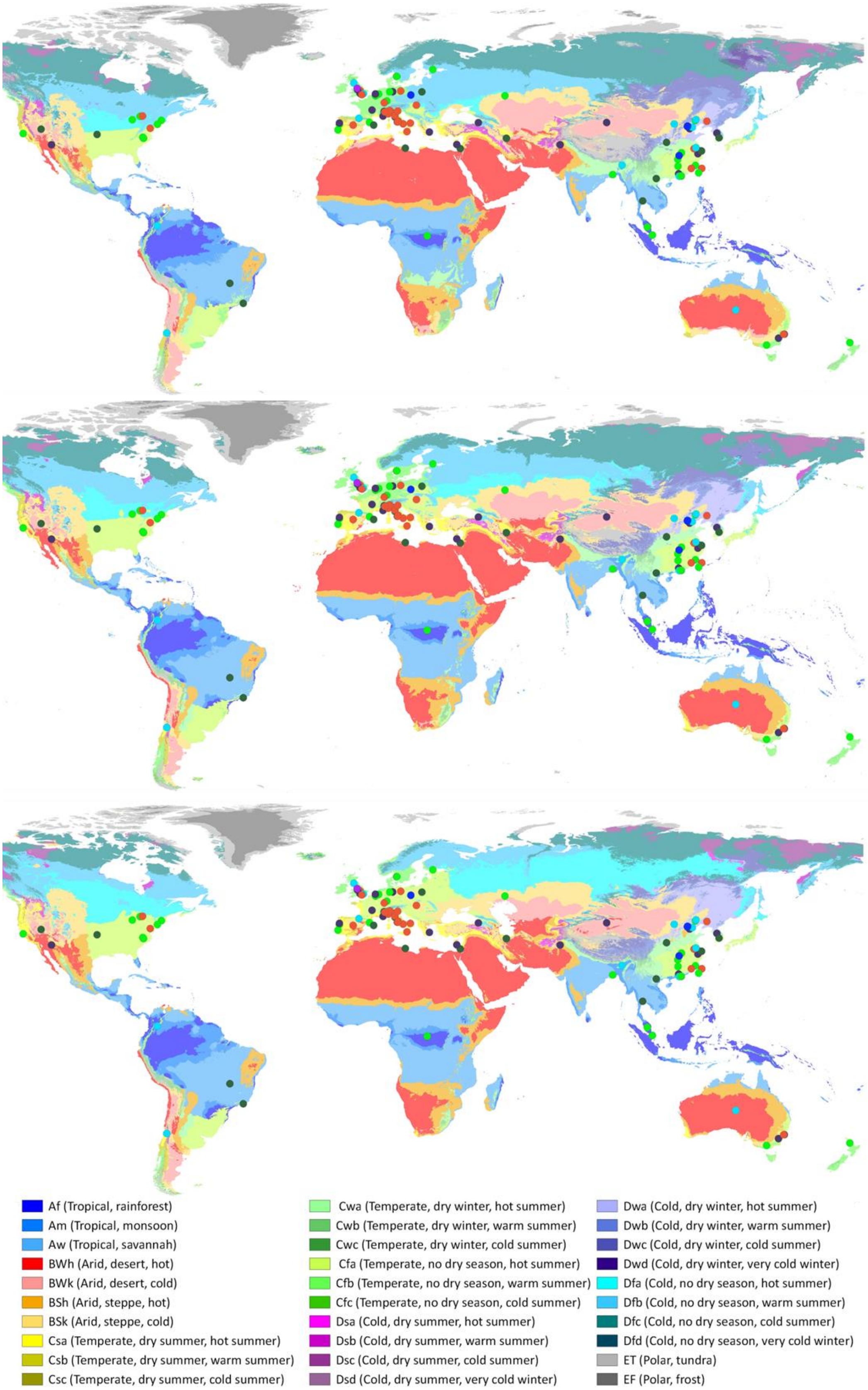

Figure S2. Base maps are Köppen-Geiger classifications, and the points are locations of eight GBGI categories: (a) shows the present-day map (1991–2020), near-future (2041-2070) and the future map (2071–2100) under the RCP8.5 scenario.

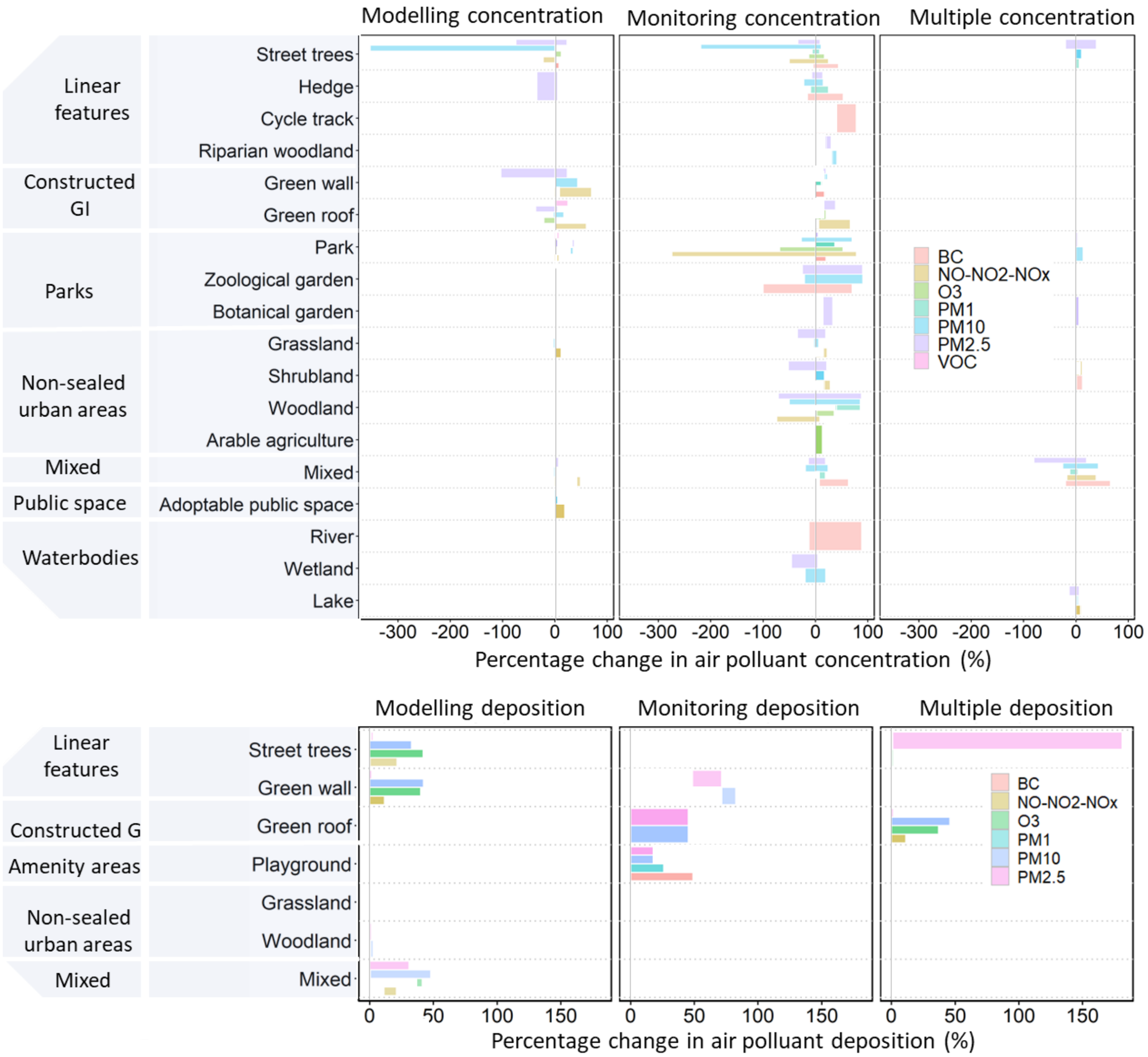

Figure S3. Extracted percentage change using different methodology (modelling, monitoring, and multiple approaches) for ambient concentration (the upper panel) and deposition (the lower panel) considering different GBGI. The percentage changes are represented in range and include the minimum and maximum changes. Negative values represent deterioration of air quality, while positive values represent improvement in air quality. The number printed on the y-axis provides studies used under each GBGI, shown in Table S4.

