Highlights

Bibliometric analysis and landscape of actors in passive cooling research.

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- The largest set of publications on passive cooling is systematically compiled.
- Meta-data is examined by bibliometric analysis.
- Passive technologies are analysed by year, countries and authorship.
- Research networks and communities of collaborations are identified.

Bibliometric analysis and landscape of actors in passive cooling research.

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ABSTRACT

This paper presents the trends and actors from research publications covering passive cooling technologies. The unprecedented growth in the provision of cooling is posing a significant risk to energy systems and the natural environment, making passive cooling an important alternative to air conditioners. This paper provides a first necessary step towards better understanding the contribution of passive cooling. By conducting a bibliometric analysis on passive cooling technologies, first, it identifies the relevant literature through structured searches. Second, it examines the actors in the field (i.e. countries, authors, research communities and funders). Further, the main researchers by specific passive cooling categories are analysed in detail in terms of the trajectory of publication and author clusters, including novel visualisations of productivity and collaboration.

The search results in a set of 2,859 unique documents, to our knowledge, the largest set in the subject. The country most named in affiliations is the United States (N=762), but since 2010, China (N=544) has driven a rapid increase in research activity. Specific technologies also show increasing trends in annual publications, with natural ventilation being the dominant passive cooling measure (N=389), followed by microclimate (N=317) and radiative cooling (N=312). In the last three years, however, publications on radiative cooling and solar control have been the most numerous and hence are promising technologies in the field. The top publishing author is M. Santamouris within a community of 41 researchers covering most technologies. Other top authors (e.g. L. F. Cabeza and S. Herkel) and their communities are also found to research multiple cooling technologies. Research in the field is currently expanding as observed by top communities mainly publishing from 2010. Only five of the main research clusters were established before 2000s. The majority of funding and support identified has come from the public sector such as grants from the European Union, national ministries or scientific budgets. This paper provides new insights on passive cooling research to date, for promoting scientific collaboration, informing decision-makers and structuring the literature.

1. Introduction

This paper presents a comprehensive overview of publications and research actors in passive cooling technologies, by drawing together and analysing the largest sample of relevant scientific literature. It responds to the main question: what is the research landscape of passive cooling? From this, stem other specific research questions addressed such as: What are the trends and trajectories of the scientific literature for these technologies? Who are the main countries, communities and funders researching in the field? How productive are the research communities and how are they connected?

Cooling is becoming an urgent challenge in the climate change debate but maybe the least addressed. By 2050, between 1.8 and 4.1 billion people will require air conditioning (AC) to avoid heat-related stresses on health and well-being [1] and the electricity needed for cooling will be equivalent to the power consumed today by the United States, Europe and Japan[2]. According to the International Energy Agency (IEA), this is equivalent to 10 new air conditioners being sold every second for the next 30 years [2]. These immense changes, if left unchecked, can drastically worsen human damage to the environment (e.g. increasing anthropogenic greenhouse gas emissions and ozone depletion) and further stress the energy grids and networks. Already in large cities around the world, the use of AC is responsible for peak electricity demand [3, 4, 5]. It is therefore urgently necessary to understand and where possible adopt alternative technologies that avoid the energy-intensive active cooling.

Active technologies (i.e. those that consume electricity during operation) have been dominant in the

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cooling market, with air conditioners and fans the most widely used [6]. The former has provided thermal comfort to millions but have high energy consumption due to their vapour-compressor cycle. To mitigate their impact, the adoption of passive cooling technologies can deliver thermal comfort with no or low energy consumption. They also provide benefits of not using refrigerants (chlorofluorocarbons (CFCs) or hydrofluorocarbons (HFCs)) which damage the ozone and have high global warming potential. Further, passive cooling technologies are low maintenance and have lower running costs [7], they are commonly incorporated within building envelopes which can allow them to blend into the surrounding architecture and can harvest local, natural-occurring renewable resources (e.g. wind for ventilation, vegetation for shade, sea and lakes for cold deep water). In some cases, passive cooling can be achieved using local knowledge and materials in the form of vernacular architecture. These advantages have driven scientific and urban planning interests given the need to decarbonise energy systems. In fact, passive cooling research in 2017 was reported to have overtaken (in the number of annual publications) that of active and solar cooling [8].

The research on passive cooling technologies has been widely structured in three categories, according to three overarching cooling mechanisms [9, 10, 11]:

(1) Heat prevention (also known as solar and heat protection) corresponds to technologies that avoid heat gains of a building or room. To block solar radiation, they are usually found in the border or outside of dwellings. Within these technologies, there are microclimate applications (i.e. the use of landscaping, vegetation and exterior water surfaces) and solar control measures (i.e. avoiding radiation penetration through shading, glazing and aperture).

(2) Heat modulation is the use of building materials that capture delay or displace peak temperatures. Within these technologies, the thermal mass of a building can be modified by the use of phase-changing materials (PCMs). These capture heat during the daytime through latent heat. At night time, the thermal mass is designed to release heat, a process which can be aided by night ventilation.

(3) Heat dissipation, which extracts heat from inside buildings and disposes of it in heat sinks such as air, water or the sky. Passive technology that uses air as a heat sink consists of different ventilation modes. Namely, natural ventilation is driven by wind or buoyancy effects, or the use of Trombe walls and solar chimneys. Passive cooling that uses water as a heat sink is known as evaporative. These are direct (i.e. when air is exposed to water directly and gains humidity while lowering its temperature) or indirect (where water and air are not in contact). Those technologies that use the sky as a heat sink are radiative. These either dispose of heat through radiative panels and/or using radiant walls to extract the indoor heat.

The above indicates high diversity in passive cooling technologies for passive cooling. This is promising in terms of finding multiple solutions but is challenging in terms of comparing the performance between them. Contrary to active technologies, where the coefficient of performance (COP) is widely standardised, different performances metrics are reported for passive cooling technologies [12]. For example, energy savings or temperature differences are reported with different baseline scenarios. This limits comparability as control cases vary (e.g. using air conditioners, other passive measures or buildings without cooling measures. A sole metric, to our knowledge, is not yet reported in the literature to compare passive cooling technologies and is needed.

As a step towards a better understanding of the developments in these technologies, mainly qualitative literature reviews of varied scopes are found (as will be discussed in Section 2). In this paper, first, the potential bias of qualitative reviews is reduced by performing a systematic and reproducible search for literature in all known categories of passive cooling technologies. By this, the work contributes to the literature by bringing together, to the authors' knowledge, the largest sample of research documents on passive cooling technologies. Second, the bibliometric analysis serves to identify the trends of publications and the focus of top researchers in the whole field of passive cooling. It is a novelty to include all passive cooling technologies in one bibliometric analysis. Thus, the work is an indication of where the field stands and where it is heading. By having visibility of the whole field, gaps in research funding can be indicated and research policy informed. Finally, the analysis of specific passive cooling technologies is carried out by considering their latest classification [11, 9]. This can have implications in promoting scientific collaboration and inform decision-makers of where the expertise in the field lie. This is the first urgent step in understanding the potential of passive technologies as a lever for change [13] in decarbonising the future demand for cooling.

The paper begins by providing context on related work by summarising previous qualitative and quantitative reviews in the field (Section 2). Thereafter, the methodology is presented for the structured search, the bibliometric analysis of documents and processing of data to produce, for example, author collaboration networks (Section 3). The results are structured in two parts. First, the work presents the analysis of the whole set of documents found (Section 4.1.1), with the annual publications per countries, and identification of top authors and communities (Section 4.1.2). Second, a closer inspection is performed on the scientific publications of specific passive cooling technologies. For this, subsets of the documents found through the systematic search are considered following the classification of Bhamare et al. [11]. Bibliometric analysis of these subsets is reported, together with the identification of authors and communities found in each technology. Novel visualisations, specifically designed to map research clusters, their international collaboration and productivity are presented. The paper ends by consolidating these insights in a discussion (Section 5) to inform future roadmaps of passive cooling research which is necessary to distil the results and understand their implications.

2. Literature Review

This section presents how the academic literature has previously reviewed (qualitatively and quantitatively) the three cooling mechanisms (prevention, modulation and dissipation) and specific passive cooling technologies. Qualitative reviews involving several mechanisms of passive cooling are found from 1992 when Antinucci et al. [7] studied them. Those authors considered heat modulation as part of heat dissipation and reported the state-of-the-art of passive (and hybrid) cooling systems for buildings. They manually reviewed 119 sources covering the design of techniques and components used in heat protection and heat dissipation. Their review called for more research in estimating and shifting heat loads of buildings, reducing CFCs and implementing high-efficient heat pumps. Later, in 2013 Samuel et al. [12] conducted a review of 112 papers on the performance, benefits and limitations of passive cooling systems. The authors classified passive cooling technologies based on whether these displace heat to heat-sinks or prevent heat ingress to buildings. These authors considered heat modulation (i.e. thermal mass of buildings) as a technique that supported the other two cooling modes. That same year Santamouris et al. [9] acknowledged thermal modulation as an independent passive cooling mode. The focus of the latter qualitative review, however, was on heat dissipation techniques, in particular, the fundamentals, applications, modelling and performance of three commercially available technologies: earth to air heat exchangers, direct and indirect evaporative cooling, and night ventilation. In 2017, Panchabikesan et al. [10] brought together 127 references to examine evaporative, nocturnal radiative, and PCM with free cooling, for different climatic conditions in India. This review gives an overview of the technologies and depth review of experimental and numerical work on passive cooling. The author reports technologies according to the three cooling mechanisms and the desired conditions (air temperature, time attenuation and heat dissipation). There are several technologies, however, that can belong to different categories. More recently, in 2018 Oropeza-Pérez and Østergaard [14] reviewed 10 passive and 3 active cooling technologies from 244 references. The authors used a technology classification based on the elements of a buildings energy balance: i) internal heat gains or ii) heat transfer through envelope between indoor/outdoor. They further categorised the technology depending on whether it blocked or expelled heat (similar to the heat protection and heat dissipation mechanisms). Omrany et al. in 2016[15] examined cooling through building envelopes with an unconventional classification too by considering green, Trombe and cavity walls. As the above overarching qualitative reviews show, there is diverse categorisation used to analyse passive cooling technologies. The most granular and closest to mutually exclusive classification of passive technologies found in a literature review is that by Bhamare et al. [11] in 2019. The authors built on the previously reported categories of passive cooling technologies [16], reviewed 255 documents and contributed additional sub-categories. The only passive heat dissipation classification not included above is that using the ground as a heat-sink, e.g. earth to air heat exchangers which lower temperature by circulating air through underground tubes[9]. As Section 3 will show, the latter is added as a technology for the technology part of our analysis.

In terms of qualitative reviews for specific passive cooling technologies, recent studies (from 2015) are mainly found for two heat dissipation types: using air or sky as heat sinks. Passive dissipation of heat to air through natural ventilation is dominant[17, 18, 19, 20]. Two reviews examining windcatchers [17, 18] have reported different configurations of this technology, and how they can be used to improve the efficiency of other natural ventilation measures. A review of Trombe walls[21] for both heating and cooling covered wall configuration, designing parameters and evaluation indicators. Two articles[22, 19] reviewed natural ventilation at night-time combined with thermal mass storage. The first[22] proposes a new configuration with other passive measures, while the second[19] examines the last 20 years of research in nocturnal ventilation in terms of parameters and controls. For cooling through heat dissipation to the sky (known as radiative cooling), recent qualitative reviews[23, 24, 25] have mainly shown the progression in materials for these technologies. Review articles for solar and heat protection are recently found for microclimate[26] and glazing measures[27, 28]. Finally, for heat modulation technologies, specific technology reviews are found for cooling through PCMs[29, 30]. It is observed that the application of the latter passive cooling measures has been increasingly focused on photovoltaic panels, rather than buildings.

Qualitative reviews in the field, as seen above, have contributed towards understanding technologies, their trends and classifications. However, limitations include: i) selection of documents is non-reproducible with potential bias and ii) manual selection and analysis of content in a large set of documents. In this respect, systematic or structured online searches are reproducible and can widen the sample size of articles of qualitative reviews, while eliminating bias in the selection. When combined with bibliometric and text mining techniques, they can provide insights on trends, actors and content through automated analysis. There are bibliometric studies found for different passive cooling applications but not covering all the technologies in the classification above. The largest coverage is in Prieto et al. [8], where the authors reported a wide range of cooling technologies in passive, active and solar cooling, but specifically for office building façades. Their bibliometric review captured four to five times more documents than the previously mentioned qualitative reviews (a total of 861 articles). Similarly, three other bibliometric analyses are found to partly cover passive cooling. First, Zhao et al. [31], brought together 2,980 documents on green buildings, which included cooling but were not exclusive to it. Second, the bibliometric analysis of urban heat island by Huang et al. [32] (of 1822 papers) included cooling mitigation techniques (i.e. roofs, vegetation and urban landscaping). Finally, the works of Cabeza et al. [33, 34] include cooling literature when studying climate mitigation technologies of buildings. Other reviews with a smaller scope are found for vertical greenery [35], passive solar cooling [36], PCMs [37], green roofs [38] and cooling of other applications such as batteries [34]. These provide evidence of the vast literature on passive cooling for specific applications. However, in no case have the scale benefits of bibliometric techniques been applied to the full extent of the passive cooling technologies.

