



COBEM2021-0661

INTERFACES BETWEEN ATMOSPHERIC WATER HARVESTING AND SOLAR ENERGY: EVIDENCES FROM A BIBLIOMETRIC STUDY

Ana Carolina Lamas da Silva
Elias Rocha Gonçalves Júnior

Federal Institute of Education, Science and Technology of Espírito Santo, Avenue Vitória, 1729, Vitória, Espírito Santo, Brazil.
anacrolamas@gmail.com; eliasrgjunior1@gmail.com

Virgínia Siqueira Gonçalves

Federal Institute of Education, Science and Technology Fluminense, Dr. Siqueira Street, 273, Campos dos Goytacazes, Rio de Janeiro, Brazil.
virginiasideiragoncalves@gmail.com

Abstract. *This paper aims to map quantitatively and qualitatively scientific research on studies that establish relationships between atmospheric water harvesting and solar energy, in order to provide an overview of the academic production of the subject. Using the bibliometric method, several publication characteristics were obtained, such as countries of origin of the articles, year of publication, authors, institutional affiliation, research topics, as well as a content analysis of the database by wordcloud to measure its consistency. Due to the volume of results found, it was restricted to only original articles and reviews articles published in journals, reducing the set to 135 papers. The results show an increase in the number of papers published in the last five years, with emphasis on the period from 2017 to 2020. It was possible to identify the prominence of China, the United States and Saudi Arabia in the researches on the subject. It was clearly observed that the intersection of atmospheric water harvesting and solar energy has been figured as a central research theme for an individual or a group of researchers worldwide. In general, the paper shows that bibliometric study is a useful to provide a base of knowledge in the development of researches and projects.*

Keywords: *atmospheric water harvesting, renewable energy, solar energy, bibliometrics.*

1. INTRODUCTION

Globally, the number of people lacking access to water is 2.2 billion, while 4.2 billion people have inadequate sanitation and clean water source (United Nations, 2020). Atmospheric water, which is present regardless of geographical and hydrologic conditions, is emerging as an alternative water resource (Zhou *et al.*, 2020) and shows a great promise in supplying water, especially for community use in arid areas (Fessehaye *et al.*, 2014).

In general, any viable atmospheric water-harvesting technology must satisfy five primary criteria: it should be efficient, cheap, scalable, wide-band, and stable enough to operate for a whole year or at last a monsoon season (Tu *et al.*, 2018). Since the source of the atmospheric water is normally clean, the water quality is good enough for drinking and for other domestic and agricultural purposes (Khalil *et al.*, 2016).

The amount of energy consumed to harvest water from the air dramatically increases as the humidity or ambient temperature decreases (Zhou *et al.*, 2020), which could be mitigated by using an alternative energy source. In this context, solar energy can be used to increase the process of capturing moisture from the air with atmospheric water generators (Kim *et al.*, 2018) and this topic has been receiving considerable attention from researchers around the world (Jarimi *et al.*, 2020).

This paper aims to map quantitatively and qualitatively scientific research on studies that establish relationships between atmospheric water harvesting and solar energy, in order to provide an overview of the academic production of the subject. Using the bibliometric method, several publication characteristics were obtained, such as countries of origin of the articles, year of publication, institutional affiliation, authors and research topics, as well as a content analysis of the database by wordcloud to measure its consistency.

2. MATERIALS AND METHODS

This paper is structured under bibliometric analysis. It intends to analyze quantitative and qualitative data about papers and allocating them in categories in order to provide a good comprehension about the atmospheric water harvesting processes by using solar energy as energy source. The searches were carried out from search keys related to the topic,

with a 20-year time cut being considered.

This type of analysis facilitates a cross-referencing, resulting in a previous study composed by the works that will integrate the so-called starting nucleus, where the researcher will have sufficient background for the bibliographic study (Gonçalves Jr *et al.*, 2018). In order to avoid the reduction of results, no exclusion filters were used.

The Scopus database was used in order to collect articles for the bibliography. For this purpose, two search terms were used: "atmospheric water generator" and "atmospheric water harvesting", which were later associated with the term "solar energy" to relate the technologies applied in the transformation of air moisture into water and solar energy. The results obtained from these search terms are presented in Tab. 1.

