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# Impact of urban greening on microclimate and air quality in the urban canopy layer: Identification of knowledge gaps and challenges

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Growing urbanization leads to microclimate perturbations and in particular to higher temperatures inside the city as compared to its rural surroundings, a phenomenon known as the urban heat island. Although it exists at several scales, this study focused only on the urban canopy layer, where inhabitants live. A bibliometric study was performed to describe and understand the relationships between strategies of urban greening and canopy layer urban heat island modification in terms of air quality and microclimate. Science mapping of 506 bibliographical resources was performed through co-word and co-citation analysis. A subset of forty-four articles related to microclimate and air quality modelling was extracted and synthesized. This analysis showed scientific papers were polarized into microclimate or air quality studies without strong links between both, implying small collaboration between these fields. There is need for studies coupling microclimate and air pollution modelling to assess vegetation's impacts at city scale.

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KEYWORDS
**bibliometric analysis, vegetation, atmospheric pollution, urban heat island, model, mitigation**

## Introduction

Urban areas everywhere saw their population double since 1985 and now host more than 4.3 billion people, i.e., more than half the world's population (United Nations, 2019). Fast urbanizing areas and their citizens are more and more exposed to risks due to climate change hazards, especially in the less-developed regions where urban population has almost tripled in the last 35 years (Dodman et al., 2022). In this context, understanding the urban form and shaping it through urban planning policies is essential to meet climate action in sustainable development goals. It is necessary to mitigate climate change by reduction of greenhouse gas emissions as well as to develop adaptation strategies to climate hazards like large heat waves or floods (Xu et al., 2019).

Scientific interest over "green infrastructure" (forests, wetlands…) as a complement to the classical "grey infrastructure" (roads, bridges…) has been developing over the past decades. These solutions involving restoration and management of ecosystems are not cost-free, but one cannot stop at market prices for characterizing the economic value of these ecosystems (Hsu and Chao, 2020). They prove to be more resilient to extreme climatic events and, at a larger time-scale, more cost-effective than classical urban engineering solutions if well implemented (Roberts et al., 2012). For example, Hsu and Chao (2020) calculated on a case study in Taiwan that building green infrastructure had a return on investment after approximately 8 years. Their positive impact on inhabitants' well-being is also non-negligible.

Among the risks that cities are facing or are going to face in a near future, extreme heat waves and episodes of air pollution are frequently cited (Wilby, 2008). Thus, the notion of urban heat island (UHI) is used to describe the warmer temperatures that exist in the city heart as compared to the rural surroundings (Oke, 2009). By analogy with the UHI, it is possible to define the urban pollution island (UPI) whose use is more recent. Studies dealing with the interaction between UHI and UPI are still scarce (Ulpiani, 2021). However, through the notion of green infrastructure it is possible to establish a theoretical link between both UHI and UPI.

Vegetation has a proved impact on surrounding air temperature through evapotranspiration. Tall vegetation (i.e., trees) also diminishes temperatures by creating shading (Pace et al., 2021). Moreover, vegetation affects the atmospheric composition and can modify the air quality since it absorbs several gases and aerosols which can be atmospheric pollutants and can emit gases which interact with other atmospheric compounds. Being able to establish precisely the interactions between the plant and its surrounding environment is a necessary condition for determining how vegetation affects concentrations of pollutants in the air and acts on the UHI, in particular because the plant-atmosphere exchanges are in particular temperature-dependent and influenced by soil water content.

Therefore, one question should be asked: what is the state of knowledge of the relationships between microclimate and air quality related to urban greening? A focus will be made only on the UHI and UPI at the pedestrian level, that is to say in the urban canopy layer (UCL). For this purpose, a systematic review of the research field is needed, in order to rigorously describe its structure.

Three classical options of systematic review, widely used in literature, are bibliometric analysis, meta-analysis, and systematic literature reviews. Whereas bibliometric and meta-analysis methods compute statistics on a broad set of articles (hundreds or even thousands), systematic literature reviews are usually done manually on small samples. They serve different scopes, as literature reviews are aimed at producing qualitative analysis of specific subjects, while meta-analysis and bibliometric studies help to deal with broad subjects from a quantitative point of view. To be precise, meta-analysis approaches usually have only a quantitative aim for evaluation and summarization, while bibliometric studies tend to use the quantitative information to interpret and uncover emerging trends and scientific relationships between topics (Donthu et al., 2021). Also, literature reviews being completed manually, there is a risk of bias and of lack of reproducibility (Darko et al., 2020).

The aim of the study is to investigate and describe the combination between the topics of microclimate, outdoor air quality, and urban greening. The need is to understand the quantity of articles and topics tackled, as well as to get information about their content in order to assess their interrelations. As explained earlier, a bibliometric approach seems to best fit the purpose. There are already a few systematic studies dealing with urban climate, but none was found to combine the three topics quoted. For example, Huang and Lu (2018) performed a bibliometric analysis on UHI as a broad subject, concluding that urban climate modeling shall play a big role hand in hand with remote sensing practices and field measurements, especially in the design of mitigation and adaptation strategies. Vegetation was mentioned only for mitigation purposes: even if the word "pollution" appears, the link between air quality and direct and indirect effects of vegetation on pollutants is not highlighted. Qiu et al. (2021) deal with the effects of urban greening on air quality and citizen health thanks to their bibliometric and meta-analysis on the subject. The aspects of UHI mitigation are not treated in the study. Ulpiani (2021) investigates the link between UHI and UPI in a literature review; whereas vegetation is mentioned and its role in UPI and UHI is thoroughly analyzed, there is no quantification of the interrelations between UHI, UPI, and vegetation, and therefore no indication of the development of those topics as a whole.