3. Methods

This section presents the methodology used to identify relevant passive cooling studies, subsequently, describes the techniques to perform the bibliometric analysis on document meta-data and to visualise author collaboration networks. It follows the overview flow of information presented in Fig. 1.

3.1. Document search

A systematic online search is performed to find relevant literature that contributes to determining trends and communities in passive cooling. This is driven by two criteria:

1. the content of the document (as shown in the title, abstract and/or keyword) must cover at least one passive cooling technology, and
2. the application of such technology or technique must be for human thermal comfort i.e. indoor or outdoor space cooling.

As an initial step to satisfy the criteria, search words are identified and structured as shown in Fig. 2. To find documents with passive cooling technologies (first criterion), eight sub-searches were structured. Search 1 in Fig. 2 corresponds to generic terms that capture

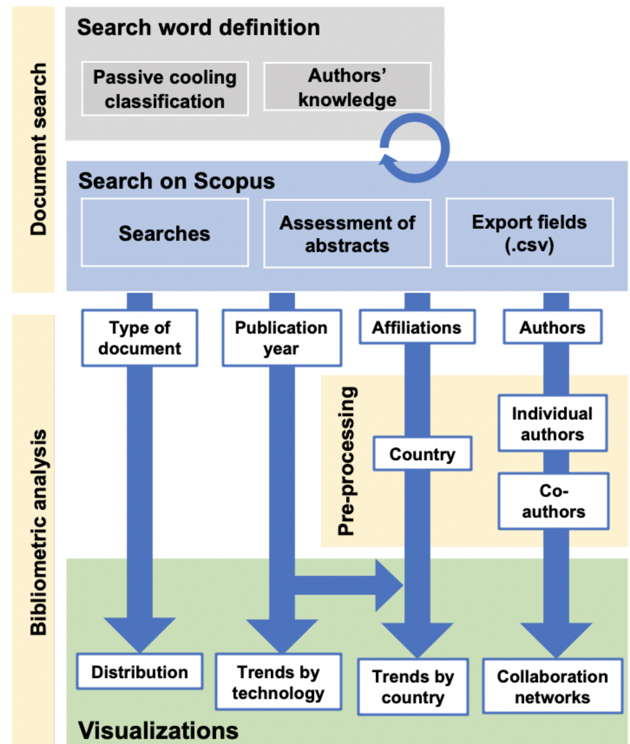

Fig. 1 Steps for the search of literature and the bibliometric analysis.

passive cooling technologies. These aim to identify the universe of literature that contains alternatives to active cooling. Hence, this literature is not classified by specific passive cooling technologies. Search 1 is used as an initial part of the analysis in the results section (Section 4). The subsequent Searches 2 to 8 in Fig. 2 are targeted to find literature reporting specific passive cooling technologies. These searches are based on the classification of Bhamare et al. [11] having added ground cooling as passive heat dissipation reported by other authors [9]. These searches are used in the second part of the analysis.

For each search, specific technology-based words were combined with a common list of contextual search words, as presented in Fig. 2. Each of the eight groups of technology search words was combined with contextual words (right block in Fig. 2). These terms capture the physical scope of cooling for thermal comfort and screen out unrelated topics such as cooling for medical treatment, cold chains or cooling in the atmosphere during ice ages. It should be noted that search words of passive context resemble some of those in the physical scope. This is to characterise both the passive technology and the infrastructure where it is applied.

As a second step, the search words are used to perform eight queries on Scopus [39]. This citation indexing platform is used as it is the largest abstract and citation database of peer-reviewed literature in differ-

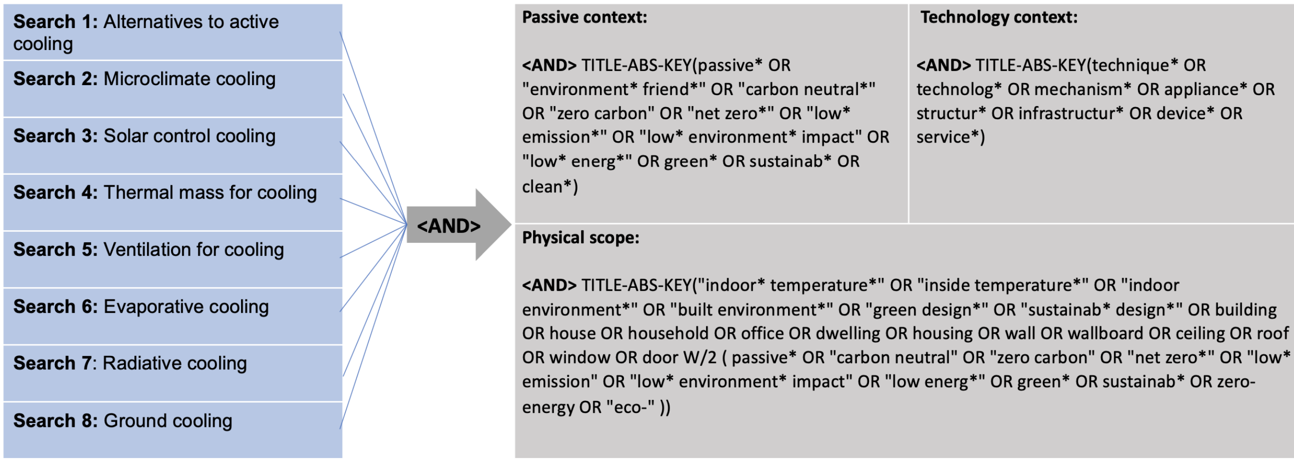

Fig. 2 Structure of the eight searches on Scopus, including common search words (grey). Left block: technology-specific search words, and right block: common contextual search words for the eight searches.

ent disciplines, and has a comprehensive search engine. The Scopus engine is set to find the search words in document topics, by scanning titles, abstracts and author keywords. The language is set to "English" for each search. This excludes research published in languages, for example, from Southeast Asia, China and India which are key countries driving the demand for cooling technologies [2, 40, 41]. However, as results will show, the search brings together a large sample size. The year and document type was not a constraint in the searches, except for the year 2020 that is ongoing at the time of the searches.

In a final step, search words are iteratively refined, based on a similar approach by Lamb et al. [42]. For this, a random sample of 20 abstracts output for each search was manually assessed against the two selection criteria. Search words evolved until more than 90% of the sample passed the assessment. The final and full list of technology search words are included in the Supplementary Material, while the final contextual search words are in Fig. 2. From the documents found through the eight final searches, the meta-data fields extracted for the analyses are:

- Year of publication
- Author affiliation(s)
- Type of document
- Name of author(s)
- Cited by
- Funding details

From the above, the three first fields are used for the bibliometric analyses. The name of authors is captured for detection of research communities and the field is used to indicate the impact of a community in terms of the number of citations that its publication has. The field 'Funding details' is used to analyse the funders per technology. Since many articles did not specify the latter, the Acknowledgment sections were inspected manually (when available) to complement this meta-data field. All data-processing and visualisations described in the following sections are performed in R Studio (Version 1.2).

3.2. Bibliometric analysis

This section presents how trends and statistics in passive cooling technologies are addressed. The publication metrics extracted from the eight searches is the basis of the bibliometric analysis. The document title is used to identify unique publications to avoid duplicates. The year of publication is used to mark the progression of publication by country and technology.

The first part of the analysis uses the documents found in Search 1 (i.e. the whole universe of publications found for passive cooling technologies) to report the trends in scientific publications by year and country. These are used as a proxy, to analyse how research on passive cooling technologies has evolved in different locations. This may have limitations as research in one institution can include engagement with those overseas. However, this type of analysis can indicate where institutions researching passive cooling are located and where funding is available for research in the field. This field containing affiliations corresponds to full addresses for all authors of a document, hence, text preprocessing is applied to tokenise the field by word and extract countries.

The second part of the analysis, reports technology trends based on the results from Searches 2 to 8. These documents are considered classified into a specific passive cooling technology. Unclassified documents (i.e.

found in Search 1 but not in Searches 2 to 8) are excluded from the second part of the analysis.

The final meta-data field extracted from the documents is "type of document". This is used to examine how research has been communicated (e.g. through articles, conferences, reviews).

3.3. Author collaboration networks

To examine the actors in the field with more granularity (i.e. further than at country of affiliation level), authors are analysed. This section explains the processing of document data to construct collaboration networks. The count of authors and pairs of co-authors are used to visualise research contribution and collaboration. Duplicates are avoided by inspecting authors with the same initial(s) and surnames. Author collaboration networks are constructed in the first part of the analysis for documents of Search 1 (i.e. the full document set) and, in the second part of the analysis, for each passive cooling technology (Searches 2 to 8).

There are four layers to build the collaboration networks. First, authors with most publications and are collaborating with others are mapped as a first layer on the networks as nodes. A threshold is applied for the minimum of publications of these authors (n_{pub}) to achieve a meaningful visualisation of the network. For example, if n_{pub}=2, this layer will only map authors who have 2 or more publications.

Second, the top co-occurring authors i.e. those pairs of authors most appearing together as co-authors in publications, are identified and added to the network. The edges between pairs of authors indicate co-authorship. Similar to the top authors, a threshold is used (n_{collab}) for each collaboration network to establish a minimum of co-occurrence between any two authors. For example, if n_{collab}=3, this layer will add those pairs of authors that have collaborated at least in three publications.

Third, to understand the scale of the research communities behind the top authors and co-authors, for each of the nodes identified previously the co-authors are added. This implies that co-authors that do not meet the thresholds above (n_{pub} and n_{collab}) are added only if they have published together with a top author or co-author pair.

As a fourth layer, communities within the networks are detected by the Newman-Girvan algorithm [43]. This partitions the network by first calculating the edge betweenness (i.e. the number of shortest paths between pairs of nodes passing through an edge). Betweenness measures the influence (centrality) of nodes. Second, the algorithm focus on the remaining edges (less central) and more likely to be between two communities. Thereafter, to visualise between 10 and 20 clusters, the two thresholds (n_{pub} and n_{colab}) are iteratively refined (starting from values of 2).

Finally, to visualise the level of international collaboration and cluster productivity, the clusters are plotted according to the number of countries they include in the author affiliation (y-axis) and the average publication per author (x-axis), respectively. The latter corresponds to the documents published within a cluster of authors divided by the number of authors in that cluster.

4. Results

There are two result parts. The first (Section 4.1.1 to 4.1.2) shows the full body of academic literature found for passive cooling technologies (Search 1). It presents trends in these publications by year, followed by the contributors (i.e. countries, top authors and research communities). In the second part of the results, the most granular known classification [11] is used to analyse the trends of research by technology (found through Searches 2 to 8). Results on classified documents are analysed in Section 4.2.1 to draw a comparison between publications and technology trends. Thereafter Sections 4.2.3 to 4.2.8 provide in-depth analysis of top author and collaborative networks for each of the passive cooling classifications.

4.1. Part 1: Academic literature covering field of passive cooling

4.1.1. Overview of publications

The systematic generic search (Search 1) for articles covering passive cooling technologies returned 2,859 unique publication titles. These correspond to documents that have not been classified into a specific cooling technology. The set of documents is the largest group of publications compiled to analyse passive cooling technologies, to the authors' knowledge.

In terms of document types, 50% of documents correspond to articles, followed by 39% conference papers/reviews (chart in Supplementary Material). Given that journal articles and many conferences papers have peer-review selection processes, these results show a high quality of original research in the documents.

Published literature on passive cooling in the dataset is found since 1970 (see Fig. 3), averaging 57 publications per year. It is noted that during the first decade, only nine documents are found. These nine initial publications mainly consider passive cooling under the overarching subject of solar houses or in combination with heating. In fact, other technology-focus searches (in Part 2 of the Results) did not find these documents, which indicates that research exclusive to any specific passive cooling technology was initially uncommon.

4.1.2. Main actors in the field

The main contributors to the field are analysed based on countries in the author affiliation, their citations, publications and funding bodies.

