Environmental Monitoring in Built Environment Through Wearable Devices: a Bibliometric Review

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***Abstract*— Wearables are mainly used for commercial purposes to enhance smartphone functionality by enabling payment for commercial items or monitoring physical activity. As emerged from a recent systematic review, many research studies focused on using wearable devices for environmental monitoring of the built environment. Those studies showed that, among the thermal, visual, acoustic, and air quality environmental factors, the last one is the most considered when using wearables, even though in combination with some others. Another relevant finding is that of the acquired studies, in only one, the authors shared their wearables as an open-source device, and it will probably be necessary to encourage researchers to consider opensource to promote scalability and proliferation of new wearables customized to cover different domains. In this case, with a bibliometric review, it was possible to complete the analysis by answering some of most statistical aspects: what are the most important authors involved in this domain of research? What are the most relevant sources? What is the geographical coverage and the collaboration among different Countries? What is the conceptual structure of the considered topic? The methodology used to answer the above questions is based on a bibliometric review using a specific package developed for R environment: bibliometrix.**

Keywords-environmental monitoring; wearable devices; wearables; bibliometric review.

I. INTRODUCTION

The term "wearable" was first used in the scientific literature in 1996 when, in [1], the author presented a personal imaging system and, in [2], where the author gave an overview of energy generation during the user's daily activities, removing the technological limitation of batteries to power wearables. A year later, in 1997, the researchers of MIT media laboratory, Picard and Healey, used the term "affective wearables" [3] to refer to a system equipped with sensors that allowed the detection of affective patterns (e.g., heart rate variability, electrodermal activity). To date, the class of wearable electronics or technologies, called "wearables" for short, has attracted increasing public interest and is generally identified as a category of devices that can be worn or tattooed on the human skin or even implanted in the human body to continuously and accurately monitor some variables (biometric in most of the cases, but also environmental in some other cases) without interrupting or restricting the user's movements [4].

Environmental Quality (EQ) can be subdivided by analysing it in terms of Indoor EQ (IEQ) or Outdoor EQ (OEQ). Both IEQ and OEQ are important to ensure the health and well-being of people.

It is well known that users spend a large part of their time indoors, so the quality of environments within buildings and the satisfaction and well-being of occupants is a hot topic today [5]. Especially in low-cost housing, where the limited indoor space may lead occupants to spend more time doing various outdoor activities, the quality of the outdoor environment is crucial [6].

Both IEQ and OEQ refer to a holistic concept that includes various environmental factors: visual, acoustic, thermal and air quality.

In all cases, monitoring all four environmental factors could be helpful to understand the complex area of interaction (cross-modal or combined) among the different environmental aspects and user perception of IEQ or OEQ.

In order to link the term wearables with the environmental aspect, some new acronyms have been introduced: Personal Environmental Monitoring System (PEMS) and Wearable Environmental Monitoring System (WEMS), to emphasise the class of wearable devices for monitoring some environmental factors [7]. This manuscript is intended to be complementary to [8], where the attention was focused primarily on the systematic analysis, defining the relevant scientific literature finding regarding environmental monitoring with wearables. The attention focused here on the bibliometric analysis, allowing to quantify the scientific production and measure its quality and impact. It is also useful to identify and analyze research's intellectual, conceptual and social structures and their evolution and dynamics.

II. METHODOLOGY

Among the different available databases (e.g., PubMed, Web of Science, Google Scholar), the Scopus search engine,

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developed by Elsevier, was used due to the high quality of the available resources, including the Institute for Scientific Information (ISI) and Scopus-indexed papers. It is a multidisciplinary database that allows defining Information Systems (IS) to think of the advanced search functionality available on the web platform by providing about 20% more coverage than Web of Science. Scopus focused primarily on physical sciences, health sciences, life sciences and social sciences [9], which is consistent with the aim of this research. The covered period is from 1966 to the present [9].

This aspect is consistent with our bibliometric review since, the oldest paper presenting a "wearable" device with computational capabilities was published in the 1990s. A detailed description of the reproducible methodology used to acquire the data can be found in [8].

III. DISCUSSION

The main results of the bibliometric review are presented in the following subsections. By applying a proven methodology, results can be provided in the form of descriptive analysis, main authors involved in the topic, geographic coverage and thematic map to complement the information provided to the scientific community by the systematic review described in [8].