Thus, a bibliometric analysis approach is suggested in order to identify, quantify, and analyze the interrelations between UHI, UPI, and urban greening, in order to make hypotheses on the existing knowledge gaps. Moreover, to support the findings, a focus on a set of articles that use models linking vegetation to microclimate and/or air quality is performed. The types and scopes of existing models are analyzed and interesting future paths of research are underlined.

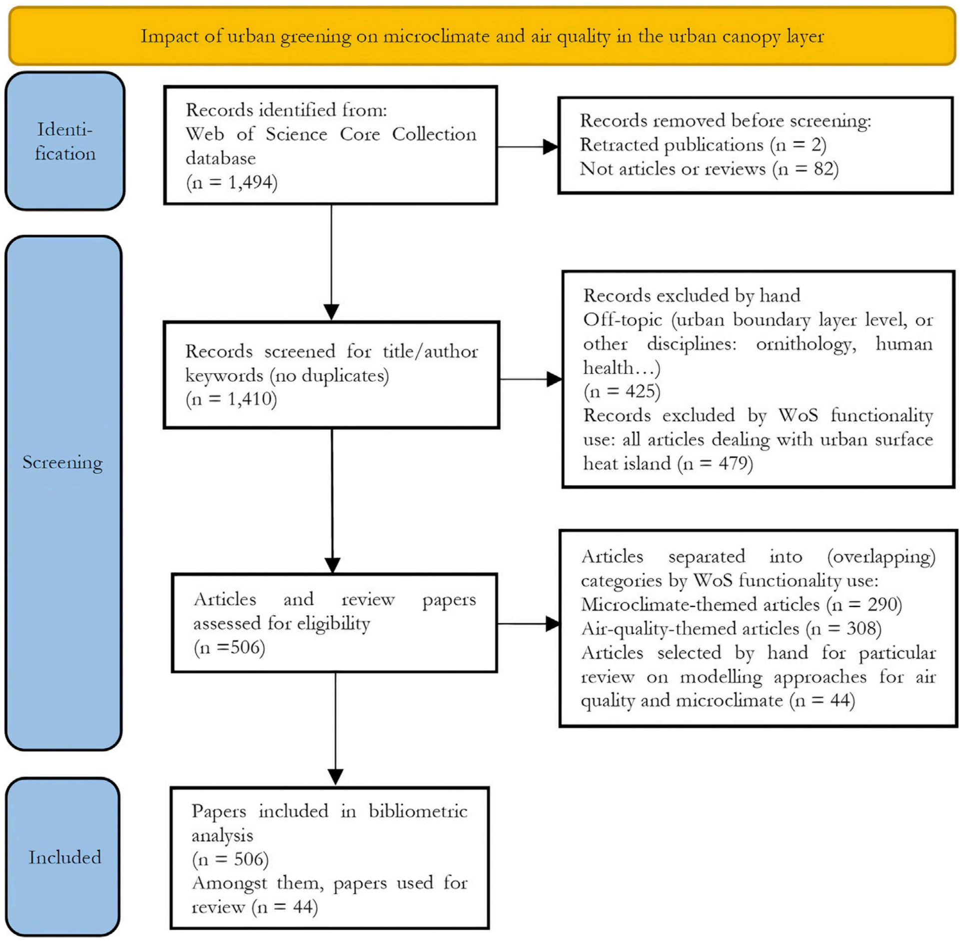


FIGURE 1
Selection process of the articles for bibliometric analysis using the PRISMA flow diagram method (Page et al., 2021).

## Materials and methods

The scientific database Web of Science Core Collection was chosen in this bibliometric study because it is one of the largest database collections of peer-reviewed journals (Huang and Lu, 2018; Kong et al., 2021).

Web of Science's advanced search query was used in the fields "author keywords" and "title" for all articles and reviews published until 2021 included. The PRISMA flow diagram (Page et al., 2021) in Figure 1 illustrates the main steps defining a stable group of articles on which to perform bibliometric analysis. First, the search query for the collection up to 2021 gave 1,494 references which were then narrowed down to 1,410 by selecting only articles and reviews. A screening was then performed manually in order to remove the articles that appeared off-topic or displaying too broad a scale for the study of UHI, which left 985 articles.

Manual browsing of the articles showed that some articles do not specify inside the title or keywords the scale and type of UHI studied. Therefore, the search was refined inside the range of articles already selected in order to exclude mentions to surface heat island. After this filtering, 506 articles remained.

These articles were then split into two overlapping categories: those dealing with microclimate issues (290 articles) and those themed with air quality (308 articles). Bibliometric analysis was then performed on three sets of articles: the group of 506 articles and its two subsections of 290 microclimate-themed articles and 308 pollution-themed articles, using the R-package Bibliometrix and its interface Biblioshiny (Aria and Cuccurullo, 2017).