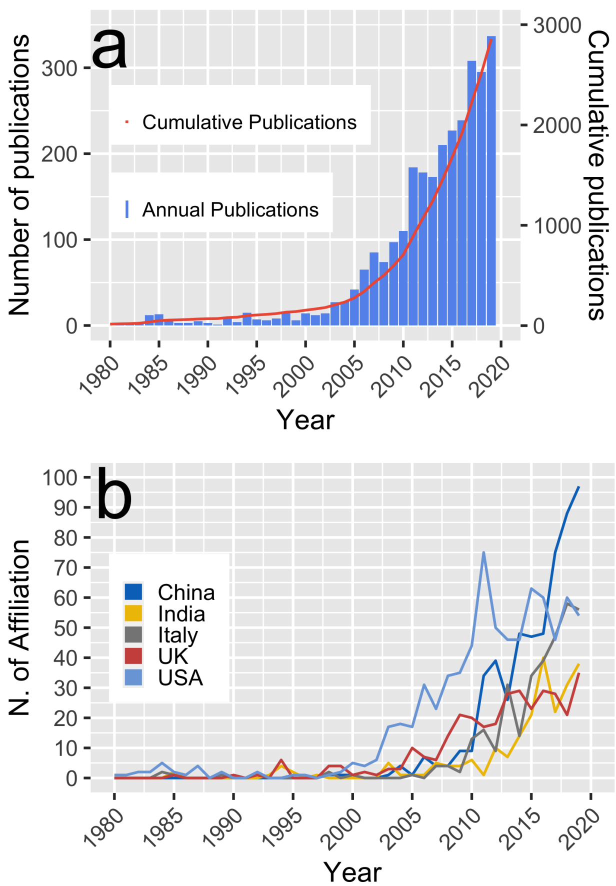

Fig. 3 Publications in passive cooling (a) annual and cummulative publications and; (b) publications for top countries.

From the 2,859 documents, there are 91 countries identified in the author affiliations in the remaining documents. There are 172 documents excluded in this part of the analysis as they did not show affiliation information.

The main body of literature has been published after 2005, with increasing trends in annual publications. The countries most found in author affiliations are the US (N= 762), China (N= 544), Italy (N=336), UK (N= 333) and India (N= 221). The trends of the annual publication for these countries are shown in Fig. 3b. It should be noted that the year 2020 is excluded, as it is ongoing at the time of the searches.

The US's lead in the publications is aligned with the country's early rate of air conditioning development and one that has the highest adoption of cooling [6]. US affiliations in the publications are first found in 1979 and 1980. The early contribution can be explained by initial movements for passive houses, especially in response to the oil embargo in the 1970s and its consequent energy crisis. Publications in the field from the US have continued to be dominant since then until 2016 when its annual publications were surpassed by China.

Chinese affiliations are the second highest in the dataset and most reported annually since 2016 (as shown in Fig. 3b). The rising curve in affiliations from this country is close to an exponential trajectory since 2003 (R^2=0.87). This trend is related to two factors. First, the country's substantial increase in energy use for space cooling in buildings has reached an average annual growth rate of 13% since 2000 [40]. Already this demand for cooling has impacted the country's electricity systems and resulted in 7% of the countries energy demand [40]. Second, China has risen as a major contributor to scientific research and technology since 2002 [44]. Driving factors include its large human capital base and government investment in science [44].

Fig. 3b also shows that publications from India have risen after others, in 2011. This short period in which India's research has significantly increased its output reflects wide efforts directed towards passive cooling technologies in recent years. It also follows the heatwave in that country in May 2010 where a 43.1% increase in deaths was reported due to the extreme temperatures (high of 46.8°C) in the city of Ahmedabad [45].

In Europe, Italy and the UK are the top countries in terms of authors' affiliations. From the results in Fig. 3a (and after in Fig. 6c), the affiliations associated with the UK have had one main increase between 2004 and 2013, while remaining at approximately 25 annual publications from this country per year since 2012. Conversely, Italy has kept steady until 2006, when a steep increase is observed. By 2015 it surpassed the UK in terms of annual publications. A common motivation for research in passive cooling for these two countries is the exposure of the vulnerable (ageing) population to more frequent heatwaves. In Italy, the Mediterranean climate exacerbates these effects, making the case for research in all cooling technologies more urgent.

Unexpectedly, Japan does not play a leading role, although 90% of its households own air conditioners [2]. This can potentially be attributed to more efforts being directed to developing intelligent electronic systems for active cooling as reported by Fijii et al. [46]. This author has claimed that passive cooling in Japan is more aligned with behaviours and culture than with the adoption of technological solutions.

The surge in research of passive cooling from countries has been attributed to national social, environmental and political drivers (e.g. heat waves, availability of research funding). From these observations, it can be concluded that the uptake of research in the field may arise from different dimensions. Content analysis of the same literature can provide further insights on the common motivations that have driven research on these technologies.

There are 6,657 authors found in the document set on passive cooling. The top authors overall are M. San-

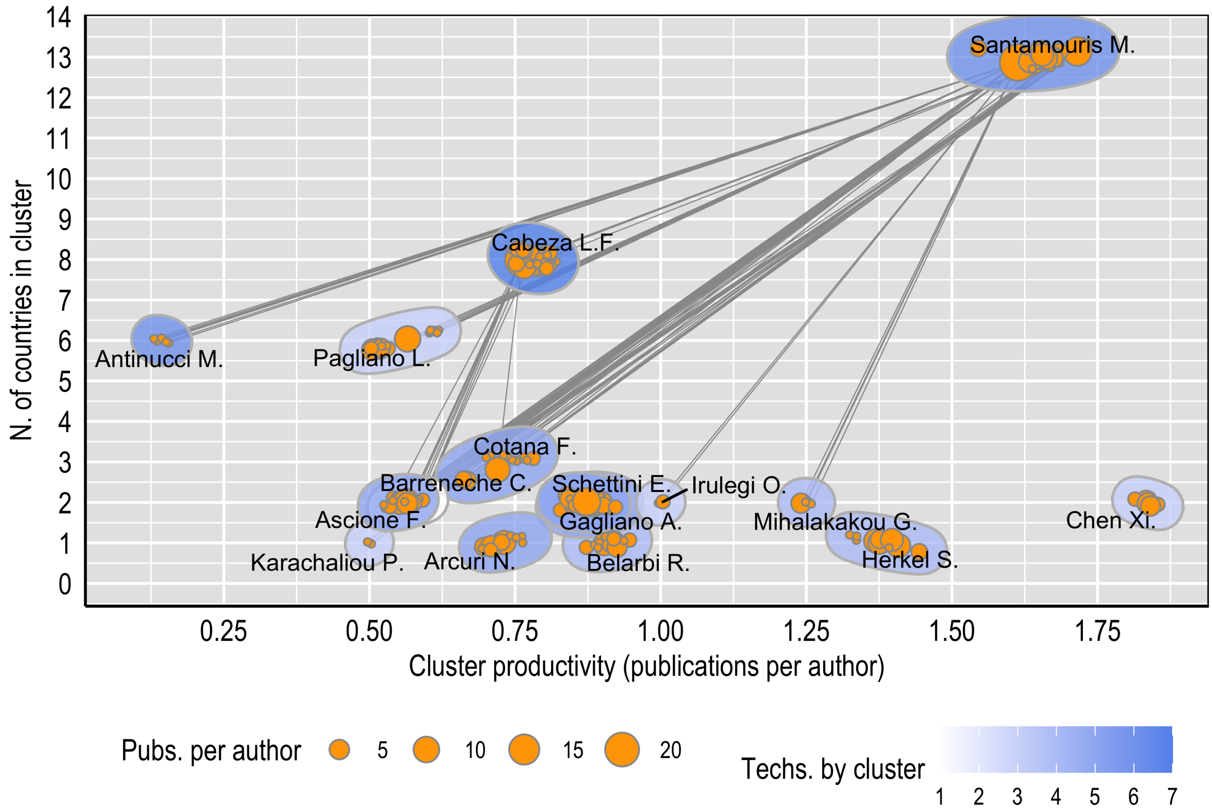

Fig. 4 Author collaboration network and communities (clusters) detected for passive cooling technologies (Search 1, $n_{pub} \geq 13$, $n_{collab} \geq 6$). Nodes are authors with diameters proportional to number of publications and names are authors with most publications ($n_{pub} \geq 13$). Edges indicate co-authorship.

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Table 1: Research communities in passive cooling as per Fig. 4.

Cluster (named by main author)	No. of Authors	Main affiliation(s)	Technologies covered[a]	Main funding or supporting projects	No. of Publ.	Citations	Years Covered	Ref.[b]
Santamouris M.	41	University of New South Wales, Australia; University of Athens, Greece.	E, M, SC, V, R & G.	EU's Horizon 2020 (678407; ZERO-PLUS); National Science Foundation (CBET-1512429 & 1752522)	68	2,919	1992-2019	[47]
Cabeza L.F. & De Gracia	33	University of Lleida, Spain; University of Barcelona, Spain; University of Antofagasta, Chile.	All	European Commission Seventh Framework (PIRSES-GA-2013-610692 INNOSTORAGE); EU's Horizon 2020 (657466 INPATH-TES); Spanish Government (ENE2015-64117-C5-1-R; ENE2015-64117-C5-3-R; ULLE104E-1305; ENE2011-22722; ENE201128269-C03-02 & BES-2012-051861); Catalan Government (2017 SGR 1537, 2014 SGR 123 & 2014 SGR 1543).	26	1,131	2011-2019	[48]
Herkel S. & Pfafferott J.	13	Fraunhofer Institute for Solar Energy Systems, Germany; University of Karlsruhe, Germany.	E, SC, V & G.	German Ministry of Economics and Labour BMWi (Energy Optimized Building 0335007C & LowEx:Monitor 0327466B); German Federal Ministry of Economics and Technology (Solar Optimised Buildings O350006R).	18	679	2004-2019	[49]
Gagliano A. & Nocera F.	16	University of Catania, Italy.	M, SC, TM, V & R.	Operational Program of European Social Funding 2014–2020 (PO FSE); Ecobios Laboratory.	14	462	1985-2019	[50]
Schettini E. & Vox G.	16	University of Bari, Italy; Italian National Agency for New Technologies, Italy.	E, M, SC, V & R.	Italian Ministry of Economic Development; University of Bari Aldo Moro.	14	91	2013-2019	[51]
Chen X. & Yang H.	6	Hong Kong Polytechnic University, Hong Kong.	M & V.	Hong Kong PhD Fellowship Scheme; Construction Industry Council of Hong Kong (1-ZVED); Research Institute for SustainableUrban Development of The Hong Kong Polytechnic University (1-ZVDR); Housing Authority of the Hong Kong SAR Government Shenzhen Peacock Plan (KQTD2015071616442225).	11	205	2015-2019	[52]
Cotana F. & Castaldo V.L.	15	University of Perugia, Italy.	M, SC, TM, R & G.	EU's Horizon 2020 Framework; European Commission Seventh Framework; CIRIAF for UNESCO (Water Resources Management and Culture).	11	251	2013-2019	[53]

Table 1 (continued).

Cluster (named by main author)	No. of Authors	Main affiliation(s)	Technologies covered[a]	Main funding or supporting projects	No. of Publ.	Citations	Years Covered	Ref.[b]
Ascione F., Bianco N. & De Masi R.F.	18	University of Naples Federico II, Italy; University of Sannio, Italy.	E, M, TM, V & G.	University of Sannio; University of Metro-campania Nordest; Italian Ministry of Education, Universities and Research (PON03PE000931).	10	303	2011-2019	[54]
Belarbi R. & Bozonnet E.	11	Université la Rochelle, France; University of Lorraine, France.	E, M, SC & V.	French Research National Agency (ANR-09-Vill-0007-04; VegDUD).	10	171	1997-2019	[55]
Pagliano L. & Carlucci S.	18	Politecnico di Milano, Italy; Norwegian University of Science and Technology, Norway.	V, R & G.	EU's Horizon 2020 (754174 & 680529) Carmelo Sapienza & Partners Engineering Firm; IEA ECBCS Annex 58; Rockwool Italia; SIEMENS Building Technologies; Intelligent Energy Europe Programme	10	178	2011-2019	[56]
Arcuri N. & Bruno R.	11	University of Calabria, Italy.	M, SC, TM, V & R.	Italian National Operational Programme, Research and Competitiveness for convergency regions 2007/2013 (Axis I PON01 02543).	8	84	2015-2019	[57]
Mihalakakou G.	4	National Kapodistrian University of Athens, Greece; University of Patras, Greece.	M, V, R & G.	University of Florence (Architecture University Diploma Project)	5	447	1997-2014	[58]
Barreneche C., Fortunati E. & Mattioli S.	7	University of Perugia, Italy; University of Lleida, Spain.	TM.	CIRIAF for UNESCO (Water Resources Management and Culture); Spanish Government (ENE2011-22722); Cassa di Risparmio di Perugia Foundation (UMBRA ARTIS 201.0223.021); Catalan Government (GREA 2014 SGR 123); European Comission Seventh Framework (PIRSES-GA-2013-610692 INNOSTORAGE); EU's Horizon 2020 (657466 INPATHTES).	4	47	2015-2017	[59]
Irulegi O. & Boemi S.N.	2	University of the Basque Country, Spain.	E, TM & R.	University of the Basque Country; Basque Government (Ekihouse).	2	33	2014-2015	[60]
Antinucci M.	7	Seminario de Arquitectura Bioclimatico, Spain.	E, M, SC, V, R & G.	E.E.C. Research (8.2000); Commission of the European Communities (D.G. 12).	1	23	1992	[7]
Karachaliou P. & Pangalou H.	2	National and Kapodistrian University of Athens, Greece.	M & R.	Not available	1	37	2016	[61]

[a]: Technology classification in accordance to Bhamare et al. [11] with one added category (ground cooling). E: Evaporative, M: Microclimate, SC: Solar Control,V:Ventilation, R: Radiative and G: Ground cooling. [b]Exemplary reference for cluster.

tamouris (N=24), L.F. Cabeza (N=19) and A. Omer (N=19). Details on the number of publications for the top 10 authors can be found in the Supplementary Material.