A. Descriptive analysis

A descriptive summary of the main bibliometric statistics is reported in Table I.

TABLE I. MAIN INFORMATION

Parameter (description)	No.
Documents (total number of documents)	68
Sources (frequency distribution of sources as journals)	55
Author's keywords -DE (frequency distribution of the authors' keywords)	237
Keywords Plus -ID (frequency distribution of keywords associated with the document by Scopus databases)	848
Period (years of publication)	2000:2021
Authors (authors' frequency distribution)	317
Authors Appearances (number of author appearances)	380
Authors of single-authored documents (number of authors of single-authors articles)	3
Authors of multi-authored documents (number of authors of multi-authored articles)	314
Authors per Article index (ratio between Authors and Documents)	4.66
Co-Authors per articles index (average number of co-authors in each document)	5.59
Average citations per Article (average number of citations in each Article)	18.78
Collaboration Index (ratio between total authors of multi-authored articles and total multi-authored articles [10] [11])	4.91

In Table I, the Co-Authors per Articles index is calculated as the average number of co-authors per Article.

In this case, the index considers the author appearances while the Authors per Article index is the ratio between the total number of articles and the total number of authors.

Consequently, even if an author has published more than one Article, it is counted only once. This is why the authors per Article index is smaller than the Co-authors per Article index [12]. Only five authors wrote each Article on average with a Collaboration Index equal to 4.91.

As the analysis period of Table 1 covers the last 20 years, only with Figure 1 it is possible to point out that the most significant increase in production was recorded only since 2012 with an Annual Growth Rate of 9.89%.

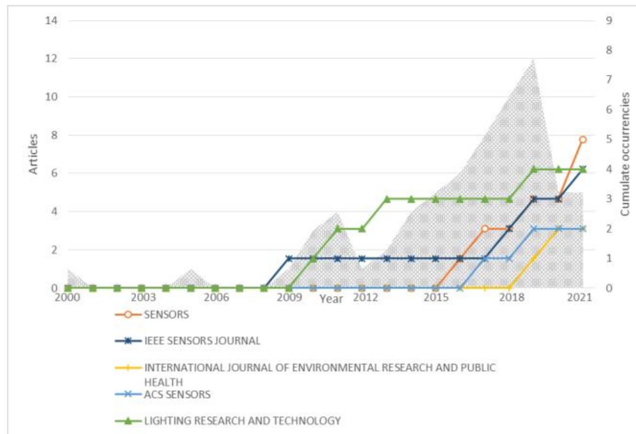

Figure 1. Annual Scientific production and Source Dynamics - Scopus, 2021

Among the 68 analysed peer-reviewed scientific articles, no preferred journal where articles on this topic were concentrated was found. However, the authors' interest in journals that deals with the all-encompassing theme of sensors is increasing in the last years, as highlighted by the distribution frequency of articles published on the "Sensors" and "IEEE Sensors Journal" as displayed in Figure 1.

B. Top 15 authors and related research studies

Figure 2 identifies the most important authors, considering the selected topic, ranked in descending order of importance as a function of the number of published articles.

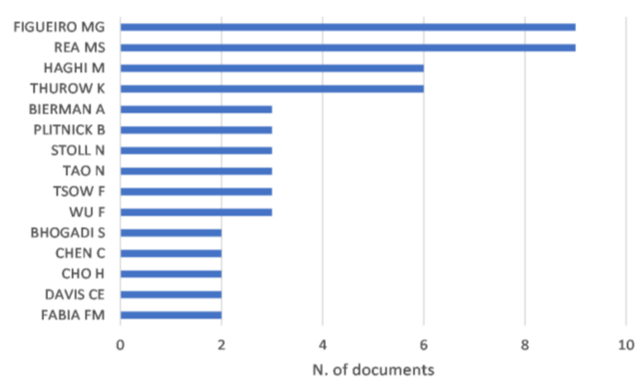

Figure 2. Top 15 authors ranked by number of articles - Scopus, 2021

A brief description of related studies identified by the Top 15 authors is reported below. While a detailed description of all the studies, subdivided by the environmental factor (i.e., visual, acoustic, thermal and air quality), can be found in [8].