Table S1. Description of the ten GBGI categories and details of 51 GBGI types under each main category.

Object type (& description)	**Object category**	**Description/Assumptions**
Gardens *(Mainly private space linked to dwellings)*	Balcony	A few plant pots, mostly flowers
	Private garden	Mostly grass, some paving, a few trees
	Shared common garden area	Mixed grass, paving and flower beds, assume few trees
Parks *(Mainly public space, but some access restrictions may apply)*	Pocket park	Small (up to 0.4 ha); Mix of paving, grass, a few trees
	Park	Larger than 0.4 ha; More grass than trees, may contain water features, some sealed surfaces and infrastructure
	Botanical garden	More trees than a park
	Heritage garden	Similar to park, often a formal layout, more flowers
	Nursery garden	Growing area for young plants; Few mature trees
Amenity areas *(Areas designed primarily for specific amenity uses)*	Sports field	Assume grass, not artificial surface
	School yard	Mostly paved
	Playground	Mix of paving, grass
	Golf course	Mostly grass, a few trees, occasional water features
	Shared open space (e.g. square)	Mostly paved
Other public space *(Areas designed primarily for specific uses (not leisure); some access restrictions may apply)*	Cemetery	Mix of grass, trees and paved surfaces
	Allotment/other growing space	Mostly low-growing crops, soil disturbed frequently
	City farm	Mostly low-growing crops, soil disturbed frequently
	Adopted public space	Mostly 'tubs' or 'planters' with flowers or small shrubs, in public space
Linear features/routes *(Linked to routeways, geographical features and boundaries)*	Street tree	Typically low to medium height trees, can be large trees
	Cycle track (as part of blue/green corridor)	Usually bare surface, with grass verge
	Footpath (as part of blue/green corridor)	Usually bare surface, with grass verge
	Road verge	Usually grass
	Railway corridor	Land alongside railway infrastructure, often shrubs or trees
	Riparian woodland	Usually mature or mixed age trees
	Hedge	Usually formed of maintained shrubs, 1-2 m tall
Constructed GI on infrastructure *(Constructed green and blue space, added to infrastructure)*	Green roof (extensive)	Usually formed of Sedum & other drought-tolerant species, some grasses
	Green wall	Contains low stature or hanging species, often maintained by complex watering infrastructure
	Roof garden (intensive)	Mix of decking, paving and plants

	Pergola (with plants)	Structure covered with climbing plants
Hybrid GI for water *(Infrastructure designed to incorporate some GI components)*	Permeable paving	Limited permeability, not usually vegetated
	Permeable parking/roadway	Reasonable permeability, typically block paving or plastic pavers with grass
	Attenuation pond	Basin with mostly grass and reeds, some trees, with managed drainage for storm events
	Flood control channel	Usually constructed with earth/stone banks or concrete, some contain natural features
	Rain garden	Small constructed drainage areas near houses/roads to intercept runoff, often planted with native shrubs, perennials, and flowers
	Bioswale	Often large, long structure, usually with grass or low vegetation, near roads/parking to retain or slow drainage water
Water bodies *(Bluespace features)*	Wetland	Natural or constructed wetland, with reeds/tall vegetation
	River/stream	Small to large river/stream, often highly modified channel
	Canal	Artificial channel, vertical sides, controlled flow (usually slow)
	Pond	Small waterbody <1 ha
	Lake	Larger waterbody >1 ha
	Reservoir	Artificially created large waterbody, water level usually controlled
	Estuary/tidal river	Tidally influenced brackish or freshwater, may include saltmarsh
	Sea (incl. coast)	Sea and coast, includes beaches
Other non-sealed urban areas (*Other un-sealed features without specified use, often on private land*)	Woodland (other)	Any woodland not defined in specific features above
	Grass (other)	Any grassland not defined in specific features above
	Shrubland (other)	Any shrubland not defined in specific features above
	Arable agriculture	Any arable land (pastures come under Grass (other); orchards come under Woodland (other))
	Sparsely vegetated land	Mostly bare earth, but some plants

Table S2. Description of Search terms for each GBGI type. Searching for each object category carried out by adding searching term(s) to: *(urban OR city OR cities OR town*) AND ("air pollution*" OR "air quality*" OR "air pollution exposure*") AND*.

	Brief description	**Object type**	**Object category**	**Search term(s)**
Predominantly green features	Mainly private space linked to dwellings	Gardens	Balcony	(balcony* OR terrace*)
			Private garden	(garden* OR backyard*)
			Shared common garden area	("shared garden*" OR "communal garden*" OR "community garden*")
	Mainly public space, but some access restrictions may apply	Parks	Pocket park	("pocket park*")
			Park	(park* NOT "pocket park*")
			Botanical garden	("botanical garden*" OR arboretum*)
			Heritage garden	("heritage garden*")
			Nursery garden	("nursery garden*")
			Zoological garden	(zoo OR zoos OR "zoological garden*")
	Areas designed primarily for specific amenity uses	Amenity areas	Sports field	(sports* OR recreation* OR football*)
			School yard	("school ground*" OR schoolyard* OR "school yard*")
			Playground	(playground*)
			Golf course	(golf*)
			Shared open space (e.g., square)	(square* OR plaza* OR piazza*)
	Areas designed primarily for specific uses (not leisure); some access restrictions may apply	Other public space	Cemetery	(cemetery* OR graveyard*)
			Allotment/other growing space	(allotment* OR "vegetable*")
			City farm	(farm*)
			Adopted public space	(tub OR tubs OR planter*)
	Linked to routeways, geographical features and boundaries	Linear features/ routes	Street tree	("street tree*")
			Cycle track (as green/blue corridor)	("*cycle path*" OR "*cycle track*")
			Footpath (as green/blue corridor)	(footpath*)
			Road verge	(roadside* OR verge*)
			Railway corridor	(rail*)
			Riparian woodland	("riparian tree*" OR "riparian wood*" OR "riparian forest*")
			Hedge	(hedge*)
Constructed features	Constructed green and blue space, added to infrastructure	Constructed GI on infrastructure	Green roof	("green roof*")
			Green wall	("green wall*" OR "green facade*")
			Roof garden	("roof garden*" OR "roof terrace*")

			Pergola (with vegetation)	(pergola*)
Blue features or those designed for water management	Infrastructure designed to incorporate some GBS components	Hybrid GI (for water)	Permeable paving	("permeable pav*")
			Permeable parking/roadway	("permeable park*" OR "permeable road*")
			Attenuation pond	("attenuation pond*")
			Flood control channel	(flood* OR channel*)
			Rain garden	("rain garden*")
			Bioswale	(bioswale*)
			Outdoor swimming pool	(swim* AND pool*)
	Blue space features	Waterbodies	Wetland	(wetland* OR marsh*)
			River/stream	(river* OR stream*)
			Canal	(canal*)
			Pond	(pond*)
			Lake	(lake*)
			Reservoir	(reservoir*)
			Estuary/tidal river	(estuar*)
			Sea (incl. coast)	(sea OR seaside OR coast* OR beach* OR shore*)
Predominantly green features	Other un-sealed features without specified use, often on private land	Other non-sealed urban areas	Woodland (other)	(wood* OR forest* OR tree*)
			Grass (other)	(grass* OR meadow*)
			Shrubland (other)	(shrub*)
			Arable agriculture	(agricultur* OR arable)
			Sparsely vegetated land	(bare* OR "building site*" OR brownfield)
			General terms for greenspace	((green OR blue) AND (infrastructure OR space)) OR (natur* AND solution*)

Table S3. Classification of GBGI based on removal mechanisms considered in evaluating air pollution change.