The top authors and their research communities are presented in Fig. 4. For details of the clusters in the figure, Table 1 presents their main authors, affiliations, technologies studied, number of publications from the cluster, and an exemplary reference of that community.

In terms of most research output, results show, the top author (M. Santamouris) belongs to the cluster with most researchers (62) and has the most publications for a single author (75). This cluster is followed by four communities mainly based in China and Hong Kong. Eight of the remaining communities have as leading institutions universities in Italy. An unexpected result is that affiliations from the U.S. do not appear to be dominant in these top clusters, even though this country is identified as the most named in affiliations. This indicates that research in passive cooling in that country is diluted, for example, by the low number of publications per author, which in turn do not meet the thresholds set in Fig. 4.

An important observation is that the top authors and their research communities are found to research different passive cooling technologies. It is therefore expected to find repeated communities of authors in the next sections (Sections 4.2.3 to 4.2.9) which examine more closely specific collaboration networks around specific technologies (i.e. according to the findings of Searches 2 to 8). These also provide more details on the research output of the most relevant authors and communities.

In terms of year of experience in the field, the range of years of publication is considered as a proxy. It is observed that 10 of the 16 clusters in Fig. 4 have started publishing from 2010. This indicates that most research communities are only starting in the last decade. Also, that the more established groups can be found before that year, where M. Santamouris (from 1992) and Gagliano (from 1985) are the most notable with the oldest publications. Antinucci is also from 1992, but the cluster from that author was closely collaborative in that year with that of M. Santamouris.

The majority of funding and support identified for the research communities is associated with the public sector. The European Commission Seventh Framework, followed by Horizon 2020 grants is repeatedly found in the top clusters of Table 1. These are followed, by funding through national ministries, agencies, local governments and universities. None of the 16 clusters is supported purely by the private sector.

4.2. Part 2: Passive cooling literature by technology

4.2.1. Classified documents

The keywords used in Searches 2 to 8 identified documents associated with specific cooling technologies and which correspond to sub-sets of the documents found in the generic Search 1. This indicates that Search 1 is widely comprehensive, capturing literature on defined passive technologies (Searches 2 to 8, N=1,090) and additional unclassified literature (i.e. not found in the other searches, N=1,772).

The documents found in Searches 2 to 8 (and by extension found for each technology) is presented in the bottom left of the upset plot (i.e. an alternative to Venn diagrams for extensive groups and intersections/overlaps) in Fig. 5. The figure shows that the passive technology most identified in the literature is ventilation (N=389), followed by microclimate measures (N=317) and radiative cooling (N=312). It is observed that there are common documents found amongst the technology-specific searches. The largest overlap is for documents covering radiative cooling (Search 7). This passive cooling technology is largely reported together with solar control (N=38), ventilation (N=34), and microclimate cooling (N=27) with only 25% of the literature found for radiative cooling, which is exclusive to this technology. The historical lack of exclusive literature on radiative cooling is an unexpected result which could be explained by two reasons: 1) this type of cooling is based on ancient practices in middle east desserts to produce ice [62] and thus it is plausible that those cooling customs may be part of a different set of literature (non-academic or technological) and; 2) radiative cooling is recently surging as daytime applications have only been experimentally proven in 2014 by Raman et al. [63]. Conversely, the largest proportion of exclusive publications for a technology is for thermal mass cooling (Search 4). For these passive cooling technologies, 43% of the search results are not related to any other technology. Less overlap can be explained by the higher level of specialisation. Particularly, research on PCMs is more experimental in nature (i.e. carried out in material science laboratories), hence, publications can be expected to be less interdisciplinary than the other wider categories for passive cooling technologies.

4.2.2. Trends by technology

To compare trends in publications by technology, Searches 2 to 8 are considered and results presented in Fig. 6a-b, enable visualisation of the global progression in research of the technologies. Results show two periods: one before 2005 with less than 10 publications per year, and thereafter, a stage with a steady increase in publications is observed across technologies.

For the first stage, initial documents for a specific cooling technology are found from 1980 for radiative, solar control and ventilation. This stage presents a

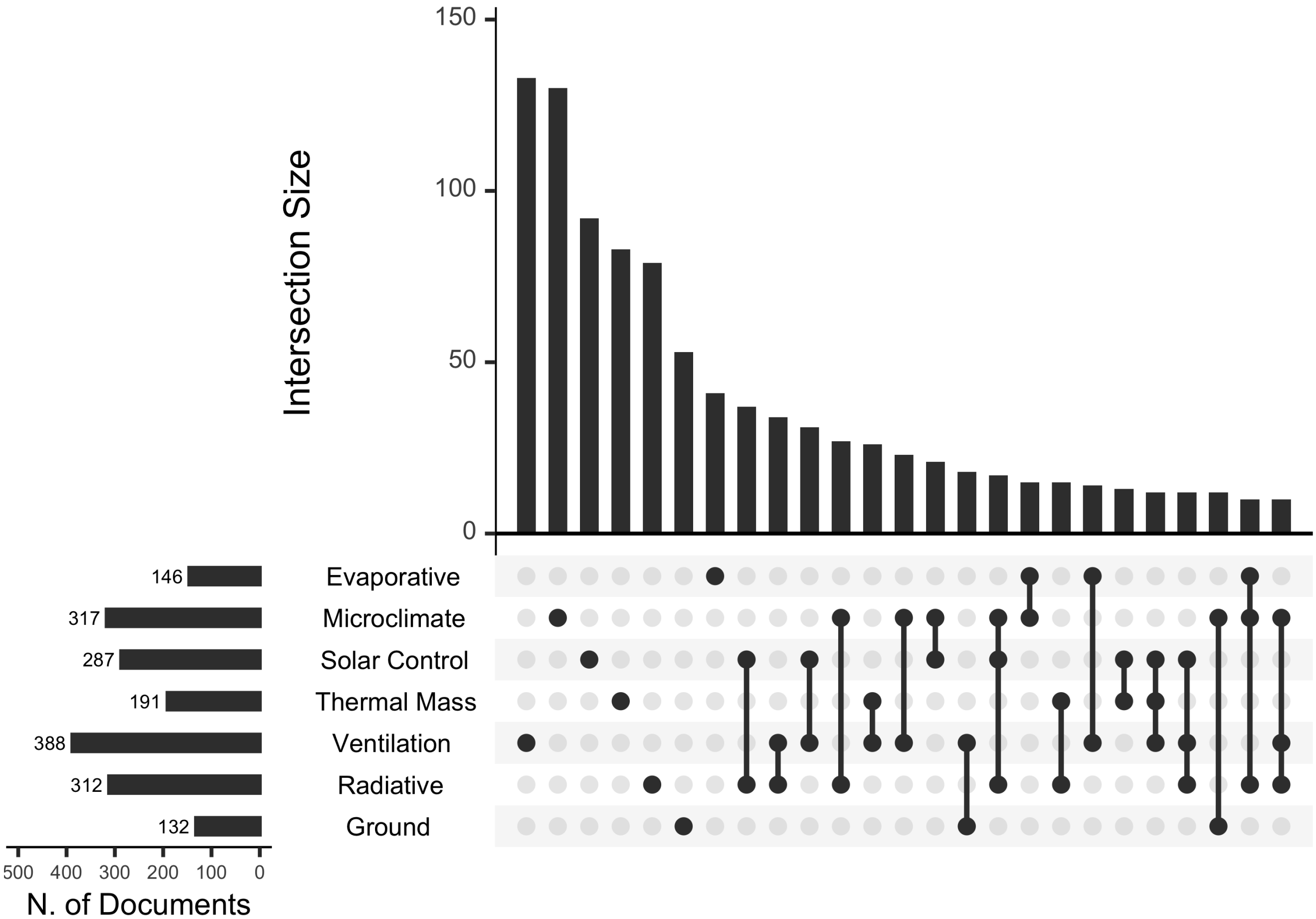

Fig. 5 Upset plot of the documents found for specific passive cooling technologies in the systematic search. Main plot (top): the y-axis is the intersections or number of common documents found for the technology searches and the x-axis corresponds to the sets of searches that found intersecting documents. Secondary plot (bottom left) corresponds to the documents found individually for each technology search (Searches 2 to 8).

surge in the mid-80s, where 26 publications are found. This raise in publications aligns to the signing of the Montreal Protocol in 1987 [64]. Results suggest that although the protocol focused on alternative refrigerants, it also drove the search for alternative cooling systems. Thereafter, a second surge in the 1990-2000s is observed, particularly for cooling through radiative and ventilation technologies. This increase could be attributed to more awareness in the need of clean cooling technologies, for example, through international environmental agreements to lower energy consumption and GHG emissions, namely, the UN Framework Convention on Climate Change in 1992 and its extension to the Kyoto Protocol signed in 1997 (entering into force in 2005).

In the second period (after 2005), a significant increase in publications is seen for 2010-11 and 2016-2018. The latter surge corresponds to the peak annual publication for all technologies and is aligned to global policy efforts to reduce GHG emissions. For example: 1) the signing of the Kigali Amendment to the Montreal Protocol (2016 - effective since 2019) which drove a series of international actions including the search for efficient cooling technologies through the Kigali Cooling Efficiency Programme (K-CEP) and; 2) the publication of the Sustainable Development Goals as a factor driving funding and research for clean energy systems (Goal 7), including more sustainable air conditioners.

Across the two stages, ventilation has been the dominant technology for passive cooling throughout the last 50 years. However, in the last three years radiative and solar control have surpassed ventilation in the publications per year. The recent increased publications in the former technologies can be attributed to daytime radiative cooling being achieved experimentally only since 2014 by Raman et al. [63] and sky windows applying this research since 2019 [65]. The increase in publications for solar control can be explained, according to results from the review of Prieto et al.[8] to research increase in middle eastern countries with a focus on shading, glazing and façades systems. It is noted that both radiative and solar protection measures, as pre-

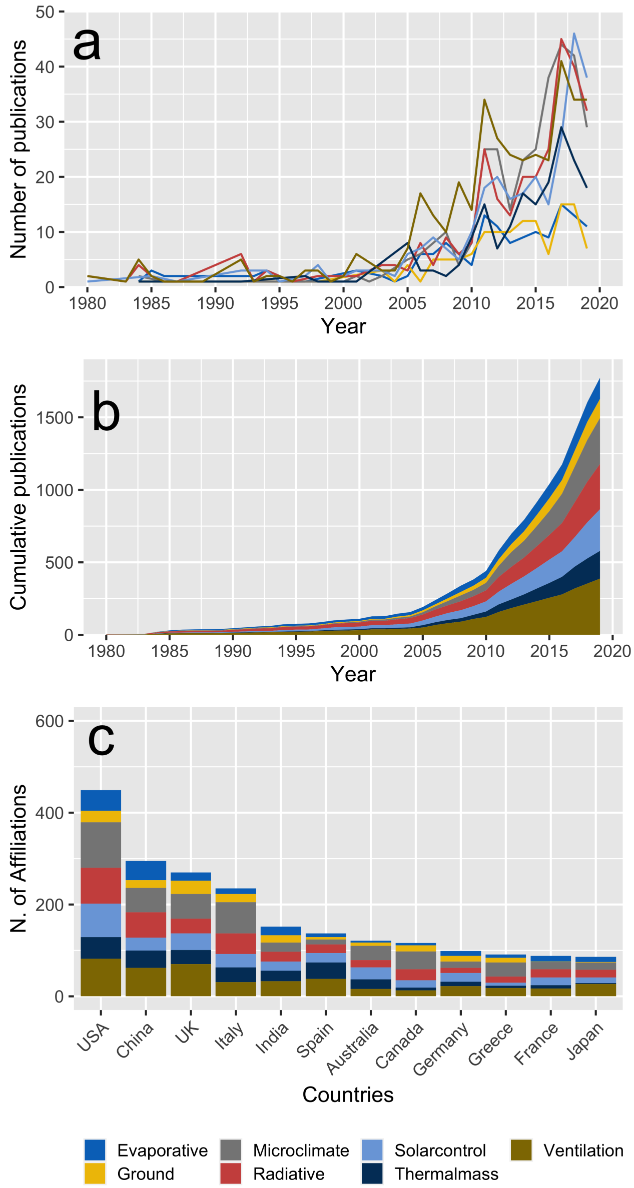

Fig. 6 Publications in passive cooling by technology (documents from Searches 2 to 8) (a) annual publications and (b) cummulative publications and; (c) affiliations per country and technology.

sented in Section 4.1.1, are commonly reported in the same literature. Hence, the profile of their annual publications is similar in Figure 6.