To be more precise, this study chose to use the main techniques of bibliometrics, that is to say both metrics evaluation (number of publications, number of contributing authors, country productivity…) and science mapping (the relationships between publications, cited publications, topics…). A choice was made between different techniques of

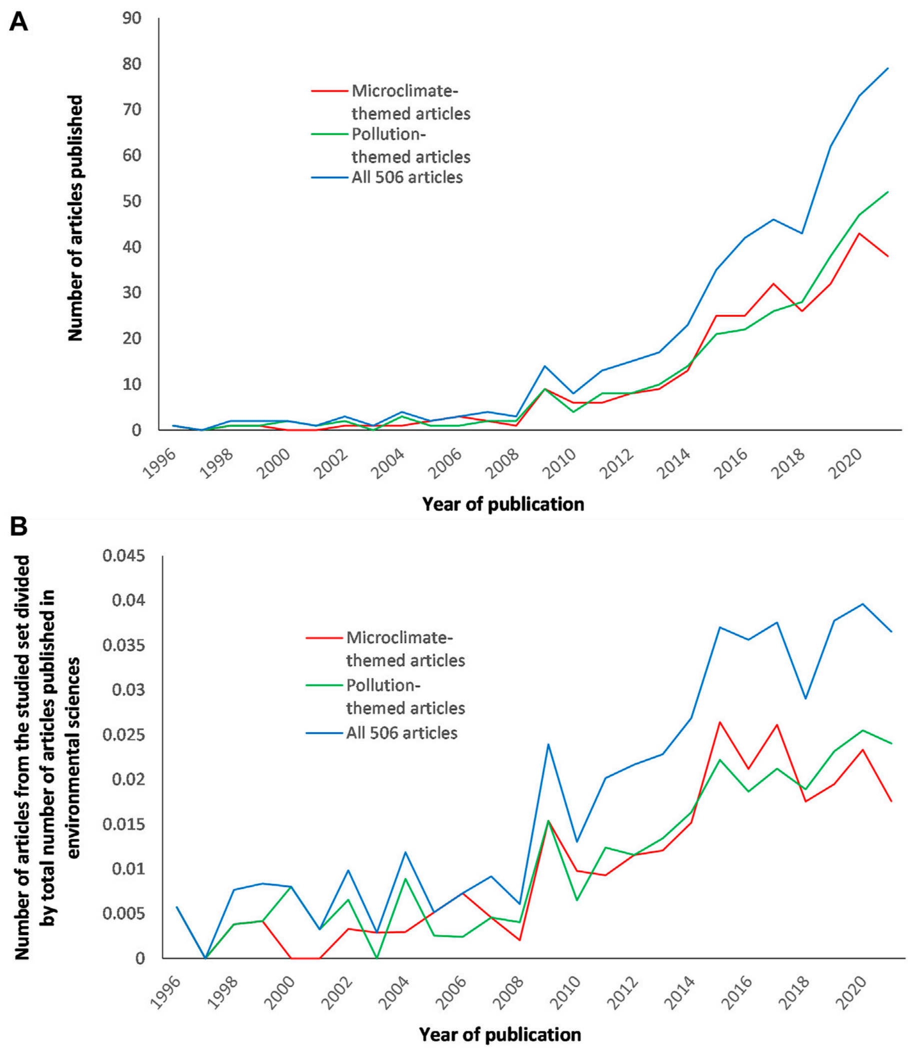


FIGURE 2
**(A)** Number of articles per year. **(B)** Normalized scientific production over the years: number of articles per year divided by the corresponding yearly production of articles in environmental sciences.

science mapping, in order to best suit the purposes of the study, which are to understand how vegetation, UHI, and UPI are thematically linked in their field of research.

Indeed, amongst the quantifiable information given by scientific articles, it is possible to produce numbers about citations, authorship, and keywords (Donthu et al., 2021). First, co-citation analysis considers that when two articles are cited together, they are thematically close. It gives the opportunity to understand how the three themes under study are linked, and was therefore chosen and performed. Another method would have been citation analysis, allowing to understand which authors are influential in the field, but thus giving less thematic information. A choice was made not to include citation analysis in the present work.

A co-word analysis, that assumes articles that have similar author keywords are thematically similar, is also performed. This choice was made because, again, it gives precious information about the interrelations between topics. Less attention was given towards examination of social interactions between researchers and their laboratories through co-authorship analysis, method that was therefore not used in the bibliometric analysis.

Amongst the 506 articles, a search was performed in order to obtain the articles which specifically presented microclimate and/or air quality models at the scale of the UCL: forty-four articles were found and browsed entirely which gave matter for further analysis and discussion.