The author Figueiro M.G. was actively involved in using wearable devices to assess circadian-effective light and its impact on alertness in different categories of users. In particular, in [13], office workers wear a pendant-mounted Daysimeter device, developed and calibrated at the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute and used in combination with a specific questionnaire to measure participant-specific Circadian Stimulus (CS), thus allowing to identify how they effectively felt significantly more vital, energetic and alert on the days with CS ≥ 0.3 compared to the baseline day. In [14], a field study was conducted with eighth-grade students to determine, using the Daysimeter, the impact of morning light on circadian timing, sleep duration and performance. In [15], he documented the spectral and spatial performance characteristics of two new versions of the Daysimeter. He found that wearing the Daysimeter or Actiwatch Spectrum [16] on the wrist provides accurate light measurements relative to locating a calibrated photosensor at the cornea plane. In [16], he described a case study where light exposure and rest-activity patterns in an older adult with dementia and his caregiver spouse were monitored with a wrist-worn actigraph. This device captures and records high-resolution human activity information to collect baseline data and an eye-level wavelength-sensitive light meter (Daysimeter). The same topic was considered in [17] and [18], co-authored by Rea and Plitnick, to identify the effect of light on the person with dementia and caregivers through the use of questionnaires to acquire subjective feedback and the same instruments, the Daysimeters and the actigraphs [19]. These researches allowed verifying how ambient lighting interventions designed to increase daytime circadian stimulation can be effectively used to increase sleep efficiency in persons with Alzheimer Disease and Related Dementia (ADRD) and their caregivers. It may also be effective for other populations such as healthy older adults with sleep problems, adolescents, and veterans with traumatic brain injury. In [20], he demonstrated the feasibility of using light through closed eyelids during sleep for promoting circadian alignment and sleep health. In [21], he measured both light/dark exposures with Daysimeter and salivary Dim Light Melatonin Onset (DLMO) to study the effects of chronotype, sleep schedule and light/dark pattern exposures on the circadian phase. In [22], the daysimeter was used to verify how a lighting intervention tailored to increase daytime circadian stimulation can increase sleep quality and improve behaviour in patients with ADRD. While promising for application, the present field study should be replicated using a larger sample size and longer treatment duration. Rea co-authored most of Figueiro studies [13]-[15][17][18][21][23][24]. In [25], authors emphasize how technologies are needed to provide information about the state of our circadian system to our conscious awareness so that we can take appropriate action to avoid and correct light-induced circadian disruption. Bierman co-authored three of the articles discussed above [15][23][24]. Plitnick co-authored also three paper previously discussed [14][17][21].

Bhogadi co-authored [26] and [27]. In [27], he described the results of a European Research Council funded project (CHAI) aimed at investigating the relationship between particulate air pollution from outdoor and household sources with information from GPS, wearable cameras, and continuous measurements of personal exposure to particles.

In [26], he used data from multiple sources (continuous personal and ambient PM2.5 concentrations; questionnaire, GPS, and wearable camera data; and modelled long-term exposure at residence) to identify the relative contribution of the time of the day (when?), location (where?), and individuals' activities (what?) to PM2.5 personal exposure in periurban South India.

Cho H. in [28] described how the use of a highly sensitive Multi-Stimuli Responsive (MSR) unit applied to a wearable motion/environmental monitoring chromic device could be used to evaluate some environmental stimuli (UV radiation, temperature) with thermal mapping capability. In [7], he presented a PEMS and WEMS that were developed by considering consumers' needs to detect and avoid exposure to air pollution.

Wu et al. in [29]-[31] demonstrated the practical application in different contexts of a wearable multi-sensor IoT network system for environmental monitoring.

Haghi and Thurow co-autored two papers [32] [33] where they emphasized the role of wearables in multiparameter monitoring, miniaturization, sensor integration and data fusion. Together with Stoll in [34]-[37] demonstrated the practical applicability of a multi-layer wearable devices.

Tsow, Tao et al. [38], and then also Chen with them [39][40] used practical examples to emphasize the role of a wearable sensing system for assessment of exposures to environmental volatile organic compounds (VOCs). The same aspect was covered by the studies of Davis and Fabia et al. [41][42], where they used different wearable to quantify the same aspect: the personal exposures to VOCs.