To analyse which technologies have been researched by country, Fig. 6c presents the documents according to the affiliation of each author and technology. It should be noted that for documents with multiple authors, each affiliation is counted, hence the total number of affiliations is higher than that of the number of documents in the dataset. All countries shown in the figure have undertaken research in at least 6 of the 7 passive cooling technologies. It is interesting to observe that, when excluding the "unclassified" documents from Search 1, Chinese affiliations become dominant. This suggests that although the contribution of Chinese institutions to the field is still overall lower than the US, these outputs cover more specific passive cooling technologies. Similar trends are observed for Italy, which in this subset of documents overpasses the total number of affiliations of the UK. Chinese affiliations are the most common for all passive cooling technology, except for ventilation and thermal mass, which is led by affiliations from the US. The next sections consider these results and discuss in further detail the development and communities in specific cooling technologies.

4.2.3. Evaporative (Search 2)

There are 416 authors that published the documents (N= 146) on passive evaporative cooling. From these, 95% have only one publication in this subject, indicating that authors may be changing research subject and not building expertise within the field.

Fig. 7 presents the main authors collaborating in research on passive evaporative cooling. To observe the top research communities, a low threshold of publications per author and co-authorship (i.e. $n_{pub}=n_{collab}\geq 2$) is used. For instance, only the top authors B. Givoni and X. Zhao (and their co-authors) with three publications each (N=3), would be observed in the network plot if the threshold was higher (i.e. $n_{pub}=n_{collab}\geq 3$). The top authors are in separated clusters and not found to collaborate in research on evaporative cooling.

The figure shows that there are 13 highly fragmented communities detected (average of 6 authors per community). Results also show that research networks in evaporative cooling have less publication output per author (when compared to other technologies). This is aligned with fewer publications as seen in the trends of Section 4.2.2. With an average of one publication per author in the top clusters in terms of productivity (clusters 2, 8, 9 11 and 14), B. Givoni has the highest collaboration in terms of bringing together authors of four different countries.

The largest community detected is conformed of 12 authors and includes X. Zhao and Z. Duan. The research of these authors has included evaporative cooling in active and passive applications, with a focus on indirect evaporative cooling mainly with counter-flow regenerative evaporation [66, 67, 68].

The second largest community includes Q. Yang and consists of 11 authors, who work on cooling (and dehumidification) performance in green-houses in China [69, 70]. Cooling is only part of their research that focuses on thermal storage in solar greenhouses, particularly for winter nights when the low temperature can affect crop growth.

The remaining communities are smaller in terms of author membership. From these, one is exclusively re-

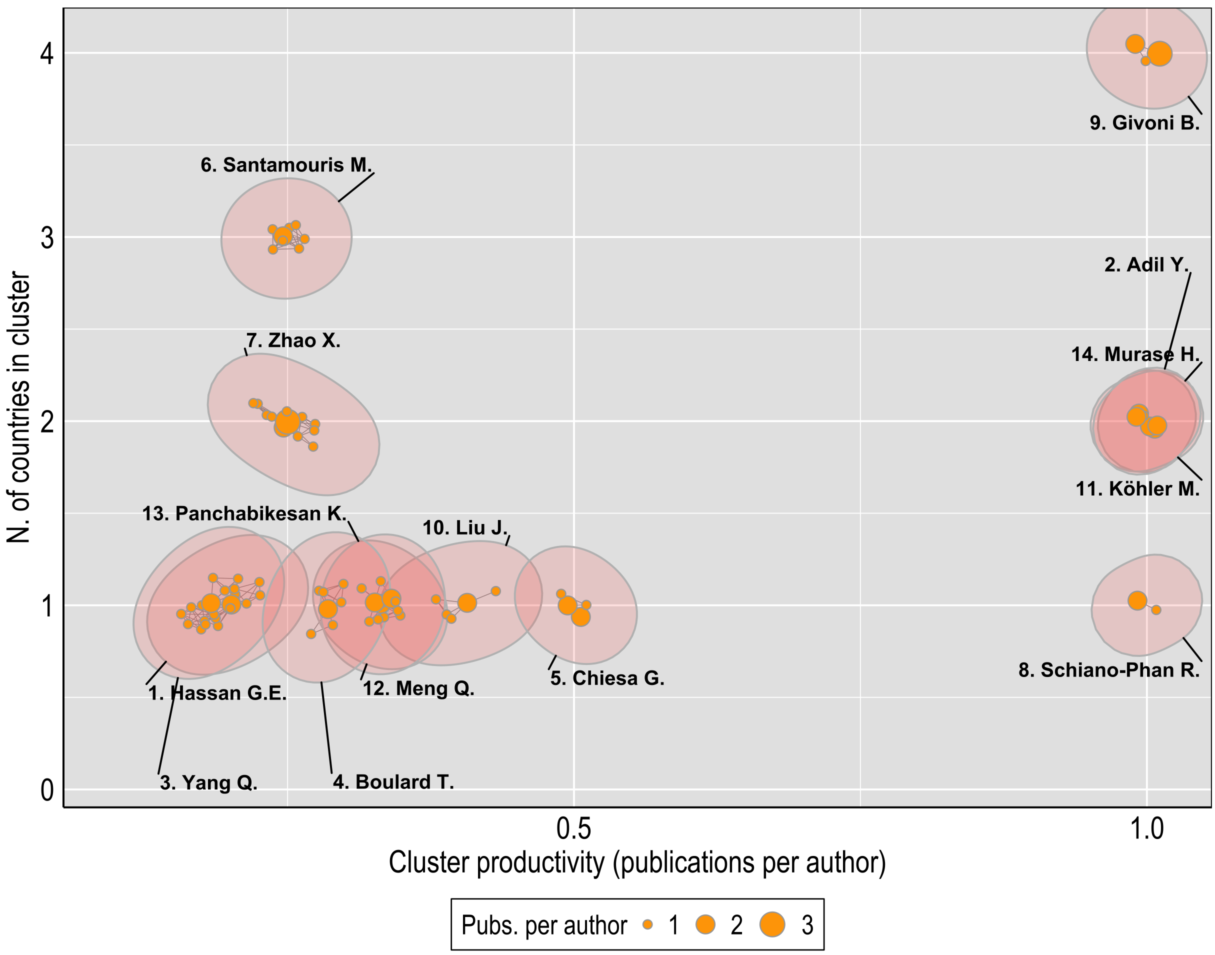

Fig. 7 Author collaboration network and communities (clusters) detected for passive evaporative cooling technologies (Search 2, n_{pub}=n_{collab}≥2). Nodes are authors with diameters proportional to number of publications. Labels are cluster ID with its main author (n_{pub}≥2). Edges indicate co-authorship.

searching evaporative passive cooling: R. Schiano-Phan (2 authors total). These authors report on the end-users perception of downdraught evaporative cooling in case studies in the US [71], with extensive work on the architecture perspective of cooling including on porous ceramic materials and urban cooling strategies [72].

The above results indicate that leading communities in evaporative cooling are from different disciplines (mainly architecture or engineering) and are part of groups that have wider research interests.

4.2.4. Microclimate (Search 3)

There are 815 authors for the 317 documents found for passive cooling through microclimate techniques. From these, 127 (or 16%) are authors of more than one document. The authors with most publications are M. Santamouris (N=11), C.Y. Jim (N=9), E. Schettini (N=7), G. Vox (N=7), R.W.F. Cameron (N=7) and J.S. MacIvor (N=7). These authors have also been found to publish documents for other passive cooling technology, e.g. M. Santamouris in ground cooling (Section 4.2.9, and, E. Schettini and G. Vox in solar control technologies (Section 4.2.5).

Fig. 8 shows 10 communities detected for microclimate. This is a large number of clusters given the high thresholds are applied for minimum publications per authors and author co-occurence (n_{pub} = n_{collab} ≥ 4). On average there are 11 authors per community, which corresponds to the largest average amongst all technologies.

The productivity of these clusters is between 0.25 and 0.83 publications per author, with the exception of the cluster of C.Y. Jim producing approximately 1.7 articles per author. The high productivity of that cluster is due to 9 publications (mainly covering the effect of meteorological factors on green roofs) which are each authored by only 1 or 2 authors.

As seen in the figure, 5 clusters are interconnected

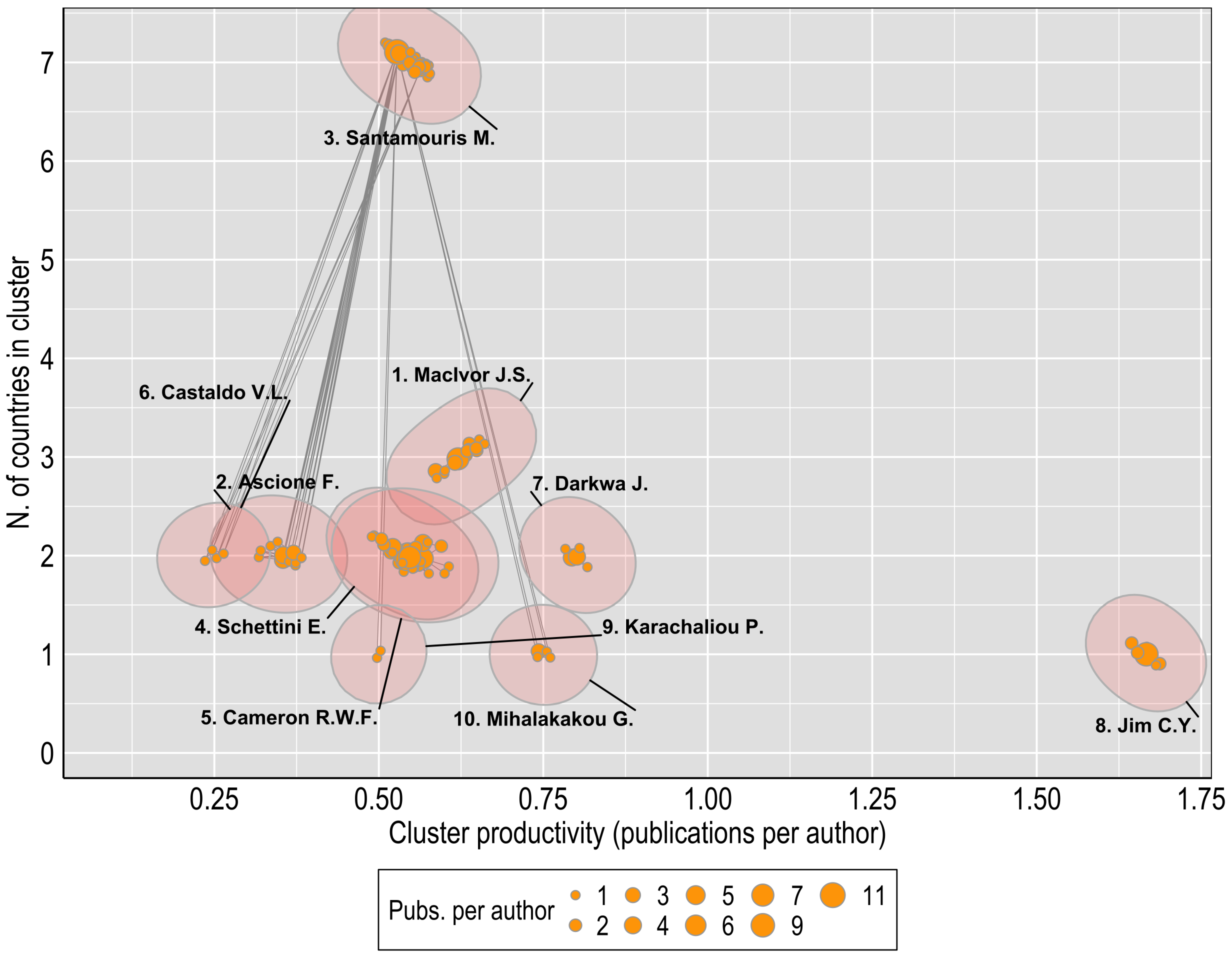

Fig. 8 Author collaboration network and communities (clusters) detected for microclimate cooling technologies (Search 3, $n_{pub}=n_{collab}\geq4$). Nodes are authors with diameters proportional to number of publications. Labels are cluster ID with main author. Edges indicate co-authorship.

and form 59 interlinked authors. This is the largest author agglomeration found for all passive cooling technologies. The main cluster within these interconnected authors is that of M. Santamouris, R.F. De Masi, N. Bianco and A. Synnefa (29 authors). The cluster of M. Santamouris has the highest international collaboration, with approximately seven countries involved. However, the productivity of the cluster is similar to most other clusters. The authors in Santamouris' cluster are highly collaborative on urban energy use and applications of different passive cooling technologies in multiple cities and building cases. Their work includes a recent review in urban greenery [47], and analyses on meeting the cooling demand sustainably in various urban locations (e.g. Greece, Australia) [54, 47, 73]. The interconnected cluster that includes F. Ascione, N. Bianco and R.F. De Masi focus on cooling in Mediterranean climates[54, 74].

