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Feasibility of MOF Water Harvesting: A Comparative Study of Arid and Tropical Humid Regions

Sena Min and Benjamin Wongu Lee
senamin3699@gmail.com, benwglee09@gmail.com

ABSTRACT

Over 2.2 billion people in the world lack access to water security. This study investigates the feasibility of atmospheric water harvesting using Metal-Organic Frameworks (MOFs), specifically MOF-303, to generate water in two distinct climatic zones: Niamey, Niger and Lagos, Nigeria. By analyzing the temperature fluctuations and relative humidity (RH), this study models the Temperature Swing Adsorption (TSA) cycle to calculate the amounts of water that can be collected in these two regions. The calculations show that despite the low RH, Niamey shows higher amounts of water collected.

INTRODUCTION

Humanity faces numerous challenges these days ranging from climate change to scarcity of resources. Among them, one of the most pressing issues that has a significant impact on human flourishing and health is water security. Today, nearly 2.2 billion people, roughly one-fourth of the world's population, lack access to safe drinking water despite its importance to human health and survival.[1] While a portion of the world suffers from natural and industrial pollution of water resources, large parts of the world do not have access to sufficient amounts of water at all.[2] For example, in regions such as Sub-Saharan Africa, the situation is particularly dire. The region faces a combination of physical scarcity, in which there is simply not enough water to meet regional demand, and economic scarcity, in which the infrastructure and capital investment required to treat water are absent.[3] Such challenge increasingly demands an economical and versatile solution that is beyond traditional methods of producing potable water.

Novel materials have been developed to seize the potential to harvest atmospheric water for such a challenge. Metal-Organic Frameworks (MOFs) have garnered attention for their groundbreaking potential for capturing matter from their surroundings.[4] MOFs are characterized by their crystalline and porous structure composed of metal nodes connected with organic linker molecules creating a cage-like structure.[4] Due to this repeating cage-like structure, MOFs have an ultra-high surface area and pore volumes presenting high potential for storage capacities.[5] For example, NU-110, a MOF material developed by a research team at Northwestern University, has a surface area of approximately 7,000 m^2 per gram,[6] meaning a single gram of NU-110 has a surface area larger than that of an American football field. In addition, MOFs have tunable structures as their properties can be tuned depending on which metal nodes and organic linkers are used in their composition. The structural characteristics and tunability of MOF materials have led to their potential utilization in a wide range of industrial applications, such as gas storage,[7] catalysis,[8] separation,[9] and drug delivery.[10] Moreover, MOFs have shown potential in addressing water security in both water filtration and water harvesting. For example, UiO-66, composed mainly of Zirconium metal clusters, is able to capture heavy metals, such as Lead or Arsenic, via chemical binding inside their pores.[11] MIL-100 is another example of MOF that shows filtering capacity for polyfluoroalkyl substances (PFAS widely known as “forever chemical”) in water.[12]

The most promising capability of MOF materials in the field of water security is its ability to harvest water by capturing water molecules that exist in the atmosphere. MOF-303, an aluminum-based MOF material, has shown very high affinity to water.[13] A laboratory-scale experiment has shown that MOF-303 can uptake 0.2 g of water per gram of MOF-303 in a desert-like environment.[13] MOF materials, including MOF-303, capture molecules by adsorption mechanism, a physical interaction between a solid surface and gas or liquid molecules creating an adsorbed phase on the surface.[14] Adsorption interaction is exothermic in nature, meaning it releases heat during the reaction. This exothermic nature of adsorption leads to increased amounts of adsorption as temperature is low and lower amounts of adsorption in high temperature conditions. Temperature Swing Adsorption (TSA) cycles can therefore be utilized through adsorption and desorption (reverse of adsorption) cycles for water harvesting.[13] At low temperatures, MOF-303 captures, or adsorbs, water molecules in its pore structure. It then releases, or desorbs, the water molecules when temperature is raised. The high adsorption affinity of MOF-303 also does not require high energy for the regeneration process unlike other water adsorbing porous materials, such as silica gel. Due to this characteristic, MOF-303 makes a great candidate for harvesting water from the atmosphere in areas where temperature difference between day and night is large. At night when temperature is low, it collects water and is able to release it with just the energy provided by the heat of the sun.[15]