Papers	GBGI	Category	Mechanism
Buccolieri et al., 2011; Salim et al., 2011a; Salim et al., 2011b; Ng and Chau, 2012; Gromke and Ruck, 2012; Hagler et al., 2012; Li et al., 2013; Amorim et al., 2013; Jin et al., 2014; Gromke and Blocken, 2015; Abhijith and Gokhale, 2015; Vranckx et al., 2015; Moradpour et al., 2017; Lin et al., 2016; Buccolieri et al., 2018; Li et al., 2023b; Baró et al., 2019; Wang et al., 2020; Jung and Yoon, 2022; Li et al., 2023a	Street trees 50	Linear features	Dispersion
Wania et al., 2012; Salmond et al., 2013; Vos et al., 2013; Al-Dabbous and Kumar, 2014; Grundström and Pleijel, 2014; Chen et al., 2015; Fantozzi et al., 2015; Tong et al., 2016b; Morakinyo and Lam, 2016b; Jeanjean et al., 2017a; Lin et al., 2020; Zhang et al., 2021; Miao et al., 2021; Miao et al., 2022b; Motie et al., 2023; Harris and Manning, 2010; Karttunen et al., 2020; Kim et al., 2017; Liu et al., 2022a; Santiago et al., 2022; Wang et al., 2022b; Jeanjean et al., 2016; Deshmukh et al., 2019; Abhijith and Kumar, 2019; Taleghani et al., 2020			Combined
Blanusa et al., 2015; Jo et al., 2020; Tallis et al., 2011; Tan et al., 2022; Sicard et al., 2018			Deposition
Gromke et al., 2016; Li et al., 2016; Wania et al., 2012; Jia et al., 2021; Taleghani et al., 2020; Li et al., 2023a	Hedge 23		Dispersion
Vos et al., 2013; Hashad et al., 2023; Tran et al., 2022; Kumar et al., 2022; Chen et al., 2021; Donateo et al., 2021; Ottosen and Kumar, 2020; Abhijith and Kumar, 2019; Santiago et al., 2019; Morakinyo et al., 2016; Vos et al., 2013; Motie et al., 2023; Karttunen et al., 2020; Liu et al., 2022a; Santiago et al., 2022; Wang et al., 2022b			Combined
Abhijith and Kumar, 2020			Deposition
Wang et al., 2021; Zhao et al., 2021; Sou et al., 2021	Riparian woodland 4		Combined
Nemitz et al., 2020			Deposition
Motie et al., 2023; Wang et al., 2022b	Road verge 4		Combined
Popek et al., 2022; Przybysz et al., 2021			Deposition
Kaminska et al., 2023; Lonati et al., 2017	Cycle track 2		Combined
Qin et al., 2018; Li et al., 2023a	Green wall 23	Constructed GI	Dispersion
Paull et al., 2020a; Srbinovska et al., 2021; Ysebaert et al., 2021; Anderson and Gough, 2020; Ghazalli et al., 2018; Morakinyo et al., 2016; Santiago et al., 2022; Tong et al., 2016b			Combined
Ottelé et al., 2010; Sternberg et al., 2010; Pugh et al., 2012; Jayasooriya et al., 2017; Weerakkody et al., 2017, Viecco et al., 2018; Weerakkody et al., 2018; Paull et al., 2020b; He et al., 2020; Pettit et al., 2021; Tomson et al., 2021b; Vera et al., 2021			Deposition
Baik et al., 2012; Saxena and Yaghoobian 2022; Rafael et al., 2018; Qin et al., 2018; Park et al., 2016; Moradpour et al., 2018; Hosseinzadeh et al., 2022; Li et al 2023a	Green roof 28		Dispersion

Luo et al., 2015; Barmparesos et al., 2020; Rafael et al., 2020; Anderson and Gough 2020; Viecco et al., 2021; Santiago et al., 2022; Wang et al., 2022c; Tong et al., 2016a; Rafael et al., 2021; Arghavani et al., 2019			Combined
Vera et al., 2021; Arbid et al., 2021; Viecco et al., 2018; Hirabayashi et al., 2012; Irga et al., 2022; Jayasooriya et al., 2017; Rowe 2011; Yang et al., 2008; Jayasooriya et al., 2017			Deposition
Heshani and Winijkul 2022	Parks 15	Parks	Dispersion
Benedict et al., 2020; Bonn et al., 2016; Klingberg et al., 2017; Qin et al., 2019; Su et al., 2022; Xing and Brimblecombe 2019; Yin et al., 2011; Cohen et al.,2014; Moradpour and Hosseini 2020; Niu et al., 2022; Gomez-Moreno et al., 2019			Combined
Fares et al., 2020; Nemitz et al., 2020; Zhou et al., 2019			Deposition
Phan et al., 2020; Maia et al., 2022	Zoological garden 2		Combined
Chen et al., 2016; Junior et al., 2022	Botanical garden 5		Combined
Szkop 2016; Hrotko et al., 2021; Liang et al., 2017			Deposition
Maher et al., 2022	Playground 1	Amenity areas	Deposition
Tong et al., 2016a; Elsunousi et al., 2021	City farm 2	Other public space	Combined
Zafra et al., 2017; Rui et al., 2018; Dai et al., 2023; Cai et al., 2020; Tiwari and Kumar 2020; Alsalama et al., 2021; Badach et al., 2020; Chen et al., 2019; de la Paz et al., 2022; Wang et al., 2021	Grassland 16	Other non-sealed urban areas	Combined
Baraldi et al., 2019; Chen, et al., 2022; Selmi et al., 2016; Wang et al., 2023b; Nguyen et al., 2015; Zhai et al., 2022			Deposition
Tiwari and Kumar 2020; Cai et al., 2020	Woodlands 6		Combined
Manes et al., 2016; Zhai et al., 2022; Fusaro et al., 2017; Nguyen et al., 2015			Deposition
Li et al 2023a	Shrubland 8		Dispersion
Niu 2022; Wang, et al., 2022a; Wang et al., 2023b; Douglas, et al., 2023			Combined
Nguyen et al., 2015; Wu et al., 2019; Zhai et al., 2022;			Deposition
Li et al., 2023a	Mixed 15	Mixed	Dispersion
Wang et al., 2022a; Liu et al., 2022b; Tiwari and Kumar 2020; Dai et al., 2023; Rui et al., 2018; Zafra et al., 2017; Santiago et al., 2022; Wang et al., 2021; Abhijith and Kumar 2019; Karttunen et al., 2020; Islam et al., 2012; Chen et al., 2015; Zhang et al., 2021			Combined
Jayasooriya et al., 2017			Deposition

Table S4. Reported percentage changes (max, min, mean and sd) in each category type, considering the studies available that provide the percentage change under each GBGI and different pollutants, study and measurement types. Negative values represent deterioration of air quality, while positive values represent improvement of air quality; the studies have employed different measurement methods and reference points to calculate the percentage differences mentioned in Sections 4, 5 and 6. The table includes values only if they were reported in at least one paper.

GBGI	**Study Type**	**Measurement type**	**Pollutant**	**Number of studies**	**Percentage change (%)**				**References**
					Max	**Min**	**Mean**	**SD**	
Street trees	Monitoring	Concentration	PM$_1$	5	8	-6	2	4	Miao et al., 2021; Miao et al., 2022; Abhijith and Kumar, 2019; Wang et al., 2020; Liu et al., 2022
	Multiple	Concentration	PM$_1$	1	6	6	NA	NA	Liu et al., 2022
	Monitoring	Concentration	PM$_{2.5}$	5	9	-33	-7	8	Jin et al., 2014; Miao et al., 2021; Miao et al., 2022; Abhijith and Kumar, 2019; Wang et al., 2020
	Modelling	Concentration	PM$_{2.5}$	5	23	-74	-7	22	Li et al., 2023; Buccolieri et al., 2018; Jung and Yoon, 2022; Jeanjean et al., 2016; Karttunen et al., 2020
	Multiple	Concentration	PM$_{2.5}$	4	39	-20	-1	7	Liu et al., 2022; Wang et al., 2022; Zhou et al., 2019; Jeanjean et al., 2017
	Modelling	Deposition	PM$_{2.5}$	2	3	1	2	1	Jeanjean et al., 2016; Jayasooriya et al., 2017
	Multiple	Deposition	PM$_{2.5}$	2	181	1	18	54	Jeanjean et al., 2017; Jo et al., 2020
	Monitoring	Concentration	PM$_{10}$	6	11	-219	-22	57	Miao et al., 2021; Miao et al., 2022; Abhijith and Kumar, 2019; Miao et al., 2023; Wang et al., 2020; Buccolieri et al., 2011
	Modelling	Concentration	PM$_{10}$	4	1	-353	-38	90	Buccolieri et al., 2011; Vranckx et al., 2015; Jung & Yoon, 2022; Karttunen et al, 2020
	Multiple	Concentration	PM$_{10}$	1	12	11	11	1	Zhou et al., 2019
	Modelling	Deposition	PM$_{10}$	1	33	33	NA	NA	Jayasooriya et al., 2017