There are two large clusters that that research cooling from a biological perspective. First, the group of 16 authors which includes J.S. MacIvor. Their extensive work is on the application of greenery in urban spaces including the selection of adequate plants and substrates for improved thermoregulation of green roofs [75, 76]. Second, the community of R.W.F. Cameron is of 18 authors with a similar biological focus. These authors study the performance of green roofs (and façades) using different plants (e.g. shrubs, climbers, perennials) [77, 78]. The similar focus with the cluster of MacIvor indicates potentials for collaboration within this area.

A final large community of 15 authors is that of E. Schettini, I. Bianco, G. Vox and C.A. Campiotti. These authors have collaborates on several publications on green façades and walls [79, 51, 80, 81], particularly in Mediterranean locations. The works of this group include modelling of thermal effects and experimental testing, with applications in livestock buildings.

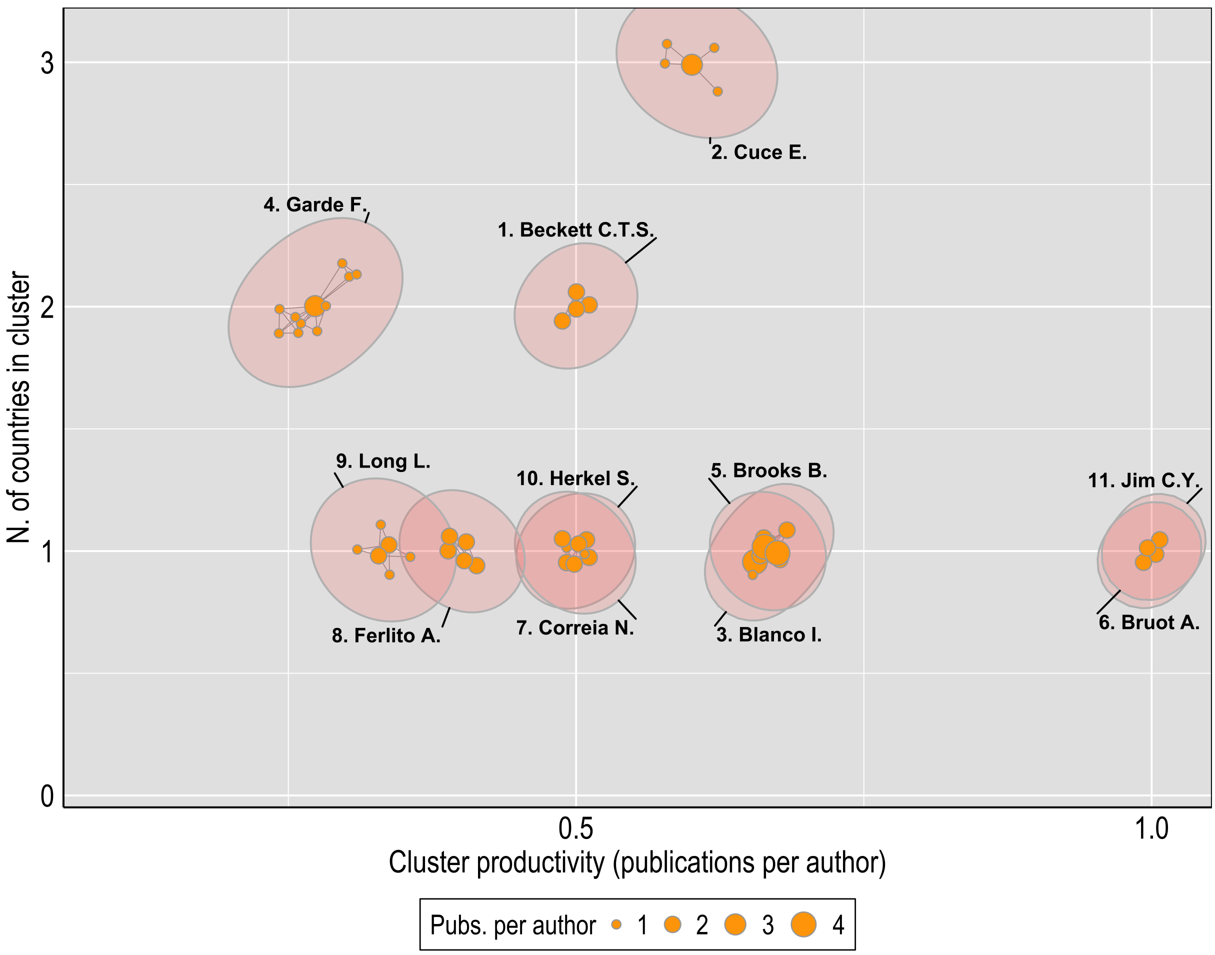

Fig. 9 Author collaboration network and communities (clusters) detected for solar control cooling technologies (Search 4, $n_{pub} \geq 3$, $n_{collab} \geq 2$). Nodes are authors with diameters proportional to number of publications. Labels are cluster ID and main author. Edges indicate co-authorship.

4.2.5. Solar control (Search 4)

There are 781 authors who have output 287 publications on cooling through solar control. From these, 48 (6%) have more than one publication. Similar to other technologies, the productivity of the clusters for solar control also varies between 0.25 and 1.00 publications per authors.

The top authors, in terms of publications, are I. Blanco, E. Schettini and G. Vox (each with 4 publications). These authors are found in one research community that focus on solar control technologies, specifically green façades [51, 81]. They are also detected as an important community in microclimate (as seen in Section 4.2.4 and radiative cooling (Section 4.2.8).

Fig. 9 shows that 11 research communities are detected. These have on average 5 authors each. It also shows that the largest community in terms of author membership is that centred around the work of F. Garde and contains 11 authors. These authors have researched thermal and visual comfort of occupants, with a particular interest in La Reunion [82, 83], and brought together occupant comfort and shading technology, to provide multi-disciplinary assessments of the cooling performance in building in tropical areas.

The author E. Cuce (and surrounding community) follows in terms of publication numbers (N=3). These mainly researched solar control through glazing technologies [28, 84] (e.g. for window application). The cluster from E. Cuce also presents the largest international collaboration with three countries in their publications.

4.2.6. Thermal Mass & PCM & Free Cooling (Search 5)

There are 560 authors that have published 191 documents on passive cooling through thermal mass applications. From these, 58 (10%) have multiple publications. The most publishing authors are L.F. Cabeza

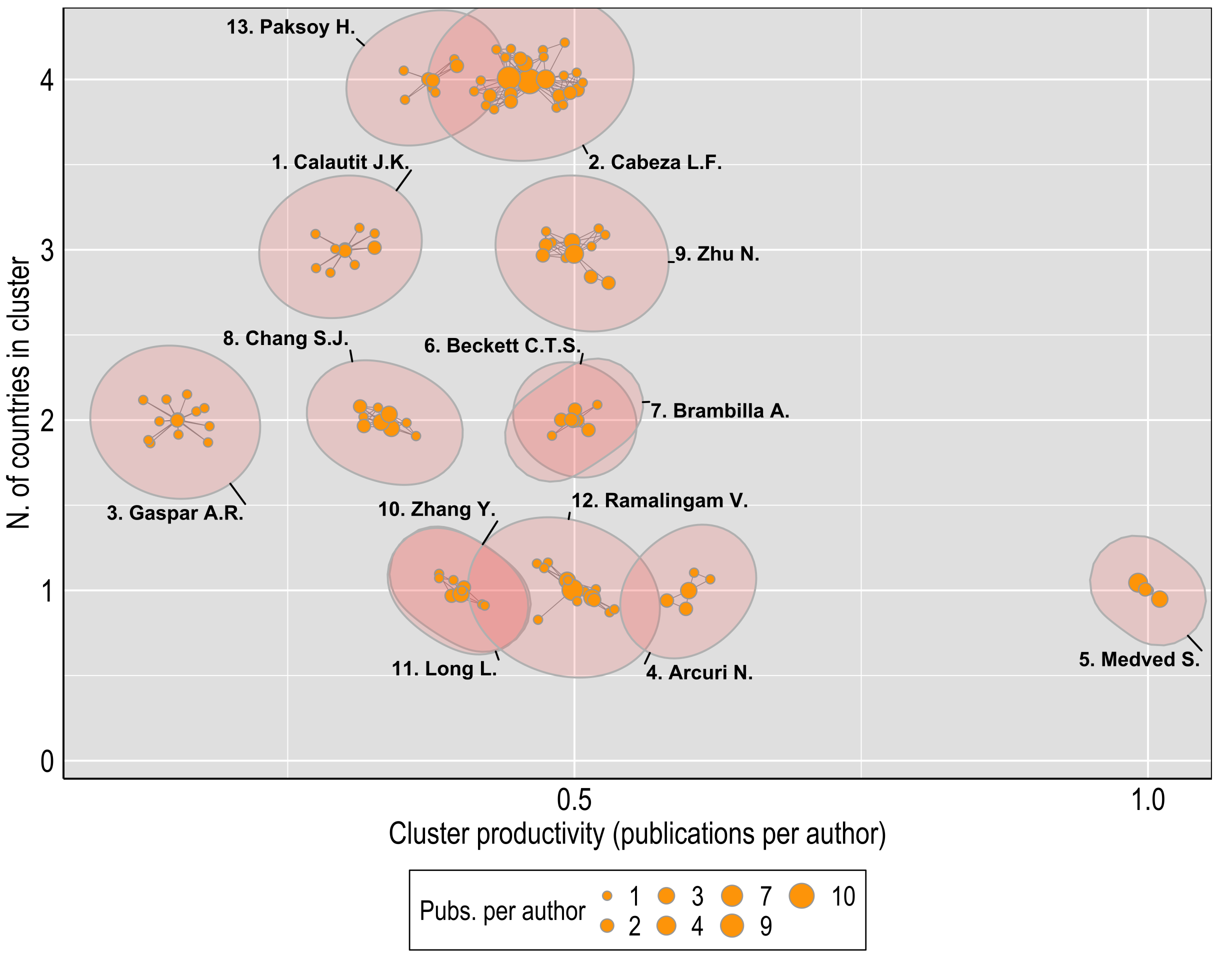

Fig. 10 Author collaboration network and communities (clusters) detected for thermal mass cooling technologies (Search 5, $n_{pub} \geq 3$, $n_{collab} \geq 2$). Nodes are authors with diameters proportional to number of publications. Labels are cluster ID and main author. Edges indicate co-authorship.

(N= 10), A. De Gracia (N=9), and Ramalingam V. (N=7).

As presented in Fig. 10, there are 13 communities detected for thermal mass cooling technologies. These have on average 9 authors each. This is the second largest average amongst all technologies (after micro-climate), showing that collaboration in thermal mass technologies is strong. The scale of these communities is unexpected as research in this field is relatively recent from the early 2000s (as seen in Section 4.2.2), indicating that collaborative networks have been more successful in establishing and expanding within a short period.

In terms of productivity, similar to other technologies, most clusters do not exceed 0.5 publications per author. An important exception for these technologies is the cluster of S. Medved, C. Arkar and B. Vidrick, which have studied different thermal mass measures, namely, free cooling and PCM.

The two top authors (L.F. Cabeza and A. De Gracia) and their collaborative network conform to the largest research community detected, with 26 authors. This community has also built high international collaboration in publications on thermal mass cooling, as seen by the number of countries in the affiliations of authors (Fig. 10). Only the cluster of H. Paksoy has the same number of countries involved in their work. Although the community of L.F. Cabeza is found for all other passive cooling technologies, their contribution to the research of thermal mass is found to be the largest in terms of publications (i.e. 11 publications in this technology, followed by 4 in ventilation). Their research has been experimenting and modelling PCMs to improve energy performance at building-scale for both heating and cooling [30, 85, 86].