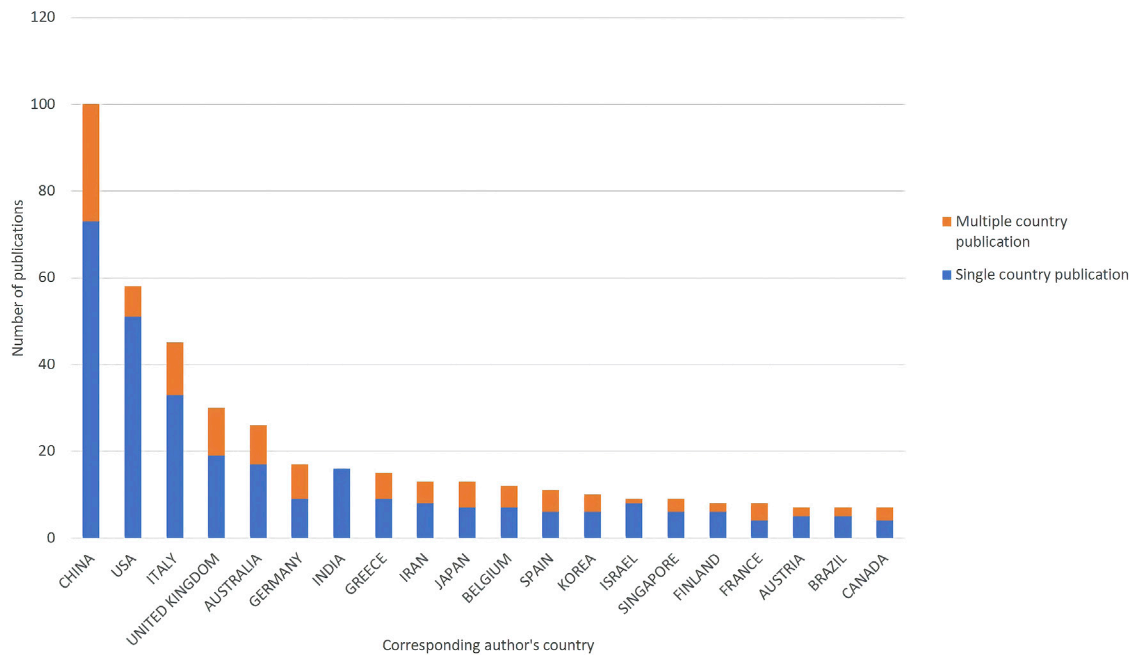


FIGURE 3
Corresponding author's country for the twenty most productive countries. Study on the group of 506 articles.

# Results

## General features for the bibliometric analysis

A total number of 506 documents were analyzed with all their features (title, abstract, authors' names and address, content of the article, sources, references). These articles covered the timespan 1996–2021 and were split into 460 articles and forty-six review articles. They came from 173 different sources (journals, books, etc), written by 1,780 authors, and twenty-nine documents were single-authored. Overall, the articles bear 1,508 author's keywords and quote 18,520 references.

The global number of publications linking urban greening to microclimate and/or air quality was found to increase across time. Yet, even if microclimate-themed articles and air pollution-themed articles were both following the same general increase, for the last 4 years the overall number of articles dealing with air pollution increased faster than microclimate-themed articles (Figure 2A). In order to take into account the general tendency of scientific production increase in the field of environmental engineering, the ratio between the number of articles from the studied set and all articles yearly published in the field of environmental engineering was calculated (Figure 2B). It is therefore possible to see that from 1996 to 2008, publications in the studied set of articles mainly followed the increasing tendency of all environmental sciences publications. From 2008 to 2015, the publications at stake in the study seemed to experience a faster growth than the general publication tendency. Since 2015 all issues from the studied set seemed to be beyond the general speed of increase in number of publications.

The geographical distribution of all the 506 articles was also studied (Figure 3). China was by far the most productive country of the set of articles: 20% of corresponding authors were located in a Chinese laboratory. In terms of publications, the USA, Italy, and the United Kingdom were ranked after China; the USA had 22% more total publications than Italy and 43% less than China. Overall, studies were led most of the time by authors originating from the same country and less frequently by international collaborations (Figure 3). Figure 4 shows the scientific production of each represented country, each author's declared affiliation accounting for the country's productivity. It was noted that Japan, Turkey, South Korea, Israel, and Singapore had a bigger productivity in the field of microclimate than air pollution, while China, United States, Italy, United Kingdom, India, Spain, Brazil, and Germany had the converse trend where themes around atmospheric pollution were more developed (Figure 4).

## Intellectual structure of the set of documents

Performing a co-citation analysis on the studied set of documents could help to underline the founding structure of knowledge related to greening, UHI, and air pollution during the past 25 years (Donthu et al., 2021). This method allowed to