C. Corresponding Author's Country and Country publications map

Figure 3 shows the origin of the main "corresponding authors" who have carried out specific research related to the considered theme: the United States of America (USA) is at the top of the list and significantly outdistances Spain, in second place and first among European nations. To the third-place China and Italy to equal merit.

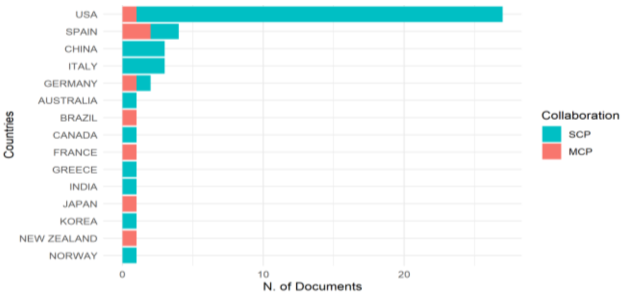

Figure 3. Corresponding Authors' Country (SCP - Single Country Publications, MCP - Multiple Country Publications)

While Figure 4 displays the geographical coverage of the Country scientific production. Each co-author of a Country, identified by the affiliation, contribute with +1 for that Country. The USA is on the top of the list of Countries with the maximum number of authors on the selected topic (200), followed by Germany (21), Italy (19), China (18), Spain (15), Australia (12), France (11), India, Romania and U.K. (10), Greece (7), Canada and Norway (6), Brazil and New Zealand (5), Belgium (4), Japan (3), Latvia and South Korea (2), Ireland and Switzerland (1).

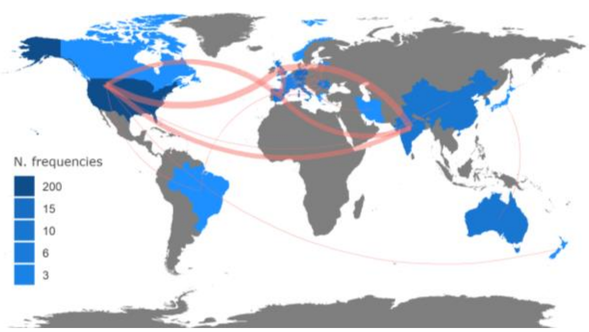

Figure 4. Co-authors Country Scientific Production and Country collaboration.

Figure 4 shows how the entire continent of Africa, Antarctica, large areas of northern Asia and the western countries of the south America, are still not involved in this scientific debate. The collaborations among the countries, highlighted by brown lines, show how USA, U.K. and India established the most active collaborations.

D. Thematic Map

The thematic mapping [43] allows delineating the conceptual structure of the topic. This latter consists of a word co-occurrence network analysis performed considering the Authors' keywords to define what science talks about in a field, main themes, and trends (see Figure 5). In Figure 5, each bubble represents a network cluster and the name attributed to each bubble is the word belonging to the cluster with the higher occurrence value. The size of each bubble is proportional to the cluster word occurrences, while the position is defined according to the cluster Callon centrality and density: the former is a measure of the importance of the selected theme in the development of the entire research domain; the latter is a measure of the theme's development [44].

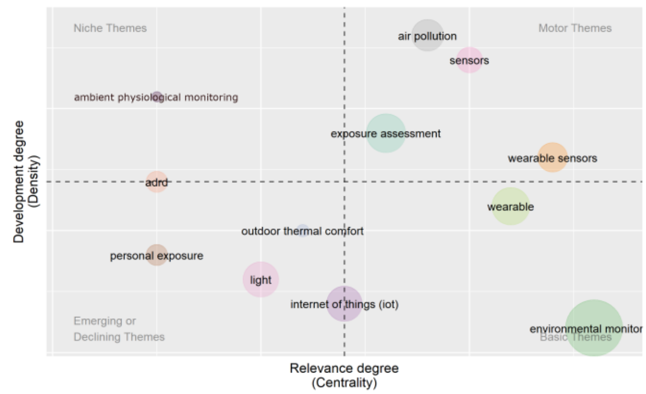

Figure 5. Thematic Map considering authors' keywords for the full period under investigation

Four different themes are shown in Figure 5. The upper-right quadrant shows the motor themes. They are characterized by both high centrality and density. Among the "motor themes" that are the more developed in the literature, the main concern is air pollution, followed by exposure assessment, which refers to studies in which exposure to air pollutants (Particulate Matter specifically) can be considered in combination with the evaluation of noise exposure.