Table 1. Search terms used.

SEARCH TERMS	RESULTS
"atmospheric water generator"	50
"atmospheric water harvesting"	72
"atmospheric water generator" AND "solar energy"	59
"atmospheric water harvesting" AND "solar energy"	79
Total	260

The searches returned a total of 260 records. By scrutinizing them for adherence to the topic addressed in this paper, 135 articles and reviews published in journals were selected to form the basis for the bibliometric study. The selected papers involve devices, methods, performance analysis, among other studies, which enable the transformation of air humidity into water using solar energy.

3. RESULTS AND DISCUSSION

Figure 1 illustrates the papers distributions between 2001 and 2020. This graph can be separated in two distinct moments: the first moment is the reduced number of papers and research stagnation from 2001 to 2015; the other moment is from 2016 to 2020 with a significant growth, which represent just over 76% of the papers analyzed. It is worth noting that 2020 had more than twice the number of papers compared to the previous year, which demonstrates a clear increase in interest in research related to the topic.

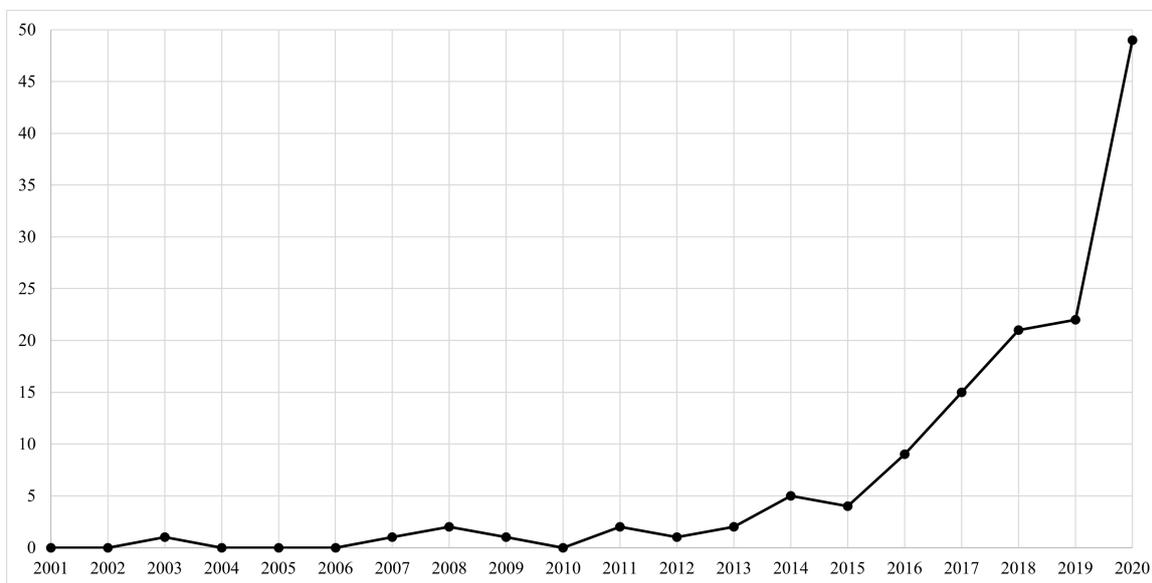


Figure 1. Papers by year.

By analyzing Fig. 1, it is not possible to draw a trend line in the graph, but considering the growth presented in the last five years, it is expected that the number of publications will continue to increase.

As the database was set, in order to validate the search terms used, the selected articles uniformity was analyzed by using the wordclouding tool. For this purpose, the Wordle software was used, based on the abstracts of the 135 selected papers and the results of this analysis are shown in Fig. 2.

Table 2. Papers by country.

COUNTRY/TERRITORY	RESULTS
United States	36
China	31
Saudi Arabia	15
India	10
Egypt	8
South Korea	8
Italy	6
Singapore	6
United Kingdom	6
Australia	5
Germany	5
Mexico	5
Russian Federation	5

Analyzing Fig. 3, four institutions stand out: Shanghai Jiao Tong University (China) e University of California (USA), with 9 records; King Abdulaziz City for Science and Technology (Saudi Arabia) e University of Texas (USA), with 8 records.