In this paper, we provide a preliminary thermodynamic feasibility assessment of using MOFs as a decentralized solution for addressing the challenge of water security in Sub-Saharan Africa. While the laboratory performance of MOFs is well-documented, their transition to field application requires a rigorous understanding of the local thermodynamics. This study provides a detailed comparative analysis through two case studies representing the climatic extremes of the region: the hyper-arid Sahelian climate of Niamey, Niger, and the tropical humid climate of Lagos, Nigeria. By modeling the Temperature Swing Adsorption (TSA) cycle against the specific diurnal temperature and humidity profiles of these regions, we aim to quantify the expected daily water yield and energy requirements. While full-scale deployment will ultimately require extensive engineering, economic, maintenance, and field-performance analyses, this paper addresses the foundational feasibility gap by evaluating whether natural temperature fluctuations in these regions are sufficient to drive the cycle without grid-dependent infrastructure.

METHODOLOGY

Material and Data Selection

As mentioned in the Introduction, MOF-303 has been reported as the most promising candidate for atmospheric water harvesting within the vast library of MOF materials. Therefore, we use the available literature data for MOF-303 to explore its feasibility in harvesting water. The standard for measuring uptake by MOF materials, or other porous materials, is by collecting adsorption isotherms,[16] which graphically represent adsorbed amounts in g/g (or mol/g) basis as a function of pressure (or RH in case of water) at a fixed temperature. Chemically, MOF-303 [Al(OH)(PZDC)] consists of aluminum-based secondary building units linked by pyrazole-3,5-dicarboxylate. The polar organic linkers act as the adsorptive sites for water molecules forming water pockets during water uptake.[17]

Two areas with extreme climate conditions were considered in this study. Niamey, the capital of Niger, represents a sub-saharan climate that is extremely hot and arid. It features a large diurnal temperature range, in which daytime temperatures spike above 40 °C while the temperatures drop to 20 °C during nighttime. Lagos, Nigeria was selected to represent a high-humidity climate with a low diurnal temperature range of approximately 10 °C. The climate data were collected using NASA POWER.[18] To demonstrate a contrast in our analysis, we have chosen to analyze climate data in January and July to highlight the extreme environmental conditions in these regions.

Thermodynamic Modeling

The water harvesting cycle is driven by the Temperature Swing Adsorption (TSA) process where the water uptake and release occur as a function of both temperature and relative humidity. The amount of water harvested per TSA cycle is the difference between the water captured at night via adsorption and the water released during daytime heating via desorption. This adsorption-desorption capacity, ΔW, can be described from the following equation:

$$\Delta w = w_{ads}(RH, T_{night}) - w_{des}(RH, T_{day}) \qquad \text{Eq (1)}$$

where w_{ads} and w_{des} are the amounts of water uptake at given RH and temperature conditions derived from experimental adsorption isotherms of MOF-303. The amount of energy required for the release of water is the sum of the sensible heat, $q_{sensible}$, and latent heat, q_{latent}:

$$q_{total} = q_{sensible} + q_{latent} \qquad \text{Eq (2)}$$

where the sensible heat is energy required to raise the temperature of the MOF mass and captured water and the latent heat is energy required to break the MOF-and-water interactions. They are defined as the following:

$$q_{sensible} = \Delta T(m_{MOF} \cdot C_{p,MOF} + m_{water} \cdot C_{p,water}) \qquad \text{Eq (3)}$$

$$q_{latent} = w_{uptake} \cdot q_{st} \qquad \text{Eq (4)}$$

where m_{MOF} and m_{water} represent mass of MOF and water, respectively, and $C_{p,MOF}$ and $C_{p,water}$ represent heat capacity of MOF and water, respectively. The isosteric heat of adsorption is represented by q_{st}.[19] The latent heat is considered much larger than sensible heat; therefore, q_{total} is approximately equal to q_{latent} and having a low isosteric heat of adsorption is important in MOF selection for water harvesting. In a practical application, an environment that can provide solar energy to overcome the latent heat is important to release water. Therefore, the environmental feasibility depends on two crucial factors: 1) the amount of water uptake by MOF-303 due to temperature fluctuations and 2) solar energy that is sufficient to break the bonding interactions between MOF-303 and water.