The upper-left quadrant shows high density and low centrality themes, which are of limited importance with high development. In this case, "ambient physiological monitoring" refers to the study [32] where environmental, behavioural, and physiological domains of influencing factors in healthcare were measured simultaneously.

In the lower-left quadrant, there are the emerging or declining themes. Using the thematic evolution and different time slices it is possible to differentiate emerging and declining themes considering the direction toward the top right or the lower left, respectively [45]. Within this particular case, light measurement with wearables was an emerging theme in particular over the period 2010-2015 considering all the studies performed by Figueiro et al.

Finally, the lower-right quadrant shows the transversal themes to the different research areas of the field: wearable and environmental monitor showing the high connection between these aspects in the selected papers.

IV. CONCLUSIONS

The theme of environmental monitoring considering wearables is increasing in terms of published papers. While in [8] it was possible to emphasize the main fields covered by the scientific production, the original value of this research is the rigorous process conducted to perform the first bibliometric mapping in the field of wearables used for environmental monitoring.

For this purpose, a total of 68 different manuscripts were considered. A possible limitation in the selection of the papers could be the bias due to the authors' decision. This aspect was limited by the fact that two authors performed time-consuming screening and, in case of disagreement, reached consensus through discussion and in consultation with the third author. The analysis of selected papers could support scientific community in identifying the main domains of investigation or the main authors involved in this research. It was possible to discover how, among the different authors, Figueiro and Rea gave a great contribution in light-induced circadian disruption assessment using a wearable device.

It was also possible to discover the geographical coverage and the collaboration among different Countries.

Additionally, the thematic map, defined considering the meaning of Callon centrality and density, allows emphasizing the most occurred topic, differentiated considering motor themes, nice themes, emerging or declined themes and basic themes. In particular, considering the motor theme/s, exposure assessment was considered as the most considered and developed theme. By merging this result with that provided by [8], it was possible to emphasize how for the exposure assessment it was primary considered the aspect related to air quality assessment and visual aspects on human well-being.

The acoustic factor was minimally treated. This is probably due to the fact that some wearable instruments that measure workers' exposure at shoulder level (e.g., dosimeters SV 104A [46]), or detect environmental noise at ear level (e.g., HEAD acoustics binaural headset BHS II [47]) are already commercially available and therefore, their design, development and use for research purpose does not constitute a novelty, except in the integration with multi-parameter or 'low cost' and open-source acquisition instruments.

The same circumstance can be highlighted for thermal aspects where temperature sensors were mainly used in combination with other instruments to acquire information about the environment without properly considering a human-centric perspective. It would be useful to identify low-cost, open-source solutions that most people can use to assess, not so much the variability of environmental parameters in the indoor environment, which, when considering workers sitting at their desks, can lose its significance. But considering the variability of the environmental conditions to which the subjects may be exposed during the day, e.g., passing from the outdoors torrid or humid climates of the summer of tropical and sub-tropical areas to indoor situations that are typically more bearable or too cold due to ineffective regulation of the HVAC plants.

By linking all this information with user feedback, algorithms not based on a physical model but, instead, based on data could be effectively applied to identify the variables that most affect the individual's perception of comfort, including aspects that are difficult to take into account (e.g., transient exposure) [48].

Probably much more work can be done, in developing new hardware devices that could monitor the environment in a holistic perspective, also considering the other 3 environmental factors (visual, acoustic and thermal) in line with the studies of Haghi and Thurow (Figure 2) which emphasized the role of wearables in multiparameter monitoring, thus making it possible to take into account any combined or cross-modal aspects resulting from the potential interaction between different environmental variables.

Furthermore, by combining the results of the bibliographic review with those of the [8], even if the growth of publications has increased considerably since 2012, with a noticeable halt in the last two years (see Figure 1), it was possible, at least theoretically, to hypothesize how the sharing of open-source solutions can encourage the proliferation of application of these devices in different contexts, promoting the design and assessment of the built environment on the basis of a human-centred approach, even in those areas not yet affected by the scientific debate on this topic (figure 4).

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