In Table 2, it is observed that the United States and China are the countries with the highest number of publications and, alongside with Saudi Arabia, it holds just over 60% of publications related to the subject. It is important to highlight that Brazil is not on the list of countries with related publications.

By intersecting the data presented in Fig. 2 and Tab. 2, it can be seen that the most relevant affiliations belong to the countries with the highest number of publications. In addition, in Tab. 3, it can be seen that there are prominent groups of scientific papers production in the institutions and countries highlighted by listing authors, affiliation, country of origin and number of publications.

Table 3. Relations between authors, affiliation, country and number of publications.

AUTHOR	AFFILIATION	COUNTRY	PUBLICATIONS
Wang, R.Z.	Shanghai Jiao Tong University	China	9
Yaghi, O.M.	University of California	USA	8
Wang, E.N.	Massachusetts Institute of Technology	USA	6
Bahadur, V.	University of Texas	USA	5
Kapustin, E.A.	University of California	USA	4
Kim, H.	Korea Institute of Science and Technology	South Korea	4
Rao, S.R.	The University of Utah	USA	4
Wang, J.Y.	Shanghai Jiao Tong University	China	4
Wang, L.W.	Shanghai Jiao Tong University	China	4

Regarding the research topics (Fig. 4), all papers were allocated to specific topics according to the Scopus database. The most prominent topics were "Engineering", "Energy", "Chemistry", "Environmental Science", "Materials Science" and "Chemical Engineering". The number of papers related to these topics is similar and many of them are allocated to more than one research topic, which demonstrates the relevance of the relationship between engineering, chemistry and materials science for the development of studies on the transformation of air moisture into water using solar energy.