RESULTS & DISCUSSION

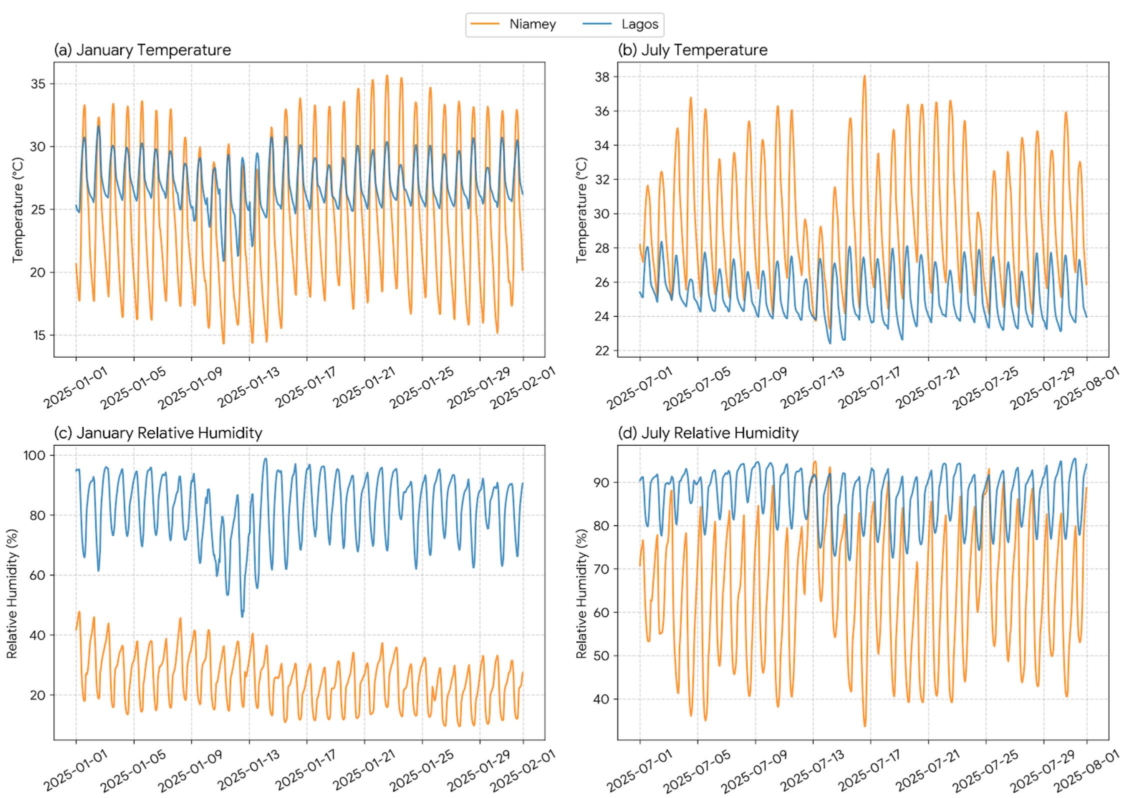

Figure 1. Hourly temperature (a and b) and humidity (c and d) data for Niamey (orange) and Lagos (blue) for the months of January (a and c) and July (b and d) in 2025. Data were sourced from NASA POWER.[18]

The temperature and relative humidity fluctuations in Niamey and Lagos in January 2025 and July 2025 are shown in Figure 1. The fluctuations demonstrate the stark differences in the two cities. Lagos shows a much smaller range of temperature fluctuations throughout both months of January and July staying within 20 to 30 °C. Niamey, on the other hand, shows a much wider range of temperature fluctuations. In January, Niamey shows temperature rising above 35 °C for a few days while the temperature drops below 20 °C at night on most days. A similar range is shown in July with the upper temperature rising higher than January. The higher temperature fluctuations of Niamey compared to Lagos suggest its better suitability for capturing water with MOF utilizing the TSA cycle. However, Figure 1(c) and (d), showing relative humidity data, paint a different picture. Lagos generally shows higher relative humidity compared to Niamey in both January and July. Due to the dependence of MOF water uptake on relative humidity, Lagos shows potential for larger water uptake.