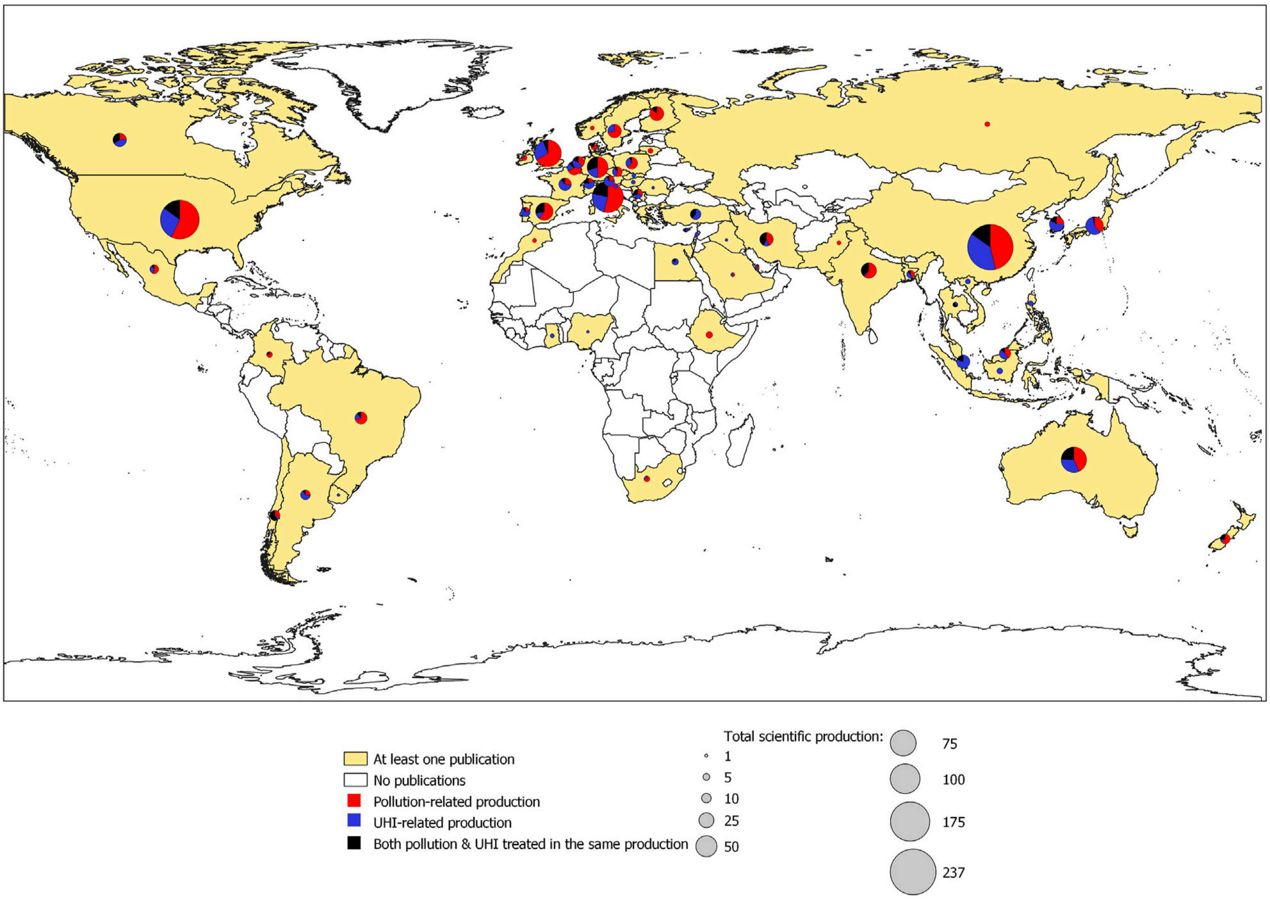


FIGURE 4
Geographical repartition of scientific production, with separation between air quality and microclimate themes. Each author's affiliation for all 506 publications accounts for productivity of countries.

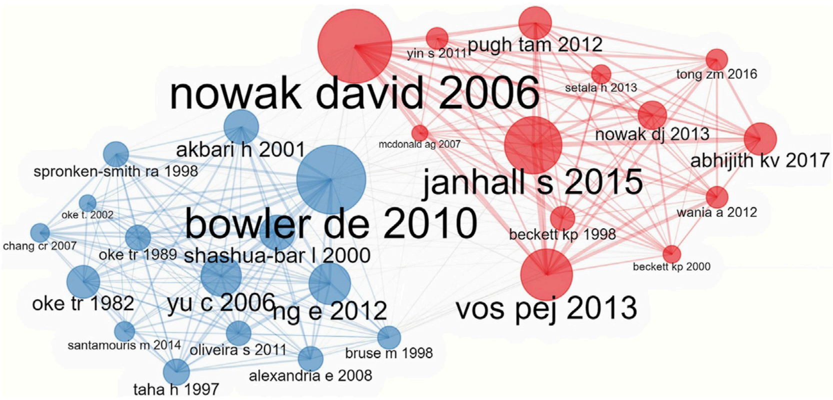


FIGURE 5
Co-citation analysis to map the intellectual structure of the studied set of 506 articles. Size of vertex indicates the number of occurrences; thickness of edge indicates the times two articles were cited together.

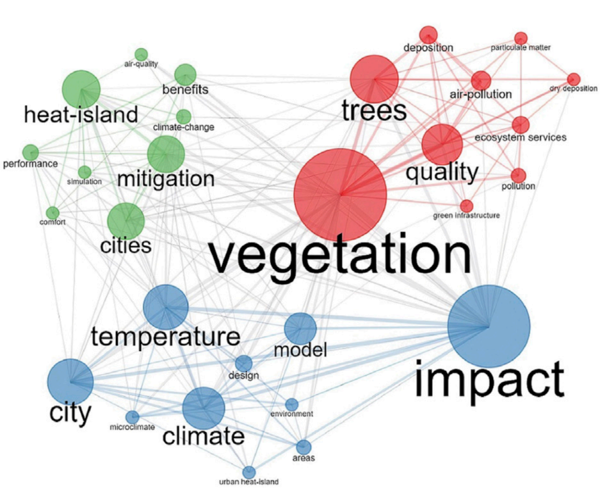


FIGURE 6
Co-word analysis, using Web of Science's "keywords plus" occurrences to map the conceptual structure of the studied set of 506 articles. Size of vertex indicates the number of occurrences; thickness of edge indicates the number of times two words were mentioned together in keyword section.