	Monitoring	Concentration	NO-NO$_2$-NOx	2	25	-50	-4	31	Harris & Manning, 2010; Klingberg et al. 2017
	Modelling	Concentration	NO-NO$_2$-NOx	1	1	-22	-8	7	Jung and Yoon, 2022
	Modelling	Deposition	NO-NO$_2$-NOx	2	21	0	7	12	Jeanjean et al., 2017; Jayasooriya et al., 2017
	Modelling	Combined	NO-NO$_2$-NOx	1	0	0	0	0	Jeanjean et al., 2017
	Monitoring	Concentration	BC	2	44	-4	12	17	Abhijith and Kumar, 2019; Brantley et al., 2014
	Modelling	Concentration	BC	1	8	8	NA	NA	Vranckx et al., 2015
	Monitoring	Concentration	O$_3$	2	17	-13	-1	16	Harris and Manning, 2010; Klingberg et al., 2017
	Modelling	Concentration	O$_3$	1	13	0	4	4	Jung and Yoon, 2022
	Modelling	Deposition	O$_3$	1	42	42	NA	NA	Jayasooriya et al., 2017
	Multiple	Deposition	O$_3$	1	2	0	1	1	Sicard et al., 2018
	Monitoring	Concentration	PM	12	77	-219	0	30	Jin et al., 2014; Miao et al. 2021; Miao et al., 2022; Abhijith and Kumar, 2019; Islam et al., 2012; Buccolieri et al., 2011; Al-Dabbous and Kumar, 2014; Brantley et al., 2014; Lin et al. (2016); Miao et al., 2022; Wang et al., 2020; Liu et al., 2022.
	Modelling	Concentration	PM	8	23	-353	-16	51	Li et al.,2023; Buccolieri et al., 2011; Vranckx et al., 2015; Tong et al., 2016; Buccolieri et al., 2018; Jung & Yoon, 2022; Jeanjean et al., 2016; Karttunen et al.,2020
	Multiple	Concentration	PM	6	39	-20	0	8	Jeanjean et al., 2017; Liu et al., 2022; Wang et al., 2022; Hashad et al., 2023; Zhou et al. 2019; Liu et al., 2022.
	Modelling	Deposition	PM	2	33	1	12	18	Jeanjean et al., 2016; Jayasooriya et al., 2017

	Multiple	Deposition	PM	2	181	1	18	54	Jeanjean et al., 2017; Jo et al., 2020
	Monitoring	Concentration	CO	1	56	21	38	25	Lin et al., 2016
	Modelling	Concentration	CO	1	54	-36	2	22	Li et al., 2022
	Multiple	Concentration	CO	1	16	-12	2	20	Amorim et al., 2013
	Modelling	Deposition	CO	1	0	0	NA	NA	Jayasooriya et al., 2017
	Monitoring	Concentration	UFP	1	63	38	50	18	Lin et al., 2016
	Modelling	Concentration	UFP	1	-15	-15	NA	NA	Tong et al., 2016
Cycle track	Monitoring	Concentration	BC	2	78	20	51	26	Kaminska et al., 2023; Lonati et al., 2017
	Monitoring	Concentration	PM	1	54	33	44	9	Lonati et al., 2017
	Monitoring	Concentration	UFP	1	54	33	44	9	Lonati et al., 2017
Road Verge	Multiple	Concentration	PM	1	11	11	NA	NA	Deshmukh et al. 2019
	Multiple	Concentration	UFP	1	11	11	NA	NA	Deshmukh et al. 2019
Riparian woodland	Monitoring	Concentration	PM$_{2.5}$	1	30	20	25	7	Sou et al., 2021
	Monitoring	Concentration	PM$_{10}$	1	41	32	37	6	Sou et al., 2021
	Monitoring	Concentration	PM	1	41	20	31	8	Sou et al., 2021
Hedge	Monitoring	Concentration	PM$_{1}$	3	25	-9	6	15	Abhijith and Kumar, 2019; Abhijith and Kumar, 2020; Kumar, et al., 2022
	Monitoring	Concentration	PM$_{2.5}$	3	14	-7	1	9	Abhijith and Kumar, 2019; Abhijith and Kumar, 2020; Kumar, et al., 2022
	Modelling	Concentration	PM$_{2.5}$	1	6	-34	-17	18	Li et al., 2023
	Monitoring	Concentration	PM$_{10}$	4	15	-22	-1	18	Abhijith and Kumar, 2019; Chen et al, 2021; Abhijith and Kumar,

									2020; Kumar, et al., 2022
	Monitoring	Concentration	BC	3	53	-15	23	31	Abhijith and Kumar, 2019; Tran et al, 2022; Kumar, et al., 2022
	Monitoring	Concentration	PM	5	59	-22	9	18	Abhijith and Kumar, 2019; Tran et al., 2022; Chen et al., 2021; Abhijith and Kumar, 2020; Kumar, et al., 2022.
	Modelling	Concentration	PM	1	6	-34	-17	18	Li et al., 2023
	Monitoring	Concentration	UFP	1	59	59	NA	NA	Tran et al., 2022
Park	Monitoring	Concentration	PM$_1$	1	37	37	NA	NA	Bonn et al., 2016
	Monitoring	Concentration	PM$_{2.5}$	1	5	5	NA	NA	Su et al., 2022
	Modelling	Concentration	PM$_{2.5}$	1	37	30	34	4	Heshani and Winijkul, 2022
	Multiple	Concentration	PM$_{2.5}$	2	3	-1	2	2	Qin et al., 2019; Xing and Brimblecombe, 2019
	Monitoring	Concentration	PM$_{10}$	2	70	-27	34	39	Bonn et al., 2016; Cohen, Potchter and Schnell, 2014
	Modelling	Concentration	PM$_{10}$	1	35	1	12	11	Moradpour and Hosseini 2020
	Multiple	Concentration	PM$_{10}$	2	14	0	6	5	Qin et al., 2019; Kim and Hong, 2021
	Monitoring	Concentration	NO-NO$_2$-NOx	4	78	-274	-3	68	Fantozzi et al., 2015; Bonn et al. 2016; Cohen et al., 2014; Yin et al., 2011
	Modelling	Concentration	NO-NO$_2$-NOx	2	8	3	6	2	Rafael et al., 2020; Moradpour and Hosseini, 2020
	Monitoring	Concentration	BC	1	20	20	NA	NA	Gomez-Moreno et al., 2019
	Monitoring	Concentration	O$_3$	4	53	-68	8	27	Fantozzi et al., 2015; Bonn et al. 2016; Cohen et al., 2014; Keiser et al., 2018
	Modelling	Concentration	VOC	1	8	4	7	2	Moradpour and Hosseini, 2020