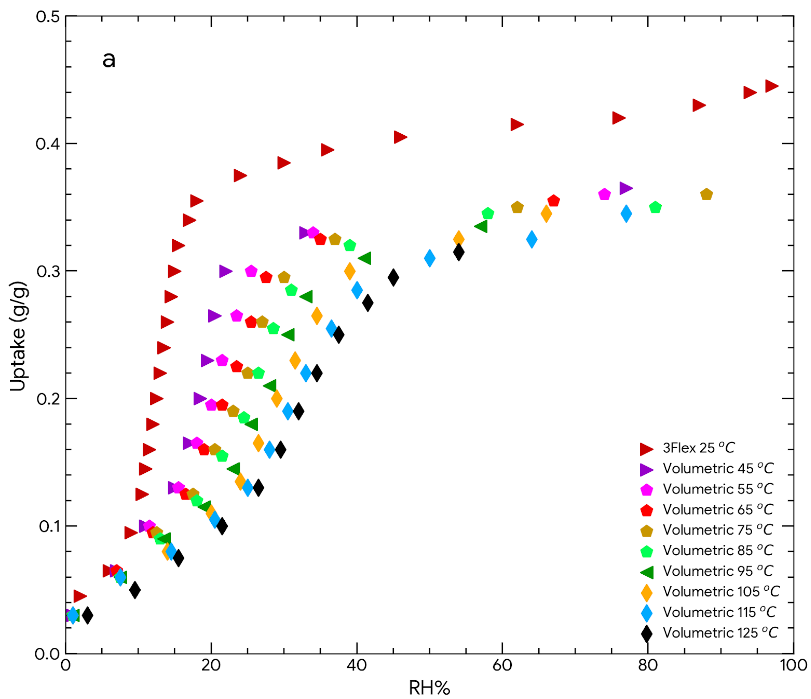

Figure 2. Water adsorption isotherms on MOF-303 at varying temperatures from 25 °C to 125 °C. Data obtained from Hastings et al.[20]

The water uptake is calculated using the water adsorption isotherm available in the literature. In this study, the water isotherms of MOF-303 were taken from Hastings et al.[20] The data were collected over a comprehensive range of temperatures up to RH ~ 100 %. Figure 2 shows water adsorption isotherms recreated from Hastings et al.[20] The water adsorption of MOF-303 are characterized by "step-like" isotherms indicating that pore-filling process begins at around 15-20 % RH. It is also around this RH environment where the water uptake varies the most with varying temperatures. According to the isotherms, a gram of MOF-303 captures above 0.3 g of water and more than 0.4 g of water at the lowest temperature (25 °C) experimented in the study.[20]