obtain a co-citation map (Figure 5) assuming that two articles cited together were thematically alike. It was possible to note the polarization of reference articles in two separate clusters (Figure 5). By analyzing the studies mentioned in each cluster, it was possible to find homogeneity in the subjects they tackled: red cluster articles referred only to pollution themes, while blue cluster articles dealt only with microclimate aspects. It was also observed that clusters did not mix both themes.

## Conceptual structure of the set of documents

A co-word analysis was performed in order to describe the conceptual structure of the set of documents studied. Co-word analysis considers the keywords gathered together in an article are thematically linked (Donthu et al., 2021). Three thematic clusters were therefore mapped (Figure 6). Words related to urban greening's impact on microclimate and words related to urban greening's impact on air quality formed two well-defined clusters (respectively blue and red in Figure 6). This observation can be linked to the co-citation analysis previously performed (Figure 5), which indicated similarly that literature is built on those two well-defined topics. A third cluster (green in Figure 6) containing words like "mitigation", "comfort", "performance", and "benefit" showed a tendency of the articles towards assessing the efficiency of different solutions, should they tackle air pollution or microclimate subjects. We could also say that looking for mitigation strategies and better performance of green solutions can be a fair link between microclimate and air pollution clusters that hardly intersect otherwise.

While conducting this co-word analysis study, it was noted an evolution of tendencies in topics and vocabulary. An analysis of the top occurrences of keywords from each article shows that the topic of air quality, with keywords like "air pollution", has taken a significative importance in the authors' speech over the second decade of the XXI$^{st}$ century. It confirms the overall increase of air pollution related articles as seen previously (Figure 2A). Terms such as "ecosystem services", "thermal comfort", "green infrastructure", and "climate change" have also appeared from this second decade of the XXI$^{st}$ century as top occurrences in the articles.

## Microclimate and air quality modelling: Analysis of articles

A more detailed reading of the set of forty-four articles related to modelling studies is used to specify the interrelations between greening, microclimate, and air quality. The articles are classified (Table 1) according to the type of model presented, the greening features investigated, and the phenomenon studied (microclimate and/or air quality). Some limitations are also presented and shall be exploited in the discussion part.

All the studies aimed to assess the impact of greening strategies on air temperature, thermal comfort, or air quality. These greening strategies encompass the planting of trees, extensive or intensive green roofs, green walls, low vegetation, and more rarely the coupling of a green area with a blue area (pond, river).

It is possible to outline the use of two main types of models: lumped-parameter models and computational fluid dynamics (CFD) models. In the set of articles, lumped-parameter models are mainly used for microclimate assessment. CFD models are split into two categories: those solving the Reynolds Averaged Navier Stokes equation (RANS) and those using a Large Eddy Simulation (LES) solving. One model was also found to use quasi-Gaussian dispersion.

The CFD model ENVI-met was combined with other types of algorithms in order to integrate different factors in the assessment of thermal comfort in a street: Jia and Wang (2021) represented pedestrian behavior in response to microclimate using an agent-based modelling software. Simon et al. (2020) aimed to design a tree model by simulating tree growth and branch geometry thanks to a Lindenmayer-System algorithm before studying its microclimate impact.

Both lumped-parameter and CFD models were used to calculate air temperature or Mean Radiant Temperature (MRT). However, differences were found in the scale of use of these types of models: lumped-parameter models could study cases dealing with the interface between plant and atmosphere, and also perform calculations at the urban canyon, district, and city scales. For CFD models, studies mostly stayed at the size of the canyon (RANS models) with exceptional studies at the scale of several canyons when using LES modelling.

TABLE 1 Classification of modelling studies according to the types and features of models used.