	Monitoring	Concentration	PM	5	70	-27	30	27	Bonn et al. 2016; Su et al. 2022; Cohen, Potchter and Schnell 2014; Yin et al. 2011; Gomez-Moreno et al. 2019
	Modelling	Concentration	PM	2	37	1	18	14	Heshani, Ekbordin Winijkul 2022; Moradpour and Hosseini 2020
	Multiple	Concentration	PM	3	14	-1	5	5	Qin et al. 2019 ; Kim and Hong 2021; Xing and Brimblecombe 2019
	Monitoring	Concentration	CO	1	30	30	NA	NA	Bonn et al. 2016
	Modelling	Concentration	CO	1	8	2	6	3	Moradpour and Hosseini 2020
	Multiple	Concentration	CO	1	0	0	NA	NA	Xing and Brimblecombe 2019
Botanical garden	Monitoring	Concentration	$PM_{2.5}$	2	33	11	22	11	Chen et al., 2016; Junior et al., 2022
	Multiple	Concentration	$PM_{2.5}$	1	6	6	NA	NA	Su et al., 2022
	Monitoring	Concentration	PM	2	33	11	22	11	Chen et al. 2016 ; Junior, Bueno, and da Silva 2022
	Multiple	Concentration	PM	1	6	6	NA	NA	Su et al. 2022
Zoological garden	Monitoring	Concentration	$PM_{2.5}$	1	90	-24	61	31	Phan et al., 2020
	Monitoring	Concentration	PM_{10}	1	91	-21	62	30	Phan et al., 2020
	Monitoring	Concentration	BC	1	70	-100	-7	64	Phan et al., 2020
	Monitoring	Concentration	PM	1	91	-24	62	30	Phan et al. 2020
Playground	Monitoring	Deposition	PM_1	1	26	26	NA	NA	Maher et al., 2022
	Monitoring	Deposition	$PM_{2.5}$	1	46	46	NA	NA	Maher et al., 2022
	Monitoring	Deposition	PM_{10}	1	40	40	NA	NA	Maher et al., 2022
	Monitoring	Deposition	BC	1	49	49	NA	NA	Maher et al., 2022
	Monitoring	Deposition	PM	1	46	26	37	10	Maher et al. 2022

Adoptable public space	Modelling	Concentration	PM_{10}	1	16	16	NA	NA	Rafael et al., 2018
	Modelling	Concentration	NO-NO_2-NOx	1	19	19	NA	NA	Rafael et al., 2018
	Modelling	Concentration	PM	1	16	16	NA	NA	Rafael et al., 2018
Green roof	Monitoring	Concentration	$PM_{2.5}$	2	38	10	19	13	Tong et al., 2016
	Modelling	Concentration	$PM_{2.5}$	3	5	-36	-3	11	Li et al., 2023; Viecco et al., 2021; Viecco et al., 2021
	Monitoring	Deposition	$PM_{2.5}$	1	45	45	NA	NA	Viecco et al., 2018
	Multiple	Deposition	$PM_{2.5}$	1	1	1	NA	NA	Jayasooriya et al., 2017
	Modelling	Concentration	PM_{10}	2	17	-3	5	6	Rafael et al., 2020; Qin et al., 2018
	Monitoring	Deposition	PM_{10}	1	45	45	NA	NA	Viecco et al., 2018
	Multiple	Deposition	PM_{10}	1	46	46	NA	NA	Jayasooriya et al., 2017
	Monitoring	Concentration	NO-NO_2-NOx	1	67	-91	-11	75	Irga et al., 2022
	Modelling	Concentration	NO-NO_2-NOx	3	60	-1	38	16	Rafael et al., 2020; Park et al., 2016; Moradpour et al., 2018
	Multiple	Deposition	NO-NO_2-NOx	1	11	11	NA	NA	Jayasooriya et al., 2017
	Monitoring	Concentration	O_3	1	20	12	16	3	Irga et al., 2022
	Modelling	Concentration	O_3	2	-1	-21	-11	6	Park et al., 2016; Moradpour et al., 2018
	Multiple	Deposition	O_3	1	37	37	NA	NA	Jayasooriya et al., 2017
	Modelling	Concentration	VOC	1	25	3	14	16	Park et al., 2016
	Monitoring	Concentration	PM	2	38	10	19	13	Tong et al., 2016

	Modelling	Concentration	PM	5	17	-36	1	10	Li et al., 2023; Viecco et al., 2021; Viecco et al., 2021.; Rafael et al., 2020; Qin et al, 2018
	Monitoring	Deposition	PM	1	45	45	45	0	Viecco et al., 2018
	Multiple	Deposition	PM	1	46	1	24	32	Jayasooriya et al., 2017
	Modelling	Concentration	CO	1	16	2	9	10	Park et al., 2016
	Multiple	Deposition	CO	1	1	1	NA	NA	Jayasooriya et al., 2017
Green wall	Monitoring	Concentration	PM$_1$	1	13	11	12	1	Donateo et al, 2021
	Monitoring	Concentration	PM$_{2.5}$	1	20	15	18	4	Donateo et al, 2021
	Modelling	Concentration	PM$_{2.5}$	3	24	-103	-3	28	Li et al., 2023; Viecco et al., 2021; Viecco et al., 2021
	Monitoring	Deposition	PM$_{2.5}$	2	71	49	60	16	Ghazalli et al., 2018; Viecco et al., 2018
	Modelling	Deposition	PM$_{2.5}$	1	1	1	NA	NA	Jayasooriya et al., 2017
	Modelling	Concentration	PM$_{10}$	2	44	0	15	15	Pugh et al., 2012; Qin et al., 2018
	Monitoring	Deposition	PM$_{10}$	2	83	71	77	8	Ghazalli et al., 2018; Viecco et al., 2018
	Modelling	Deposition	PM$_{10}$	1	42	42	NA	NA	Jayasooriya et al., 2017
	Monitoring	Concentration	NO-NO$_2$-NOx	1	0	0	NA	NA	Donateo et al., 2021
	Modelling	Concentration	NO-NO$_2$-NOx	1	70	9	28	23	Pugh et al., 2012
	Modelling	Deposition	NO-NO$_2$-NOx	1	12	12	NA	NA	Jayasooriya et al., 2017
	Monitoring	Concentration	BC	2	19	17	18	1	Tran et al., 2022; Donateo et al., 2021
	Modelling	Deposition	O$_3$	1	40	40	NA	NA	Jayasooriya et al., 2017

	Monitoring	Concentration	PM	2	38	11	19	10	Tran et al., 2022; Donateo et al., 2021
	Modelling	Concentration	PM	5	60	-103	6	25	Li et al., 2023; Viecco et al., 2021; Pugh et al., 2012; Viecco, et al., 2021; Qin et al, 2018
	Monitoring	Deposition	PM	2	83	49	68	12	Viecco et al., 2018; Ghazalli et al., 2018
	Modelling	Deposition	PM	1	42	1	22	29	Jayasooriya et al., 2017
	Modelling	Deposition	CO	1	1	1	NA	NA	Jayasooriya et al., 2017
	Monitoring	Concentration	UFP	2	38	19	28	14	Tran et al., 2022; Donateo et al., 2021
Wetland	Monitoring	Concentration	$PM_{2.5}$	1	5	-45	-20	35	Li et al., 2019
	Monitoring	Concentration	PM_{10}	1	20	-20	0	28	Li et al., 2019
	Monitoring	Concentration	PM	1	20	-45	-10	29	Li et al., 2019
River	Monitoring	Concentration	BC	1	89	-11	38	71	Kaminska et al., 2023
Lake	Multiple	Concentration	$PM_{2.5}$	3	6	-13	0	6	Zhao et al., 2021; Zhou et al., 2021; Zhu and Zhou, 2019
	Multiple	Concentration	PM_{10}	2	5	2	3	1	Zhao et al., 2021; Zhu and Zhou, 2019
	Multiple	Concentration	NO-NO_2-NOx	1	11	9	10	1	Zhu and Zhou, 2019
	Multiple	Concentration	PM	3	6	-13	1	5	Zhao et al., 2021; Zhou et al., 2021; Zhu and Zhou, 2019
Woodland	Monitoring	Concentration	PM_1	2	86	41	55	18	Bonn et al., 2016; Popek et al., 2022
	Monitoring	Concentration	$PM_{2.5}$	3	88	-71	-8	61	Nguyen et al., 2015; Popek et al., 2022; Cai et al., 2020
	Modelling	Concentration	$PM_{2.5}$	2	1	0	1	1	Nemitz et al., 2020; Chen et al., 2022
	Modelling	Deposition	$PM_{2.5}$	1	1	1	NA	NA	Chen et al., 2022
	Monitoring	Concentration	PM_{10}	2	86	-50	43	53	Bonn et al., 2016; Popek et al., 2022