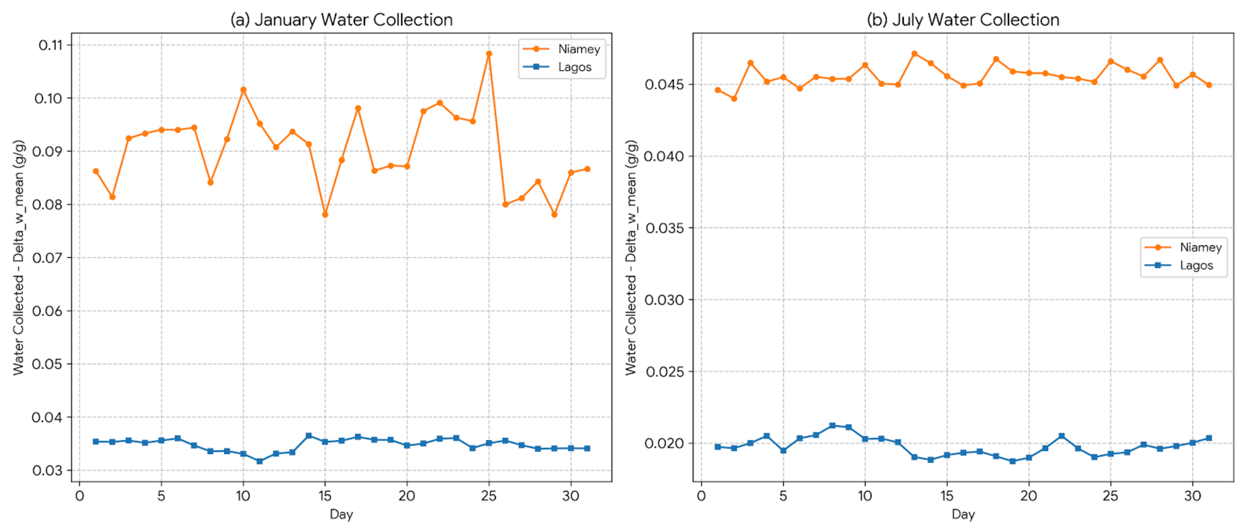

Figure 3. Estimated mean water uptake by MOF-303 in g/g per day for (a) January 2025 and (b) July 2025 for Niamey (orange) and Lagos (blue).

Equation 1 was used to calculate the amount of water that can be collected daily using the water adsorption and weather data for Niamey and Lagos. To simplify the calculations, the lowest and highest temperatures of the day from the hourly data were used and the adsorption data were interpolated using simple two-point interpolation. The RH values matching the chosen temperatures were used. For example, if the lowest temperature value during the night time is 30 °C and the corresponding RH value is 50 %, the water uptake was interpolated between 25 and 45 °C isotherms between the two data points closest to the RH value of 50 %. For temperatures under 25 °C, water uptake was extrapolated. Figure 3a shows the amount of water that can be collected by MOF-303 in the weather conditions of January 2025 in Niamey and Lagos. The water uptake in Niamey is more than double the amount in Lagos. The water uptake suggests despite the higher humidity condition in Lagos, the uptake amount is more dependent on the temperature conditions. As can be seen in Figure 2, water uptake in MOF-303 experiences significant increase up to 20-40 % RH depending on temperature then tapers, indicating that RH above 40 % does not increase the water uptake significantly. As shown in Figure 3b, the same is true for July 2025 where we see higher amounts of water collected for Niamey despite lower RH. However, July 2025 shows lower amounts of water collected for both Niamey and Lagos despite higher RH and temperatures. This observation indicates that the temperature fluctuations dominate the water collection. When RH is held constant, ΔW scales directly with ΔT. The hyper-arid environment of Niamey provides the massive daytime thermal energy required to maximize desorption, proving that for MOF-303, thermal swing dominates the overall daily water yield. This is especially the case for Niamey in January where temperature stays between 20 to 30 °C and relative humidity is approximately 30 % on average where water uptake change is most significant. According to the estimation shown in Figure 3, the amounts of MOF-303 needed to provide 3 L of water - the approximate amount necessary for a human daily intake[21] - are 33.2 and 65.8 kg for Niamey for January and July, respectively, and 86.2 and 151.5 kg for Lagos for

January and July, respectively. The isosteric heat of adsorption, q_{st}, of water-to-MOF-303 52 kJ/mol (or 2.9 kJ/g).[22] The values of q_{latent} for 3 L of water is 8.7 MJ. The values of solar irradiance energy for Niamey and Lagos are approximately 18 MJ/m^2 and 13 MJ/m^2, respectively,[23,24] requiring approximately 0.5 and 0.7 m^2 of surface area.

CONCLUSION

In this study, we have evaluated the amount of MOF required to collect sufficient amounts of water by analyzing the temperature and humidity fluctuations in two cities, Niamey and Lagos, with extremely varying weather conditions. Due to the water capturing characteristics of MOF-303, a favorable weather condition for collecting water shows high temperature fluctuations. In contrast to our initial prediction, the amount of water collected showed little dependence on relative humidity. This is due to MOF-303 reaching saturation after 40 % relative humidity. The higher temperature fluctuations in Niamey are more favorable for collecting water than the high relative humidity conditions in Lagos. The high temperature in Niamey also leads to larger solar energy which makes releasing the captured water easier as well. It should be noted that the amount of water collected is a rough estimate due to this simplifying assumption. In reality, the fluctuations in humidity and temperature during the day would affect the amount that can either be collected or released. Additionally, the water uptake isotherm data being used in this study reports water uptake at saturation, which does not show the kinetics of water adsorption. In real conditions, the kinetics of adsorption will play a significant part as water uptake may not reach saturation depending on the device design and MOF contact time with air.

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