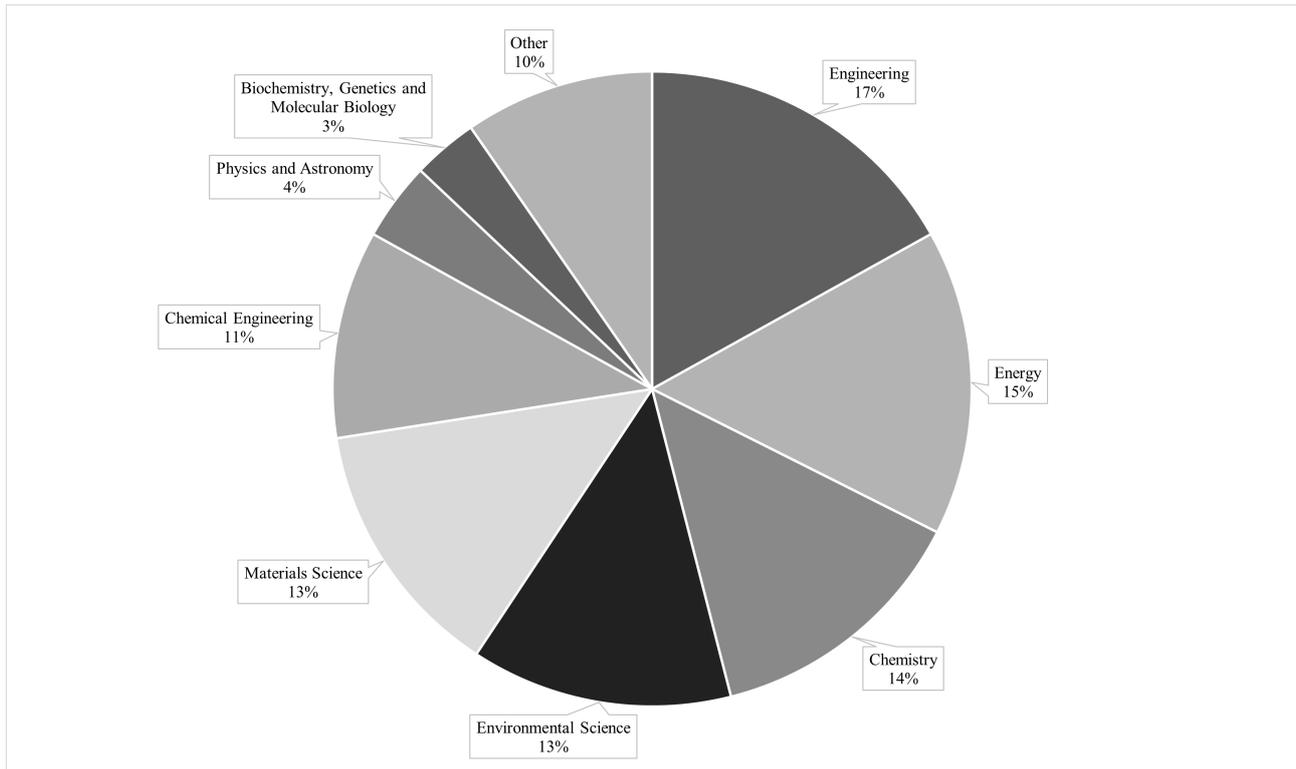


Figure 4. Papers by research topic.

Table 4 shows ten articles selected from the records under analysis, based on adherence to the topic under study and based on the number of citations, in addition to being allocated to the main research topics.

Table 4. List of most relevant papers.

TITLE	AUTHOR	YEAR	CITATIONS
Jumping-droplet-enhanced condensation on scalable superhydrophobic nanostructured surfaces	Miljkovic et al.	2013	668
Water harvesting from air with metal-organic frameworks powered by natural sunlight	Kim et al.	2017	564
Metal–Organic Frameworks for Water Harvesting from Air	Kalmutzki et al.	2018	196
Adsorption-based atmospheric water harvesting device for arid climates	Kim et al.	2018	154
Record Atmospheric Fresh Water Capture and Heat Transfer with a Material Operating at the Water Uptake Reversibility Limit	Rieth et al.	2017	122
Practical water production from desert air	Fathieh	2018	111
Tunable Water and CO ₂ Sorption Properties in Isostructural Azine-Based Covalent Organic Frameworks through Polarity Engineering	Stegbauer et al.	2015	104
Nature’s moisture harvesters: A comparative review	Malik et al.	2014	102
Progress and Expectation of Atmospheric Water Harvesting	Tu et al.	2018	97
Power generation from ambient humidity using protein nanowires	Liu et al.	2020	66

Miljkovic *et al.* (2013) used a simple fabrication method to develop a nanostructured silanized copper oxide surface that has good heat transfer efficiency in condensation. Water droplets accumulate on the surface and exhibit a jumping behavior that has been demonstrated through experiments. From this, a comparison was made between the flux and heat

transfer on this nanostructured surface and on state-of-the-art hydrophobic condensing surfaces at low supersaturations. The authors addressed the possibility of applying this technology to perform atmospheric water capture and dehumidification, in addition to demonstrating ways to achieve high-flow superhydrophobic condensation.

Kim *et al.* (2017) presented the design of a device based on a porous metal-organic framework (MOF) that uses natural sunlight and captures water from the atmosphere at ambient conditions. According to the authors, solar energy is advantageous for this application, as in regions of low relative humidity, solar incidence is abundant and the temperature variation throughout the day is considerable. This device was capable of harvesting 2.8 liters of water per kilogram of MOF daily at relative humidity levels as low as 20% and requires no additional input of energy.

Kalmutzki *et al.* (2018) proposed a selection method for the most efficient metal-organic frameworks (MOFs) for atmospheric water uptake and presented the concepts of the MOF models to be applied in water collection based on passive adsorption. To this end, MOFs parameters and how they influence water adsorption were discussed, such as chemical factors, structural diversity, precision in pore adjustment and hydrophilicity. In addition, they presented the most common water adsorption mechanisms in micro and mesoporous metal-organic structures and how to achieve fine-tuning of the adsorption behavior through reticular chemistry.

Kim *et al.* (2018) developed an air-cooled sorbent-based atmospheric water collection device using a metal-organic framework (MOF) to operate in arid climates, at a relative humidity between 10 and 40%. In a daily cycle, this equipment produced 0.25 liters of water per kilogram of MOF, with a thermal efficiency of 14%. The authors also carried out a comparison between its collector and a state-of-the-art condensing technology, which does not operate with relative humidity below 40% and has high energy consumption.