| Model type | Model name | Microclimate features | Air pollution: Compounds studied | Scale of use | Greening system | Limitations |
|---|---|---|---|---|---|---|
| Lumped-parameter model | Green Cluster Thermal Time Constant (Green CTTC) (Shashua-Bar and Hoffman, 2002; Shashua-Bar et al., 2010) | Air temperature | x | Street canyon | Tree | Need to study lower vegetation (lawns, groves) |
| | Multi-Layer Urban Canopy Models (Krayenhoff et al., 2014; Park et al., 2018, 2019)<br>Town Energy Balance (TEB) (de Munck et al., 2018) | Air temperature, mean radiant temperature (MRT) | x | Street canyon, district | Green roofs, trees, green grass Watering of vegetation | Energy balance of vegetation not implemented Need of better horizontal resolution Need to consider shading effect of trees |
| | Building Effect Parametrization (BEP) (Cady et al., 2020) Urban Weather Generator (UWG) (Dardir and Berardi, 2021) | Air temperature | x | District | Tree and low vegetation | Tested only for low cloud coverage |
| | Single-Layer Urban Canopy Model (SLUCM) (Arghavani et al., 2019) | X | Dispersion and deposition of $SO_2$, $NO_2$, VOCs, $O_3$ | City | Tree, bush, low grass | |
| | i-Tree suite (Petri et al., 2019; Wu et al., 2019; Pace et al., 2021) | Air temperature | Gaseous deposition of $O_3$ | Tree | Tree and its behaviour in case of hydric stress | Need of more studies for drought seasons and extended areas Feature of greening implementation impossible on impervious surfaces Uncertainties on vegetation types and physical characteristics |
| | SOLWEIG (Lindberg and Grimmond, 2011) RayMan (Matzarakis et al., 2007) | MRT | x | Urban canyon | Trees, bushes | More spatial variability needed for parameters Stationary model only (RayMan) |
| Quasi-Gaussian air dispersion model | Atmospheric Dispersion Modelling System (ADMS) (Tiwari and Kumar, 2020; Komalasari et al., 2021) | X | Dispersion and deposition of $NO_x$ | City | Tree, grassland | Does not study secondary pollutant creation |
| CFD—Reynolds Averaged Navier Stokes (RANS) or Large Eddy Simulation (LES) | SOLENE-microclimate (Robitu et al., 2006; Malys et al., 2014) | Air temperature, MRT | x | District scale | Green wall, water and tree | Need of more experimental data for green walls' impact assessment Computing time prohibitive Better urban scene description needed |
| CFD—LES | Karttunen et al., 2020; Lin et al., 2020; Bannister et al., 2021 | X | Dispersion and deposition of PM 2.5 or PM 10 | Street canyon to district scale (100 canyons) | Tree | More space parameters and better wind description necessary Need to take into account thermal effects of trees |
| CFD—RANS | Fluidyn-PANACHE (Moradpour and Hosseini, 2020) | X | Dispersion and deposition of PM 10, $NO_x$, VOC, CO | Park | Tree | |
| | | Air temperature | x | Skygarden | | |

(Continued on following page)

TABLE 1 (*Continued*) Classification of modelling studies according to the types and features of models used.

| Model type | Model name | Microclimate features | Air pollution: Compounds studied | Scale of use | Greening system | Limitations |
|---|---|---|---|---|---|---|
| | Fluent (Mohammadi et al., 2020) | | | | Trees and hedges on a skygarden | Investigate factors like solar radiation, view factor, meteorological variability |
| | Vranckx et al., 2015; Hong et al., 2017; Qin et al., 2018; Qin et al., 2019 | X | Dispersion and deposition of PM 10 or PM 2.5 | Street canyon | Green walls and green roofs Trees | Non-isothermal study needed Need to consider growth of trees and differences in tree species |
| | Star CCM (Santiago et al., 2019) | x | Dispersion and deposition of Black carbon | Street canyon | Hedgerows and trees | Need of more precise meteorological, vegetation and traffic data |
| | Santiago et al. (2017) | x | Dispersion and deposition of $NO_x$ | District | Tree | |
| | ENVI-met (Mahdavinejad et al., 2018) | x | Dispersion of CO | Park | Tree | |
| | ENVI-met (Morakinyo et al., 2017; Daemei et al., 2018; Forouzandeh, 2018; Ma et al., 2019; Bachir et al., 2021) | Air temperature or MRT or physiologically equivalent temperature (PET) | x | Urban block | Green roofs and walls, low vegetation, trees | Need to perform study at larger scales Model highly dependent on boundary conditions |
| | ENVI-met (Cruz et al., 2021) | Air temperature | x | District with river | River and trees | |
| CFD—RANS equation + photochemistry model | Moradpour et al. (2017) | x | Dispersion of NO-$NO_2$-$O_3$ | Street canyon | Tree | Study variability of temperature conditions |
| CFD—RANS + crowd simulator Agent Based Modelling | Jia and Wang, (2021) | MRT | x | Street canyon | Green roofs, trees, green walls | Need to consider anthropogenic emissions and different wind directions |
| CFD—RANS + generation of trees through Lindenmayer-System | Simon et al. (2020) | PET | x | Tree | Tree leaves | Need to strengthen the model by data measurement |

Differences were also noted with regard to the type of pollutant studied: between the articles using lumped-parameter models, none is quantifying dispersion and deposition of particulate matter on vegetation, contrary to CFD-based studies. Both CFD and lumped-parameter models assess the dispersion and deposition of $NO_x$, Volatile Organic Compounds (VOCs), CO, and $O_3$.

Two models from the studied set can be used for both microclimate and pollution studies: ENVI-met and i-Tree. ENVI-met is mainly used for microclimate studies but one study was found in the set where ENVI-met was used to assess dispersion of CO (Mahdavinejad et al., 2018).

# Discussion

## Bibliometric review

The bibliometric review underlined a growing interest in greening's potential to mitigate the urban heat island over the last 25 years. It was the case especially in countries whose highly-urbanized cities are suffering from high thermal discomfort in the summer in a context of climate change. Many interrogations were also raised on the services or disservices of vegetation related to air quality, as the question is at the center of attention of policy makers and urban planners for places where the urban pollution island causes major health concerns.