	Modelling	Concentration	PM_{10}	1	95	0	38	47	Nemitz et al., 2020
	Modelling	Deposition	PM_{10}	2	26	1	6	11	Tallis et al., 2011; Nemitz et al., 2020
	Monitoring	Concentration	NO-NO_2-NOx	2	8	-74	-33	58	Grundström and Pleijel, 2014; Bonn et al., 2016
	Modelling	Concentration	NO-NO_2-NOx	1	2	0	1	1	Nemitz et al., 2020
	Monitoring	Concentration	O_3	2	36	3	26	13	Grundström and Pleijel, 2014; Bonn et al., 2016
	Modelling	Concentration	O_3	1	15	0	9	7	Nemitz et al., 2020
	Monitoring	Concentration	PM	4	88	-71	29	48	Bonn et al. 2016; Nguyen et al., 2015; Popek et al., 2022; Cai et al., 2020
	Modelling	Concentration	PM	2	95	0	36	44	Nemitz et al., 2020; Chen, Lin, & Chiueh, 2022
	Modelling	Deposition	PM	3	26	1	6	9	Tallis et al., 2011; Nemitz et al., 2020; Chen et al., 2022
	Monitoring	Concentration	CO	1	36	35	35	0	Bonn et al., 2016
Grassland	Monitoring	Concentration	$PM_{2.5}$	3	20	-34	0	15	Wang et al., 2021; Nguyen et al., 2015; Cai et al., 2020
	Modelling	Concentration	$PM_{2.5}$	1	0	0	NA	NA	Tiwari and Kumar, 2020
	Modelling	Deposition	$PM_{2.5}$	1	1	1	NA	NA	Jeanjean et al., 2016
	Monitoring	Concentration	PM_{10}	1	6	-3	2	4	Wang et al., 2021
	Modelling	Concentration	PM_{10}	2	1	-3	0	2	Rui et al., 2018; Tiwari and Kumar, 2020
	Monitoring	Concentration	NO-NO_2-NOx	1	22	11	16	6	Dai et al., 2023
	Modelling	Concentration	NO-NO_2-NOx	1	12	12	NA	NA	Tiwari & Kumar, 2020

	Monitoring	Concentration	PM	3	20	-34	1	12	Wang et al., 2021; Nguyen et al., 2015; Cai et al., 2020
	Modelling	Concentration	PM	2	1	-3	0	2	Rui et al., 2018; Tiwari & Kumar, 2020
	Monitoring	Deposition	PM	1	1	1	NA	NA	Przybysz et al. 2021
	Modelling	Deposition	PM	1	1	1	NA	NA	Jeanjean et al., 2016
Shrubland	Monitoring	Concentration	$PM_{2.5}$	2	24	-52	-14	53	Nguyen et al., 2015; Niu, 2022
	Monitoring	Concentration	PM_{10}	1	17	17	NA	NA	Niu, 2022
	Monitoring	Concentration	$NO\text{-}NO_2\text{-}NOx$	1	28	17	23	4	Dai et al., 2023
	Multiple	Concentration	$NO\text{-}NO_2\text{-}NOx$	1	12	7	10	3	Deshmukh et al. 2019
	Multiple	Concentration	BC	1	13	1	8	6	Deshmukh et al. 2019
	Monitoring	Concentration	PM	2	24	-52	-4	42	Nguyen et al., 2015; Niu, 2022
	Multiple	Concentration	PM	1	17	-27	-5	31	Deshmukh et al., 2019
	Multiple	Concentration	CO	1	25	25	25	0	Deshmukh et al., 2019
	Multiple	Concentration	UFP	1	17	-27	-5	31	Deshmukh et al., 2019
Arable agriculture	Monitoring	Concentration	O_3	1	13	13	NA	NA	Bonn et al., 2016
	Monitoring	Concentration	CO	1	34	34	NA	NA	Bonn et al., 2016
Mixed	Monitoring	Concentration	PM_1	1	19	7	13	8	Abhijith and Kumar, 2019
	Multiple	Concentration	PM_1	2	4	-12	-4	8	Jia et al., 2021; Wang et al., 2022
	Monitoring	Concentration	$PM_{2.5}$	3	19	-13	0	10	Kim et al., 2017; Abhijith and Kumar, 2019; Wang et al., 2021

	Modelling	Concentration	PM$_{2.5}$	2	7	0	2	3	Viecco et al., 2021; Wang et al., 2023
	Multiple	Concentration	PM$_{2.5}$	3	20	-80	-12	24	Jia et al., 2021; Wang et al., 2022; Morakinyo et al., 2016
	Modelling	Deposition	PM$_{2.5}$	3	31	0	11	14	Jayasooriya et al., 2017; Zhai et al., 2022; Wu et al., 2019
	Monitoring	Concentration	PM$_{10}$	3	24	-19	5	9	Chen et al., 2015; Abhijith and Kumar, 2019; Wang et al., 2021
	Modelling	Concentration	PM$_{10}$	1	-2	-2	-2	0	Rui et al., 2018
	Multiple	Concentration	PM$_{10}$	3	43	-25	3	26	Jia et al., 2021; Wang et al., 2022; Zafra et al., 2017
	Modelling	Deposition	PM$_{10}$	2	48	0	14	21	Jayasooriya et al., 2017; Zhai et al., 2022
	Modelling	Concentration	NO-NO$_2$-NOx	1	49	42	45	3	Hosseinzadeh et al., 2022
	Multiple	Concentration	NO-NO$_2$-NOx	2	38	-17	4	20	Deshmukh et al., 2019; Taleghani et al., 2020
	Modelling	Deposition	NO-NO$_2$-NOx	1	21	11	16	7	Jayasooriya et al., 2017
	Monitoring	Concentration	BC	2	63	4	33	30	Abhijith and Kumar, 2019; Tran et al., 2022
	Multiple	Concentration	BC	3	66	-20	14	36	Jia et al., 2021; Santiago et al., 2019; Deshmukh et al., 2019
	Modelling	Deposition	O$_3$	1	41	36	38	4	Jayasooriya et al., 2017
	Monitoring	Concentration	PM	6	88	-19	9	20	Chen et al., 2015; Kim et al., 2017; Abhijith and Kumar, 2019; Tran et al., 2022; Wang et al., 2021; Tomson et al., 2021
	Modelling	Concentration	PM	4	7	-57	-10	19	Zhang et al., 2021; Viecco et al., 2021; Rui et al., 2018; Wnag et al., 2023
	Multiple	Concentration	PM	5	43	-80	-7	21	Jia et al., 2021; Wang, A., et al., 2022; Deshmukh et al., 2019; Morakinyo et al., 2016; Zafra et al., 2017
	Modelling	Deposition	PM	3	48	0	12	16	Jayasooriya et al., 2017; Wu et al., 2019

	Monitoring	Concentration	CO	1	53	23	33	11	Li et al., 2016
	Modelling	Concentration	CO	1	26	26	NA	NA	Li et al., 2016
	Multiple	Concentration	CO	1	25	0	13	18	Deshmukh et al., 2019
	Modelling	Deposition	CO	1	1	0	1	0	Jayasooriya et al., 2017
	Monitoring	Concentration	UFP	1	31	31	NA	NA	Tran et al., 2022
	Multiple	Concentration	UFP	1	32	-15	8	33	Deshmukh et al., 2019

Table S5. Reported percentage changes (max, min, mean and SD) in each category type, considering the studies available that provide the percentage change under each GBGI and different pollutants and built environment (open road and street canyon). Negative values represent deterioration of air quality, while positive values represent improvement of air quality; the studies have employed different measurement methods and reference points to calculate the percentage differences mentioned in Sections 4, 5 and 6. The table includes values only if they were reported in at least one paper.