The second largest community (of 14 authors) includes the authors V. Ramalingam, K Panchabikesan and M. Rajagopal. These authors have published on

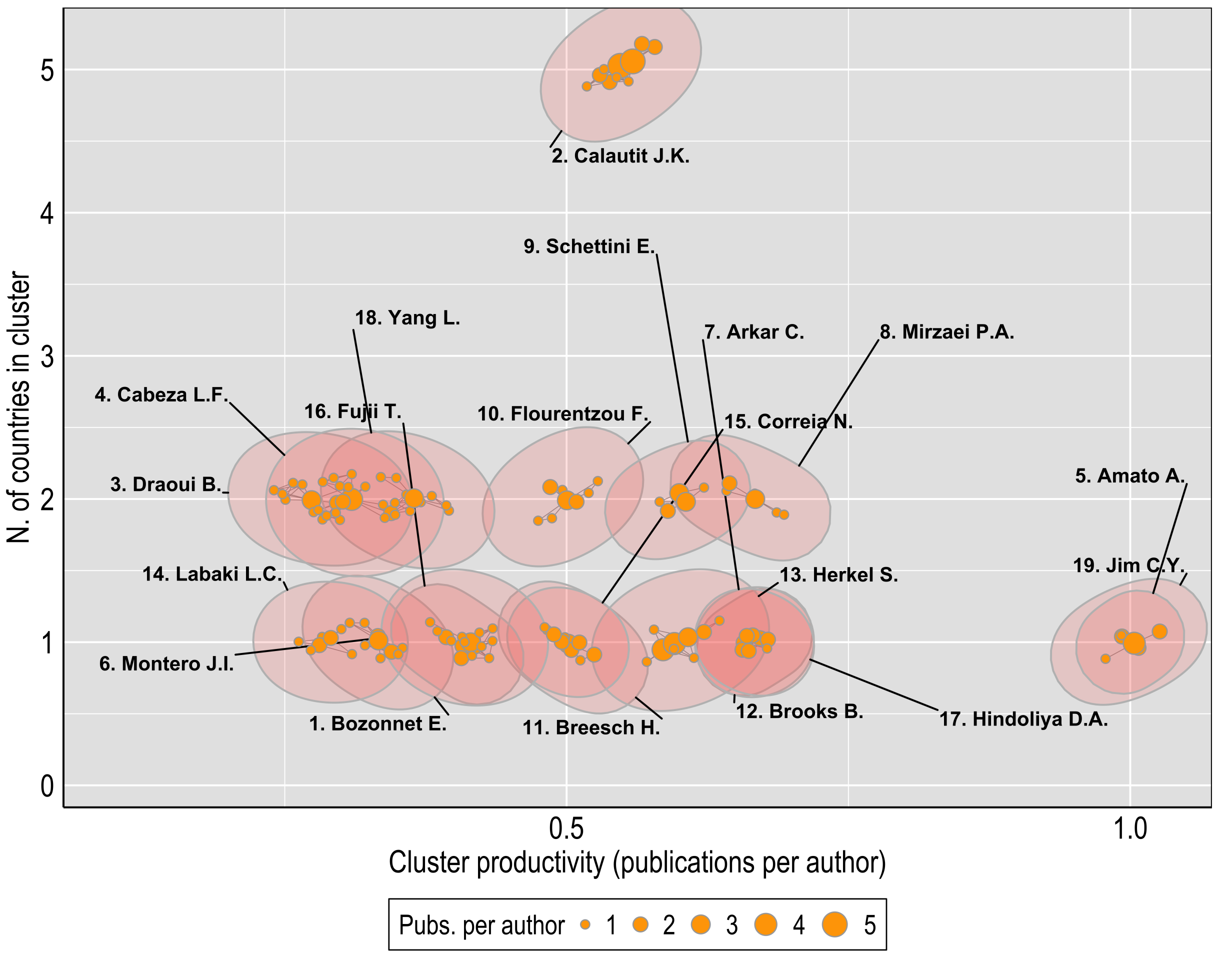

Fig. 11 Author collaboration network and communities (clusters) detected for ventilation cooling technologies (Search 6, $n_{pub} \geq 3$, $n_{collab} \geq 2$). Nodes are authors with diameters proportional to number of publications. Labels are cluster ID and main author. Edges indicate co-authorship.

the application of PCMs in buildings for free cooling (i.e. process to assist active cooling systems by storing available night energy to cool the building during daytime) [87, 88]. Particularly, they have a focus on the application of such thermal mass technologies in cities and buildings of India.

The community to follow is that of N. Zhu and P. Hu (with a total of 12 authors). These authors have mainly reported on the modelling and experimental studies of PCMs in wallboards [89, 90].

4.2.7. Ventilation (Search 6)

The 388 documents found in Search 6, are published by 953 authors. This corresponds to the largest set of authors for a technology, aligned with significantly more publications. From these authors, 11% have more than one publication. The authors with the most publications are A.M. Omer (N= 7), J.K. Calautit (N= 5) and B.R. Hughes (N= 5). It should be noted that the former is not shown in the collaboration network of Fig. 11 as all publications are as a single author (i.e. not identified as part of a wider community). The publications from this author have focused on low-energy design of buildings, considering hybrid between natural cooling (ventilation) and mechanically-driven (active) technologies [91, 92]. The author's works expand to cooling integration with heating and renewable energy.

Fig. 11 shows that there are 19 research communities detected for passive cooling through ventilation (average of 8 authors per cluster). From these, the largest community is conformed of 18 authors and includes J.I. Montero. Works from this cluster cover passive cooling of greenhouses in urban areas, particularly, roof-tops [93, 94]. Specifically, the author's publications have studied different configurations to combine natural and mechanical ventilation (including air exchange with host building), through CDF simulation and experimental setups.

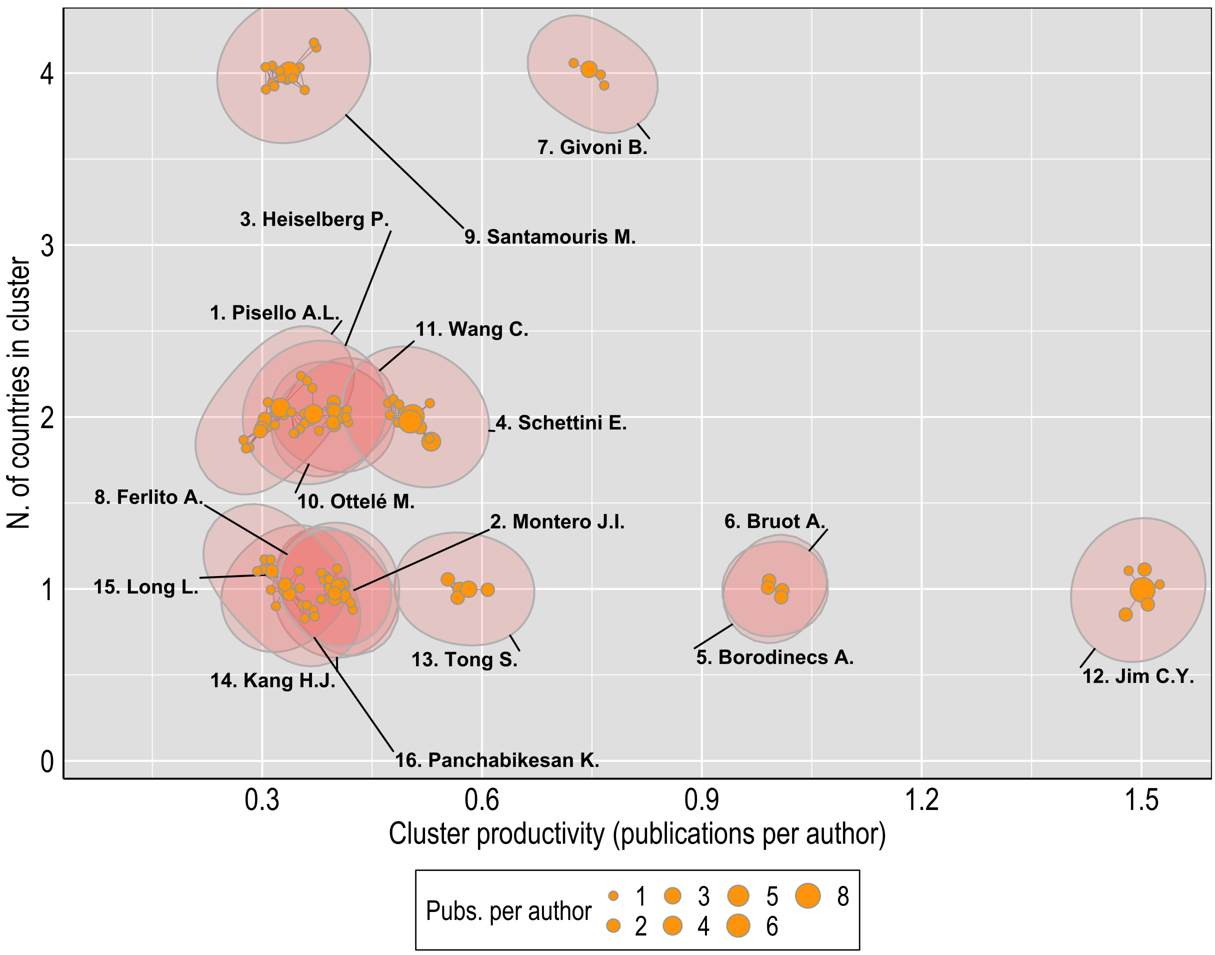

Fig. 12 Author collaboration network and communities (clusters) detected for radiative cooling technologies (Search 7, $n_{pub}\geq3$, $n_{collab}\geq2$). Nodes are authors with diameters proportional to number of publications. Labels are cluster ID and main author. Edges indicate co-authorship.

Thereafter, the second largest community is of 13 authors and includes L.F. Cabeza. As in previous technologies, this is detected a top research collaboration cluster. For ventilation, these authors have examined ventilation as part of other passive cooling measures. In particular, the effect of green façades and walls acting as wind barriers [95, 96] and the combination of PCMs performance enhanced by night ventilation [30].

There are two communities of 12 authors each that follow. First, the authors A. Wanger, S. Herkel, J. Pfafferott and their surrounding research community have collaborated in studying night ventilation in demonstration buildings [97, 98] and office buildings [99] in Germany. Particularly, they have assessed the performance of night ventilation (natural and mechanical) in the hot summer months. Second, also with 12 authors, is the community which includes L. Yang. These authors have reported the application of passive technology to achieve zero-energy or ultra-low energy buildings [100, 101, 102]. In terms of passive cooling, they have examined the potential (i.e. resulting temperatures) of night ventilation. Particularly they report PCMs that absorb extra heat during the daytime while at night ventilation removes this heat.

The community which includes B.R. Hughes and J.K. Calautit have published work on wind towers. Specifically, they modelled the buoyancy effect through computer fluid dynamics to study how air flows operate in Middle East buildings [103], and affect thermal comfort[104] and how these wind towers can be combined with other technologies to increase the cooling effect in hot climates[105]. This cluster is also higher in international collaboration, with five countries identified in affiliations of their work. Most clusters researching ventilation only include one or two countries (as observed in Fig. 11).