The studies analyzed considered urban greening under all its forms as a relevant strategy of urban adaptation to climate change. This involved the definition and study of greening techniques, and therefore the design of more accurate calculation techniques to assess pedestrian thermal comfort, or building energy consumption.

The bibliometric study showed an equal concern in the research field over urban climate and urban air quality. These themes co-existed thematically and intellectually in most of the studies, but with only weak interactions. No cluster was found to mix air quality and microclimate issues. Therefore, it is possible to assume that there is fewer research on the coupling of these two subjects. There is however need for supplementary analysis to confirm the identification of a knowledge gap: forty-four articles selected as defined previously (Figure 1) were analyzed, dealing with modelling of microclimate and air quality in a context of urban greening.

## Microclimate and air quality models

The analysis of the forty-four articles first confirmed the findings from the bibliometric study, i.e., microclimate and air quality assessments were most of the time studied independently (Table 1).

It would be inaccurate to state that models simulating microclimate and air quality together as a result of plant interactions do not exist in the research field. It is possible to cite, within the set of articles studied, two examples of models assessing both. First, the i-Tree suite claimed to allow city planners to study both microclimate and air quality impacts of planting trees. Petri et al. (2019) underline the limitations of such a tool by making a case for coupling i-Tree with a CFD tool like ENVI-met for better assessment of microclimatic impacts. The scale of the i-Tree model is the tree level.

Another tool claiming to assess greening's impacts on both microclimate and air quality is the CFD-based ENVI-met model. Its scale of study is often limited to a few streets (e.g., Daemei et al., 2018; Bachir et al., 2021) and highly dependent on set boundary conditions (Forouzandeh, 2018). Therefore, among the articles studied, none was found to suggest a model that could support city planner's decision-making at the city scale.

CFD models reach computing time limitations when confronted to too large an area of modelling, thus their applications remain at street scale or small neighborhood. However, they allow for a better description of the variability of physical parameters along a defined mesh. On the contrary, lumped-parameter models can compute temperature and concentrations on larger areas. However, representing geometry elements by single nodes can be limitative to describe their spatial variations. Also, handling meteorological data can prove challenging when studying the largest scale of the urban canopy. A balance therefore still needs to be found between a model that can ensure the transition from interfaces to larger scales and that can integrate the necessary range of details and variations for better accuracy.

Some studies dealing with air pollution related to greening underline that their models were used in hypothetical thermal conditions even if vegetation's behavior is temperature-dependent (Moradpour et al., 2017; Qin et al., 2018). A more accurate calculation could be made by joining microclimate evaluation to pollutant concentration computing through the functioning of vegetation. There is therefore need to describe plant functioning sharply enough: the studies at stake recognize developments are needed regarding the behavior of plants, for example regarding the modification of their impact on the atmosphere during hydric stress (de Munck et al., 2018; Pace et al., 2021). Another key of improvement could be better consideration of vegetation species (Wang et al., 2021) and of vegetation growth phases (Petri et al., 2019). More detailed vegetation modelling could be the key to bridging the gap between microclimate and air pollution studies.

It is all the more important to explore the link between urban greening, UHI, and UPI since strong interactions exist between plant functioning, microclimate, and atmospheric composition. Indeed, quantifying pollution absorption sharply depends on temperature. For instance, too high temperatures can induce stomatal closure, therefore decreasing pollution absorption by vegetation. Hence, not considering vegetation influence on UCL temperature would lead to underestimating pollutant deposition and vegetation impact on the UPI. Moreover, temperature impact on atmospheric chemistry is well-known: for instance, production of ozone knows a two ppbv increase per degree Celsius (Coates et al., 2016): vegetation-induced cooling could therefore diminish ozone production in the atmosphere. Similar dependencies can be stated for dispersion phenomena, which are also highly influenced by temperature and thus could be influenced by greening.

# Conclusion

A bibliometric analysis was performed on 506 articles collected in the Web of Science Core Collection database. The goal of the study was to analyze the structure of research dealing with the impact of greening on the UHI and the UPI. Both co-citation and co-word analysis showed the interest in microclimate or air quality issues related to greening. The intersection between the two topics was however relatively small.

The topic was then narrowed down to modelling studies through detailed analysis of forty-four articles. The difficult balance between transitions of scale, computation time, and detail of calculation was witnessed. Vegetation models existed that linked air quality and microclimate topics, but their scale did not exceed the urban canyon size.

If the direct effects of vegetation on air quality were largely studied overtime, a case can be made for better assessment of vegetation's indirect effects on pollution. Vegetation is able to cool air temperatures, which will have consequences on dispersion and photochemistry in the atmosphere, as well as actions on stomatal uptake of pollutants. It is therefore necessary to integrate coupling of both microclimate and pollutant in models which would assess more accurately vegetation's effects at city scale.

This need for modeling tools that could take into account the effect of vegetation both on microclimate and air quality is all the more precious in a context where climate change shall influence plants' behavior during heat waves and droughts.

## Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## Author contributions

The initial idea for the work came from a study by SL, PS, and EP. ME developed and improved the research and the bibliometric analysis, including research methodology and visualization. ME wrote the initial version of the paper, PS revised the paper and all co-authors contributed to the discussion and final version of the paper. PS, ML, EP, and BL supervised the whole work.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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