GBGI	**Built environment**	**Pollutant**	**Number of papers**	**Percentage change (%)**				**References**
				Max	**Min**	**Mean**	**SD**	
Street trees	Street canyon	PM_1	4	7.7	-6.0	1.4	4.0	Miao et al., 2021; Miao et al., 2022; Wang et al., 2020; Liu et al., 2022
Street trees	Open road	PM_1	1	8.0	1.0	4.5	4.9	Abhijith and Kumar, 2019
Street trees	Street canyon	$PM_{2.5}$	11	23.3	-74.3	-4.6	13.5	Jin et al., 2014; Miao et al., 2021; Miao et al., 2022; Li et al., 2023; Jeanjean et al., 2017; Buccolieri et al., 2018; Liu et al., 2022; Wang et al., 2020; Jung & Yoon, 2022; Jeanjean et al., 2016; Karttunen et al., 2020
Street trees	Open road	$PM_{2.5}$	1	9.0	-7.0	1.0	11.3	Abhijith and Kumar, 2019
Street trees	Street canyon	PM_{10}	7	11.0	-353.0	-33.2	79.5	Miao et al., 2021; Miao et al., 2022; Buccolieri et al., 2011; Vranckx et al., 2015; Wang et al., 202; Jung & Yoon, 2022; Karttunen et al., 2020
Street trees	Open road	PM_{10}	1	10.0	-2.0	4.0	8.5	Abhijith and Kumar, 2019
Street trees	Street canyon	NO-NO$_2$-NO$_x$	2	0.6	-22.2	-6.7	7.2	Jung & Yoon, 2022; Jeanjean et al., 2017
Street trees	Open road	NO-NO$_2$-NO$_x$	1	-21.0	-50.0	-35.5	20.5	Harris & Manning, 2010
Street trees	Street canyon	BC	1	8.0	8.0	8.0	NA	Vranckx et al., 2015
Street trees	Open road	BC	2	44.0	-4.0	12.0	16.6	Abhijith and Kumar, 2019; Brantley et al., 2014
Street trees	Street canyon	O3	1	12.5	0.0	3.8	4.2	Jung & Yoon, 2022
Street trees	Open road	O3	1	17.0	17.0	17.0	NA	Harris & Manning, 2010
Street trees	Street canyon	Overall PM	14	23.3	-353.0	-7.9	33.0	Jin et al., 2014; Miao et al., 2021; Miao et al., 2022; Li et al., 2023; Buccolieri et al., 2011; Vranckx et al., 2015; Jeanjean et al., 2017; Buccolieri et al., 2018; Liu et al., 2022; Wang et al., 2020; Jung & Yoon, 2022; Jeanjean et al., 2016; Karttunen et al., 2020; Liu et al., 2022

Street trees	Open road	Overall PM	7	77.0	-15.0	22.5	29.0	Abhijith and Kumar, 2019; Islam et al., 2012; Al-Dabbous and Kumar, 2014; Brantley et al., 2014; Tong et al., 2016; Lin et al., 2016; Hashad et al., 2023
Street trees	Street canyon	CO	2	53.5	-36.4	2.0	21.4	Amorim et al., 2013; Li et al., 2022
Street trees	Open road	CO	1	56.1	20.8	38.5	25.0	Lin et al., 2016
Street trees	Open road	UFP	2	63.2	-15.0	28.6	39.9	Tong et al., 2016; Lin et al., 2016
Hedge	Street canyon	PM_1	1	-9.0	-9.0	-9.0	NA	Kumar, et al., 2022
Hedge	Open road	PM_1	2	25.0	-1	11.1	13.1	Abhijith and Kumar, 2019; Abhijith and Kumar, 2020
Hedge	Street canyon	$PM_{2.5}$	2	5.6	-34.0	-15.1	17.2	Li et al., 2023; Kumar et al., 2022
Hedge	Open road	$PM_{2.5}$	2	14	-7	3.1	10.5	Abhijith and Kumar, 2019; Abhijith and Kumar, 2020
Hedge	Street canyon	PM_{10}	2	13.7	-17.0	-1.7	21.7	Chen et al., 2021; Kumar, et al., 2022
Hedge	Open road	PM_{10}	2	15.0	-22.0	0.1	19.5	Abhijith and Kumar, 2019; Abhijith and Kumar, 2020
Hedge	Street canyon	BC	1	9.0	9.0	9.0	NA	Kumar et al., 2022
Hedge	Open road	BC	2	53.1	-15.0	27.0	36.8	Abhijith and Kumar, 2019; Tran et al., 2022
Hedge	Street canyon	Overall PM	3	16.4	-34.0	-6.6	18.4	Li et al., 2023; Chen et al., 2021; Kumar, et al., 2022
Hedge	Open road	Overall PM	3	59.2	-22.0	12.5	19.6	Abhijith and Kumar, 2019; Tran et al., 2022; Abhijith and Kumar, 2020
Hedge	Open road	UFP	1	59.2	59.2	59.2	NA	Tran et al., 2022

Table S6. Overview of meta-analysis results across the different GBGI and pollutants. This table summarises key information extracted from the meta-analysis and includes the rate of change, STD, reduction (%), *p*-value, 95%CI, prediction interval, I^2 and imputed reduction rate.

GBGI	Pollutant	Rate of Changes	STD	Reduction %	P-value	95%CI		Prediction Interval		I^2	Imputed rate of changes in number of publication	Study type	References
Green Roofs	$PM_{2.5}$	0.02	0.01	-2.00	0.09	-0.03	0.003	-0.11	0.08	99.89	No bias		Irga et al., 2022; Viecco et al., 2021; Tong et al., 2016; Li et al., 2023
Hedge	BC	0.003	0.25	-0.30	0.99	-0.49	0.50	-1.98	1.99	100.00	No Bias	Multiple	Tran et al., 2022; Kumar et al., 2022;Abhijith and Kumar, 2019
	PM_1	-0.070	0.09	7.00	0.48	-0.25	0.12	-0.98	0.84	99.85	-0.02		Abhijith and Kumar, 2019; Abhijith and Kumar, 2020;Kumar et al., 2022
	$PM_{2.5}$	-0.15	0.13	15.00	0.27	-0.41	0.11	-1.12	0.82	99.99	No Bias		Abhijith and Kumar, 2019; Abhijith and Kumar, 2020;Kumar et al., 2022; Li et al., 2023
	PM_{10}	0.06	0.07	-6.0	0.40	-0.08	0.20	-0.46	0.57	99.95	0.130		Abhijith and Kumar, 2019; Abhijith and Kumar, 2020;Kumar et al., 2022; Chen et al., 2021
Mixed	$PM_{2.5}$	-0.24	0.01	24	0.000	-0.26	-0.21	-0.37	-0.11	99.99	No Bias	Multiple	Wang et al., 2021; Kim et al., 2017;Jia et al., 2021; Abhijith and Kumar, 2019
	PM_{10}	-0.09	0.004	9	0.000	-0.01	-0.08	-0.140	-0.04	100.00	No Bias		Chen et al., 2015; Abhijith and Kumar, 2020; Jia et al., 2021; Wang et al., 2021
	BC	-0.28	0.06	28	0.000	-0.40	-0.16	-0.73	0.18	100.00	No bias		Abhijith and Kumar, 2019; Tran et al., 2022; Jia et al., 2021;Santiago et al., 2019; Deshmukh et al., 2019
Parks	PM_{10}	-0.100	0.130	10.00	0.430	-0.350	0.160	-1.10	0.990	100.00	No Bias	Multiple	Bonn et al., 2016; Qin et al., 2019; Cohen et al., 2014
Shrublands	$PM_{2.5}$	0.08	0.050	-8.00	0.12	-0.02	0.18	-0.28	0.44	100.00	No Bias	Multiple	Niu et al., 2022; Wang et al., 2022; Nguyen et al., 2015
Street trees	PM_1	-0.060	0.01	6.00	0.000	-0.070	-0.04	-0.13	0.02	100.00	No Bias	Multiple	Miao et al., 2022b; Miao et al., 2021; Abhijith and Kumar, 2019
	$PM_{2.5}$	-0.004	0.010	4.00	0.000	-0.060	-0.03	-0.15	0.06	No Bias	-0.100		Miao et al., 2021; Abhijith and Kumar, 2019; Jin et al., 2014; Hagler

													et al., 2012; Li et al., 2023
	PM_{10}	0.08	0.010	-8.00	0.000	0.05	0.10	-0.03	0.19	100.00	0.030		Miao et al., 2022a;Miao et al., 2022b; Miao et al., 2021;Hagler et al., 2012
	TSP	0.120	0.010	-12.00	0.000	0.07	0.180	-0.120	0.370	100.00	No Bias		Miao et al., 2022a;Miao et al., 2022b; Miao et al., 2021;Islam et al., 2012