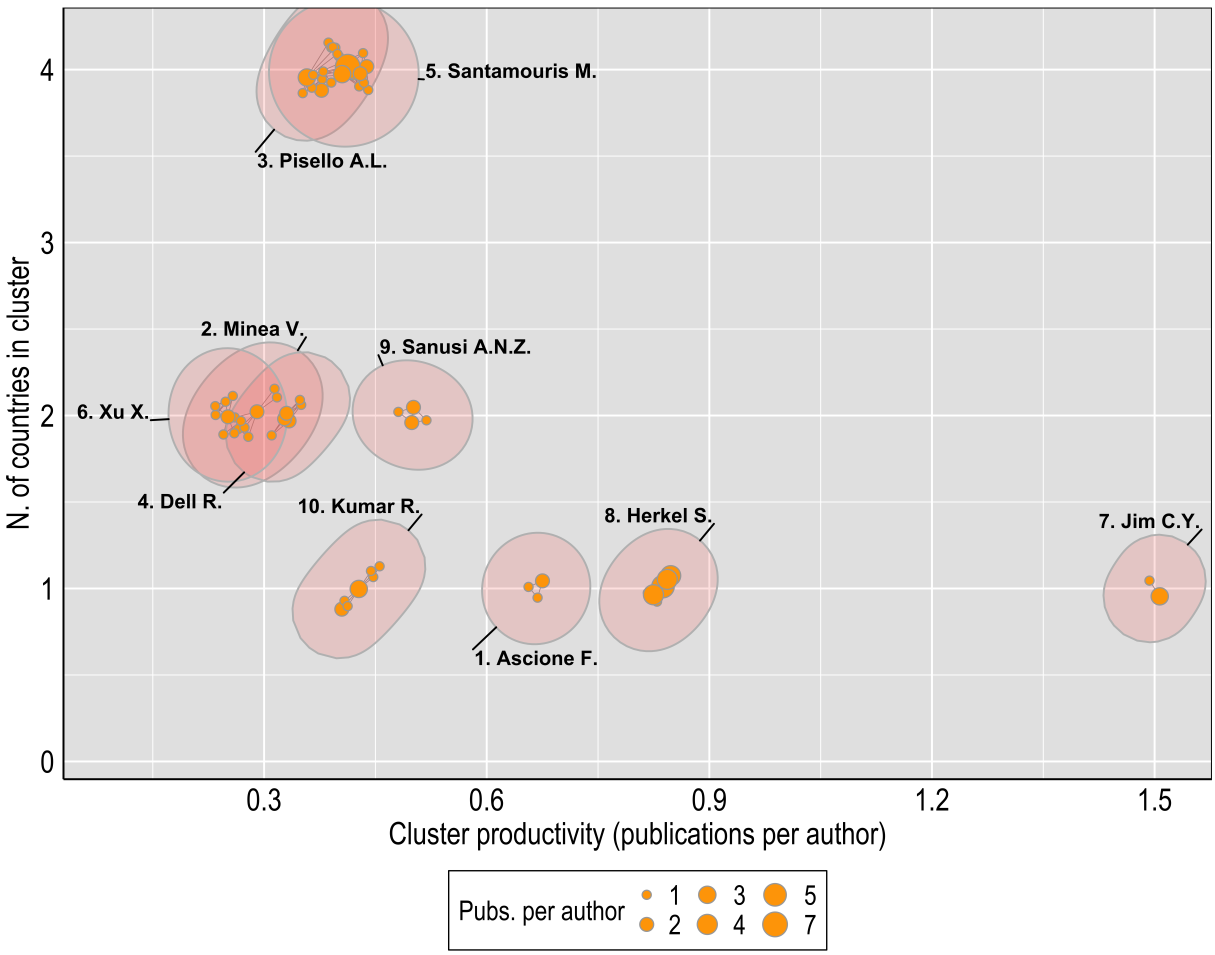

Fig. 13 Author collaboration network and communities (clusters) detected for ground cooling technologies (Search 8, n_{pub}=n_{collab}≥2). Nodes are authors with diameters proportional to number of publications. Labels are cluster ID and main author. Edges indicate co-authorship.

4.2.8. Radiative and radiant cooling (Search 7)

There are 835 authors of the 312 publications for radiative passive cooling. It is noted that 8% of these authors have published more than one document. The authors with most publications are C. Y. Jim (N= 8), E. Schettini (N= 6), G. Vox (N= 6), and M. Santamouris (N= 5).

In Fig. 12, the 16 top clusters are presented for radiative cooling. On average there have 8 authors per cluster. All communities in the figure are also present (fully or partly) in other technology-specific searches.

The largest community is that which includes L.F. Cabeza and A.L. Pisello (a total of 16 authors). This community is detected within several passive cooling technologies. Specifically for radiative cooling, this research group has studied radiant walls performance [48, 106] (i.e. walls with internal pipes carrying coolant fluid). In their experimental work radiant wall were coupled with heat pumps, to dispose of excess heat to either air, water or ground. This technology is not strictly under the radiative classification of Bhamare et al. which uses the sky as a heat sink [11]. This shows that there are hybrids of passive technologies that can fit in multiple classifications.

Thereafter, the research community surrounding M. Santamouris is the second largest for radiative passive cooling. The authors therein have examined reflective roofs [107] and predicted how solar reflectance will reduce urban heat island effect and building cooling demand [47]. The authors have combined these studies with research on green roofs. This cluster is also that found with the most international collaboration for radiative cooling (involving four countries), together with that cluster of B. Givoni (see Fig. 12).

Following in terms of cluster size is the community of C.Y. Jim which has examined radiative features, as Santamouris, together with green surfaces. Specifically, their work has assessed the reflective radiation from green walls and roofs [108, 109] through experiments and thermodynamic models.

A surprising result is that the more recent research in passive daytime radiative cooling [63] is not found in the search or in the top research communities. This could be explained by the fact that this technology is in its early years with major efforts in commercialisation [110], thus, academic literature is not yet extensive.

Radiative cooling is shown to be a promising solution for sustainable cooling based on the trends seen in the previous sections. This is also shown by the interest of top authors in the field of passive cooling, who are specifically researching these technologies.

4.2.9. Ground cooling (Search 8)

There are 322 authors in the 132 documents found through Search 8. Only a small fraction of authors presents multiple publications (8%). The top authors in ground cooling are A. Omer (N=8), M. Santamouris (N=7), and S. Herkel (N=5). The former is also the top authors for ventilation (see Section 4.2.7) and is not shown in Fig. 13 as not detected as part of a cluster. The work of A. Omer is on ground heat exchangers harvesting renewable geothermal energy for both cooling and heating [111, 112]. The author has also examined active ground cooling, in particular, the need for greener refrigerants in ground sourced heat pumps [113].

Fig. 13 presents the 10 communities detected for passive ground cooling technologies. These have an average of 7 authors each.

A large interconnected group of authors is surrounding M. Santamouris. This is composed of two clusters of 17 and 8 authors, centred around M. Santamouris and A.L. Pisello, respectively. Santamouris has reported the potentials for ground cooling to mitigate urban heat island effects [114, 115, 116, 117]. In particularly, proposing earth to air heat exchangers as a viable solution, which does not require refrigerants. The two interconnected clusters have the highest international collaboration for this type of passive technology (with four countries in their affiliations).

There are 8 other smaller research communities found for ground cooling. From these, the community of 4 authors, including A.N.Z. Sanusi and L. Shao, is exclusively found for this technology. These authors have published research on the application of earth to air heat exchangers in Malaysian buildings. The research has been experimental, measuring temperatures at different ground depths and the effect of these on the performance of the exchangers [118, 119].

Passive ground cooling appears to be behind other technologies, for example it is not yet found in the wide classification of Bhamare et al. [11]. This may be as ground technologies are considered active when they are in the form of heat pumps. However, there is an increasing number of authors (including the top author in the field of passive cooling - M. Santamouris) that describe its potential to contribute towards sustainable cooling by being a passive measure.

5. Discussion

This work recognises the merit that passive cooling technologies may have in achieving a sustainable future for cooling. The exhaustive set of academic documents identified (the largest in the subject) covering passive cooling technologies shows that research literature is diverse in technologies and vast in author communities.

In terms of passive cooling diversity, the classification of these technologies is still developing. The latest and most comprehensive classification reported is from Bhamare et al. [11], however, it still does not consider all technologies, for example, passive ground cooling which is recognised as a passive technology by others [9]. The need for an overarching classification is urgent, as a first step to understand the potential of these systems in a lower carbon future and gaps that need to be addressed by research. A further step is to provide standardise performance metrics for passive cooling technologies, as today comparability between systems is not possible as for active technologies.

Despite the need to continue improving the classification and metrics, this work shows that there is sufficient literature to analyse trends and actors for different technology. Research in passive cooling has progressed since the 1970s, starting within other areas (e.g. passive houses) and in the past 15 years, the basis of knowledge steadily grown as indicated by cumulative publications and the number of top research communities established from the 2000s.

The number of publications has increased for all technologies. These trends are promising as they show that research and developments in passive cooling have continued to expand regardless of active technologies being the dominant application. If considering the historical publications, natural ventilation has been the dominant technology. This could thus be considered the more mature technology and one that is more likely to have a larger impact aligned in the IPCC and SDG decarbonisation timelines. Radiative and solar/heat protection have recently overtaken ventilation in terms of publications per year. The increasing research in radiative cooling has been attributed to recent development in affordable materials for radiative panels which can expel heat to the sky while directly exposed to sunlight [63]. This is a major advancement in the field, given that historically radiative cooling has only been used at night (e.g. to make ice in desert areas), not at daytime when cooling needs are necessary. The commercialisation of this promising technology is ongoing in the U.S. It is expected that advances in materials could also see effects on PCM. These are currently expensive but effective, hence, require further development. The increase in publications on solar protection has been explained by Prieto et al. [8] by a surge in research in middle eastern countries on shading, façades and glazing systems. Some emblematic cases in the region that show the application of solar control systems (jointly with air conditioners) in recent years include outdoor cooling of stadiums [120]. Regarding upcoming technologies, it has been observed that there is a gap in the literature to understand the upscaling of these technologies for decarbonising purposes. This also aligns with the difficulty to compare the performance of passive cooling systems, as discussed above.

Regarding collaboration networks found in this work, M. Santamouris is the lead researcher in the field in terms of community size, publications and citations. There are two important results found for the majority of the authors. First, top authors and their communities commonly research different technologies. For example, all authors shown in collaboration networks for microclimate, solar control and thermal mass are not exclusively researching these technologies. There are fewer and smaller research clusters working exclusively in a single technology. Their lower publication output could be due, for example, early stages of research. Second, authors mainly have one publication which can indicate that expert knowledge is not remaining in the field.

In terms of publication years, it is anticipated that clusters with a longer timespan will have higher citations. Nevertheless, high proportions of identified clusters have been mostly active in the last 15 years. This coincides with the increasing attention on climate change in general and the impacts of typical air conditioning systems in particular. The rise of research activities from highly impacted countries on cooling demand, e.g. China and India, is also driving the surge of interests in passive cooling.

Research works on passive cooling technologies have been mainly supported by public funding through multinationals agencies, national agencies, local governments, and universities. The interest of the public sector can be explained by the closed couplings between passive cooling technologies and the built environment/infrastructure. For instance, improving the energy efficiency of building stocks and reducing the impacts of urban heat island are in the immediate interest of the national and local government. Furthermore, dominant passive cooling measures, such as natural ventilation and microclimate, have less potential financial gain which might deter the private sector from providing research funding. The significant roles of the European Union and national government of European countries as funders are in line with the emergence of energy efficiency and heatwaves issues in Europe in the past decades.

Finally, the results of this work have two important implications:

(1) Having identified lead authors by technology and presented highlights of their research, this work may promote further collaboration of authors with similar interest. Moreover, stakeholders of net-zero plans at different scales (e.g. policy- and decision-makers in countries, cities or companies) hereby can find the experts in the field for consultation.

(2) The analysis of the content of documents from top authors shows that the academic literature is missing the decarbonisation potential of passive cooling technologies. Having examined case studies, experimental setups, models and theoretical work for different passive cooling technologies, it is observed that large-scale assessments of these systems are lacking. In particular, future work should compare scenarios of the extensive application of these systems against a carbon-intensive "business-as-usual" scenario in which air conditioners continue their current trajectory. For this, a clear classification of passive cooling technologies and standardised metrics of performance are urgently needed to be defined.

6. Conclusion

The scientific literature on passive cooling is examined in this paper. It is urgent to further our understanding of these technologies particularly as they hold the potential to cool buildings in a less carbon-intensive manner than energy-consuming air conditioners. Specifically, the work presents a landscape of publications on passive cooling, by applying bibliometric techniques, including structured literature searches and analysis of research actors in the field. The paper focuses on identifying actors and trends in the field by using, for the first time all sub-classification of passive cooling technologies (i.e. heat prevention, modulation and dissipation measures) are brought together. The analysis provides insights on the countries, researchers and funders in the literature as a whole, but also by technology.

The search results in the largest set of articles focused on passive cooling technologies (2,859 unique documents). Publication trends show that the countries at the front of research are the US and China. The latter has output the most publications per year since 2016. The motivation behind the rising research uptake can be attributed to national and international drivers, from different dimensions and scales, e.g. from a local heatwave in India to multi-national agreements for climate change.

In terms of technology, there is significant overlap in articles found for different technologies, which indicate that studies mainly research multiple forms of passive cooling. The trend shows that ventilation has historically been the dominant passive cooling technology. However, since 2016 research on cooling through radiative measures and solar control has had the most annual publications. The analysis by technology also shows that most authors only publish one document for a single technology, except top authors and their communities. These results suggest that exclusive research groups investigating a single technology are not common. When inspecting by technology, mainly disjointed clusters of authors are detected, indicating a potential for further collaboration. There are exceptional communities found to be interconnected and forming larger groups, specifically for microclimate and ground cooling.

A limitation of the community detections is that it is applied for top authors and co-occurrences in terms of the number of publication, hence, there is a substantial set of authors (and their work) that is excluded. For future work, insights can be gathered on the evolving topics in the field by analysing document content (e.g. by text mining of abstracts) irrespectively of authorship. Automatic content analysis is also promising to examine the nature of the unclassified documents (Part 2 of the results).

The provision of this landscape allows identifying the past trajectories and contributors (countries, authors and communities) to all classifications of passive cooling technologies. It contributes towards identifying lead researchers, technologies and future collaboration amongst research communities. It discusses content published by main actors in the field and noted that research from these are advancing technologies, but still efforts are needed to provide evidence on the potential of these to decarbonise the future cooling demand.

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