Rieth *et al.* (2017) reported a metal-organic framework (MOF) with a pore diameter smaller than the critical diameter for the capillary action of water, allowing water to be captured at reversibility limit. This framework was exposed to a simulation of desert conditions, relative humidity below 30%, with a cooling capacity of 400 kWh m⁻³ per cycle, creating a difference of 20 °C between the ambient temperature and the outlet temperature. Under these conditions, 0.82 kg of water per kg of MOF were captured, nearly double the quantity of fresh water compared to the previous best material.

Fathieh *et al.* (2018) carried out experiments, in the laboratory, with a metal-organic framework (MOF) to capture atmospheric water simulating desert conditions, and later in the Arizona desert (USA). The equipment used natural cooling and ambient sunlight as a source of energy during its operation, producing 100 g of water per kilogram of MOF at each cycle, day and night. A second device was reported, its structure was an aluminum based MOF, and provided more than twice as much water as the first device.

Stegbauer *et al.* (2015) presented atmospheric water uptake using azine-based isostructural covalent organic frameworks (COFs) as adsorbents. Two frameworks with adjustable sorption characteristics were presented from the design of the chemical nature of the pore walls, the less polar one acts as a water capture and release reservoir and has a greater capacity to absorb water at low pressures. In addition, the more polar framework has a high absorption of carbon dioxide under equilibrium conditions and low pressures, while the non-polar COF has a high selectivity of CO₂ in relation to N₂. Another analysis was the doping of the pore walls of the two frameworks with metallic salts, which resulted in a greater uptake of CO₂.

Malik *et al.* (2014) gathered information consisting of a list of fauna and flora species from arid and dry regions that perform moisture harvesting. The information was collected because the surface characteristics of these species, together with the direction of water flow in them, can help in the development of devices that perform atmospheric water harvesting.

Tu *et al.* (2018) reviewed technological advances in atmospheric water harvesting equipment, identifying achievements, challenges and barriers to its application. The authors sought to evaluate the water production of the devices under different climatic conditions, trying to find an efficient way to produce water from air moisture. Several harvesting methods based on materials, system designs, thermodynamic cycles were discussed, presenting at the end a systematic comparison and a solution for the performance of previously proposed devices, discussing the variables that interfere in the effectiveness and end up increasing the cost.

Hanikel *et al.* (2019) reported two experiments, in desert laboratory conditions and another in the Arizona desert (USA), using two prototypes based on metal-organic frameworks (MOF): MOF-801 and MOF-303. Both structures used sunlight and natural cooling during their operations. The results obtained provided the discovery of criteria that rule the needs of air, materials and energy for the water harvesting from moisture of the desert air.

4. CONCLUSION

This paper proposed to present a research about the interfaces between atmospheric water harvesting and solar energy, with the objective of presenting a selection of articles as a preamble for an analysis of the most relevant papers related to the proposed theme by using the bibliometric method.

The main conclusion of this paper is that the intersection between atmospheric water harvesting and solar energy has been figured as a central research topic for an individual or a group of researchers around the world. From 2001 to 2020, 135 articles were produced by using solar energy in the atmospheric water harvesting processes, most of them involving

metal-organic frameworks application, as we saw in majority of the most relevant papers.

"Engineering", "Energy", "Chemistry", "Environmental Science", "Materials Science" and "Chemical Engineering" are the research topics in which collaborations of this kind of assessment can be more easily tracked and perceived, which remains as a subject for future studies. We also verified that there are prominent groups of scientific papers production in institutions in United States, China and Saudi Arabia.

The applied method proved to be adequate, as it provides the researcher a guideline to start a research, which is supported by scientific papers with greater relevance and credibility, with results obtained from refinements in related searches, which leads to the identification of the research topics with the largest number of papers already published, the largest number of authors with related publications, the countries with the greatest scientific application of the subject, and still being able to verify and explore the chronology of the publications.