Table S7. Percentage change in pollutant levels for street trees in street canyon with varied aspect ratio definitions

Built environment	Names	Pollutant	Number of papers	Percentage change (%)			
				Max	Min	Mean	SD
Moderately deep street canyon[1]	Monitoring	PM_1	4	7.7	-6	0.9	4.0
Moderately deep street canyon	Multiple	PM_1	1	6.2	6.2	NA	NA
Moderately deep street canyon	Monitoring	$PM_{2.5}$	5	2.5	-72.3	-10.6	13.8
Moderately deep street canyon	Modelling	$PM_{2.5}$	2	23.3	-74.3	-7.0	23.8
Moderately deep street canyon	Multiple	$PM_{2.5}$	1	1.1	-16.7	-4.9	5.6
Moderately deep street canyon	Monitoring	PM_{10}	4	11	-83.3	-13.4	30.1
Deep[2]	Monitoring	PM_1	1	3.2	3.2	NA	NA
Deep	Monitoring	$PM_{2.5}$	1	-1.9	-1.9	NA	NA
Deep	Monitoring	PM_{10}	1	-6.6	-6.6	NA	NA
Shallow or wide street canyons[3]	Modelling	PM_{10}	1	1.4	1.4	NA	NA

[1] $0.5<H/W<2$; [2] $H/W\geq2$; [3] $H/W\leq0.5$

Table S8. Indicative evolutionary patterns from published literature of the role of different GBGI components on the human health and climate change adaptation initiatives.

Description	Green	Blue	GBGI
Health			
Positive impact on physical and mental health	Maas et al. (2006); Barton and Pretty (2010); Coombes et al. (2010); Frumkin et. al. (2017); Ward Thompson et al. (2012)	Smith et al. (2021)	Gascon et al. (2015); Andreucci, M. B., et al (2019); Subiza-Pérez et al. (2020); Li et al. (2023)
Protective effect on mortality and premature death	Mitchell and Popham (2008); Villeneuve et al. (2012)	Smith et al. (2021)	Potter et al., 2023
Public health and environmental justice, including equitable access issues	Wolch et al. (2014); Alcock et al. (2017)	PasanenT.P et al. (2019); Georgiou et al. (2021); Smith, N., et al (2022)	Everett et al. 2021; Marin et al. (2022)
Positive effect on cognitive development in primary schoolchildren, academic performance	Forns et al (2017) Opbroek et al (2024)	Dadvand et al. (2015)	Choe et al., 2020.
Health benefits from stormwater and flood management	Venkataramanan et al.(2019)	Wilbers et al. (2022)	Venkataramanan, et al. (2019)
Climate change adaptation			
Carbon sequestration	Liu & Russo (2021)	Moritsch et al., 2021	Alves et al. (2019)
Urban Microclimate/ Heat island reductions	Kumar et al. (2024)	Manteghi et al. (2015); Ampatzidis and Kershaw (2020)	Kumar et al. (2024)
Energy savings for buildings (emissions related to heating/cooling)	Herath et al. (2018)	Ampatzidis et al. (2020)	Sanusi, R., Jalil (2021)
Enhance biodiversity through protection of natural ecosystems	Capotorti et al. (2019)	Donati et al. (2022)	Langemeyer, Baró (2021)

Table S9. The impact of current and future climate on air pollution and the role of GBGI in managing air pollution under future climate change scenarios.

Region	Current climate	Future climate	Current green-blue solutions	Future green-blue solutions	Trend		Air pollutants/pollutants
					Temperature	Precipitation	
Western Europe	Cfb	Cfa and Cwa	Street trees Hedges Green roofs Green wall Mixed Woodland	Street trees Hedges Green roofs Park Mixed Woodlands Lake Grassland	Expected to increase. This warming trend is projected to lead to hotter summers and milder winters. Heatwaves are likely to become more frequent and intense.	Extreme precipitation events, such as heavy rainstorms, are expected to become more common.	Increasing temperatures can potentially lead to increased formation of ground-level O3 and the volatilization of certain pollutants, which may contribute to higher levels of air pollution.
Southern Europe	BSk	BSh	Street trees	Green roofs Green walls	Average temperatures are increasing. More frequent and intense heatwaves. Both daytime and nighttime temperatures are likely to rise.	Reduced summer precipitation.	O3 (rising temperatures and more frequent heatwaves, there is a higher likelihood of increased photochemical reactions in the atmosphere, leading to the formation of ground-level ozone). O3 levels tend to rise during periods of hot, sunny weather, exacerbating air quality issues, particularly in urban areas. Enhanced Particulate Matter Accumulation - Reduced summer precipitation can lead to drier conditions, contributing to the accumulation of particulate matter from various sources such as vehicle emissions, industrial activities, and natural dust. Without sufficient rainfall to remove particles from the atmosphere, concentrations of PM10 and PM2.5 may increase, leading to degraded air quality and associated health impacts.
	Csb and Cfb	Csa and BSk					
	Csa and Csb	BWh and BWk					
Eastern Europe	Dfb	Dfa	Woodland Cycle track River	Street trees Woodland	Increasing temperatures. More Frequent Heatwaves. Warmer Winters. Both daytime and nighttime temperatures are projected to increase.	Increased Intensity of Rainfall Events.	Due to increased temperature Increased O3 formation. Due to altered precipitation patterns Formation of Ground-Level O3. Changes in PM Levels

Northern Europe	Cfb	Cfa/ Dfb			Increasing Temperatures. More Frequent Heatwaves. Warmer Winters. Both daytime and nighttime temperatures are projected to increase.	Precipitation patterns are expected to become more variable, with changes in the timing, intensity, and distribution of rainfall. Changes in temperature may influence the form of winter precipitation, with more frequent occurrences of rain rather than snow in some areas.	Warmer temperatures in the transition to a warmer climate (Cfa) can facilitate the formation of ground-level ozone through photochemical reactions involving precursor pollutants like nitrogen oxides (NOx) and volatile organic compounds (VOCs). Altered precipitation patterns and drier conditions, particularly in continental climate areas (Dfb), may contribute to the accumulation of particulate matter from sources such as industrial emissions, vehicular exhaust, and biomass burning. Reduced precipitation can result in less effective removal of PM from the atmosphere.
China	Dwa, Dwb	Cwa, Cwb	Shrubland Street trees Mixed	Mixed Street trees Park Green roof Zoological garden	Temperatures are projected to rise.	some regions experiencing more intense rainfall events while others may face prolonged droughts.	Increased Ground-Level Ozone: Higher temperatures enhance the formation of ground-level ozone, exacerbating smog issues. Particulate Matter Formation Changes in temperature and precipitation can influence the formation and dispersion of particulate matter, contributing to respiratory issues.
		Cfa, Cfb		Woodland Mixed Green walls Hedges Park Street trees Botanical garden Green roofs			

Table S10. Average percentage changes and number of studies for each GBGI category considering all pollutants. Negative values represent deterioration of air quality, while positive values represent improvement of air quality; the studies have employed different measurement methods and reference points to calculate the percentage differences mentioned in Sections 4, 5 and 6. The table includes values only if they were reported in at least one paper.

GBGI	**Number of available studies**	**Average percentage change in air pollutants (%)**
Road verge	1	11.3
Riparian woodland	1	31.0
Zoological garden	1	39.9
Playground	1	40.3
Arable agricultural	1	19
Adoptable public space	1	17.5
City farm	1	1.6
River	1	38.4
Wetland	1	-10.1
Cycle track	2	48
Botanical garden	3	18.0
Lake	3	3.6
Shrubland	4	11.7
Hedge	7	14.3
Grassland	7	2.9
Woodland	8	20.5
Green wall	10	14.2
Green roof	14	13.5
Park	14	8.7

Mixed	22	6.8
Street trees	35	-3.1

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