5. REFERENCES

- Fathieh, F., Kalmutzki, M., Kapustin, E., Waller, P., Yang, J. and Yaghi, O., 2018. "Practical water production from desert air". *Science Advances*, Vol. 4, No. 6.
- Fessehaye, M., Abdul-Wahab, S.A., Savage, M.J., Kohler, T., Gherezghiher, T. and Hurni, H., 2014. "Fog-water collection for community use". *Renewable and Sustainable Energy Reviews*, Vol. 29, pp. 52–62.
- Gonçalves Jr, E., Souza, C. and Gonçalves, V., 2018. "Interfaces between wind energy aspects analysis and weibull distribution: Evidences from a bibliometric study". *International Journal of Advanced Engineering Research and Science*, Vol. 5, pp. 138–143.
- Hanikel, N., Prévot, M., Fathieh, F., Kapustin, E., Lyu, H., Wang, H., Diercks, N., Glover, T. and Yaghi, O., 2019. "Rapid cycling and exceptional yield in a metal-organic framework water harvester". *ACS Central Science*, Vol. 5, No. 10, pp. 1699–1706.
- Jarimi, H., Powell, R. and Riffat, S., 2020. "Review of sustainable methods for atmospheric water harvesting". *International Journal of Low-Carbon Technologies*, Vol. 15, No. 2, pp. 253–276.
- Kalmutzki, M., Diercks, C. and Yaghi, O., 2018. "Metal-organic frameworks for water harvesting from air". *Advanced Materials*, Vol. 30, No. 37.
- Khalil, B., Adamowski, J., Shabbir, A., Jang, C. and Rojas, M., Reilly, K. and Ozga-Zielinski, B., 2016. "A review: dew water collection from radiative passive collectors to recent developments of active collectors". *Sustainable Water Resources Management*, Vol. 2, No. 1, pp. 71–86.
- Kim, H., Rao, S., Kapustin, E., Zhao, L., Yang, S., Yaghi, O. and Wang, E., 2018. "Adsorption-based atmospheric water harvesting device for arid climates". *Nature Communications*, Vol. 9, No. 1.
- Kim, H., Yang, S., Rao, S., Narayanan, S., Kapustin, E., Furukawa, H., Umans, A., Yaghi, O. and Wang, E., 2017. "Water harvesting from air with metal-organic frameworks powered by natural sunlight". *Science*, Vol. 356, No. 6336, pp. 430–434.
- Malik, F., Clement, R., Gethin, D., Krawszik, W. and Parker, A., 2014. "Nature's moisture harvesters: A comparative review". *Bioinspiration and Biomimetics*, Vol. 9, No. 3.
- Miljkovic, N., Enright, R., Nam, Y., Lopez, K., Dou, N., Sack, J. and Wang, E., 2013. "Jumping-droplet-enhanced condensation on scalable superhydrophobic nanostructured surfaces". *Nano Letters*, Vol. 13, No. 1, pp. 179–187.
- Rieth, A., Yang, S., Wang, E. and Dincă, M., 2017. "Record atmospheric fresh water capture and heat transfer with a material operating at the water uptake reversibility limit". *ACS Central Science*, Vol. 3, No. 6, pp. 668–672.
- Stegbauer, L., Hahn, M., Jentys, A., Savasci, G., Ochsenfeld, C., Lercher, J. and Lotsch, B., 2015. "Tunable water and CO₂ sorption properties in isostructural azine-based covalent organic frameworks through polarity engineering". *Chemistry of Materials*, Vol. 27, No. 23, pp. 7874–7881.
- Tu, Y., Wang, R., Zhang, Y. and Wang, J., 2018. "Progress and expectation of atmospheric water harvesting". *Joule*, Vol. 2, No. 8, pp. 1452–1475.
- United Nations, 2020. "Water". United Nations, Peace, dignity and equality on a healthy planet, <https://www.un.org/en/global-issues/water>. Accessed 28 march 2021.
- Zhou, X., Lu, H., Zhao, F. and Yu, G., 2020. "Atmospheric water harvesting: A review of material and structural designs". *ACS Materials Letters*, Vol. 2, No. 7, pp. 671–684.

6. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.