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CASE STUDY

Sustainable water captured from air for fulfilling the SDGs

Yoshiyasu Takefuji[1]

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Abstract

Background In the event of a natural disaster, water is often unavailable. Natural disasters often prevent the existing water infrastructure from functioning to supply water to citizens. Existing water systems are also vulnerable to poisoning such as terrorism and can be destroyed in war because they are centralized infrastructure systems. In the U.S.A, a huge investment of $50 billion is required just to improve infrastructure for drinking water, wastewater, and stormwater. Scope and Approach This paper introduces state-of-the-art technologies for sustainable water harvesting to prepare for natural or human-induced disasters to fulfill the Sustainable Development Goals (SDGs). A literature review was conducted on drinking water technology. Key findings The latest water-harvesting technology uses Metal–Organic Framework materials. The properties of MOFs allow us to survive and efficiently harvest water from air. We can create a sustainable society with MOF materials where the society will become resilient to natural and human-induced disasters for fulfilling the SDGs. Conclusions This paper will show that MOFs play an important role in enhancing urban water sustainability and resilience with the most economical and ecological engineering technology.

Keywords Water harvesting · Sustainable water · Resilient water · Water from air · Metal–organic framework (MOF)

1 Introduction

In times of disaster, it is of utmost importance to ensure reliable infrastructure for the provision of basic resources such as food, water, energy, shelter, medical services, and access to information and communication technologies (Chester, 2021).

The performance and hydration characteristics of nanopowders, such as clay powder, nano-silica, and nanoplastic waste, were examined for their potential use in ecology (Abdelzaher, 2022a; Abdelzaher, 2022b; Abdelzaher, 2023). The addition of 5% clay bricks powder to white cement pastes can improve their performance, especially their compressive strength and microstructure (Abdelzaher, 2022a). The addition of nano-silica to white cement can improve its performance, but the maximum content should not

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✉ Yoshiyasu Takefuji
takefuji@keio.jp

[1] Faculty of Data Science, Musashino University, 3-3-3 Ariake Koto-ku, Tokyo 135-8181, Japan

exceed 5% to avoid negative effects (Abdelzaher, 2022b). The COVID-19 pandemic has led to a significant increase in plastic waste, including food packaging, masks, gloves, and personal protective equipment (PPE). To address this problem, a new type of eco-cement has been developed that partially substitutes ultrafine demolition waste and nanoplastic waste for white cement. This new cement has enhanced mechanical strength and better workability, making it both economical and environmentally beneficial. The decreased construction costs and improved raw material sustainability of this new cement make it a promising solution for the future of construction (Abdelzaher, 2023).

There are two main types of drinking water systems: centralized and distributed. Centralized drinking water systems deliver water to homes and businesses through a network of pipes, while distributed systems rely on individual systems.

This research explores the properties of nanopowder such as Metal-Organic Frameworks (MOFs), which are promising new materials for water purification. MOFs are lightweight and portable, making them ideal for use in disaster relief efforts and in economically centralized drinking water systems. By removing contaminants from water, MOFs can help reduce water treatment costs and meet the growing demand for clean drinking water.

Conventional centralized water systems require water pipes to be laid in urban areas, while decentralized water systems do not. The cost of re-laying water pipes due to age-related deterioration has become a major issue. According to the American Water Works Association (AWWA), replacing all aging drinking water piping in the U.S.A alone would require an investment of more than $1 trillion over 25 years (Congress, 2022). In the U.S.A, a huge investment of $50 billion is needed just to improve infrastructure for drinking water, wastewater, and stormwater based on the centralized water system (EPA, 2023).

According to EPA (EPA, 2023), the following budgets will be spent just for safe drinking water in the U.S.A: (1) $11.7 billion to the drinking water state revolving fund (SRF), (2) $15 billion to the drinking water SRF for lead service line replacement, (3) $4 billion to the drinking water SRF for emerging contaminants, and (4) $5 billion to water infrastructure improvements for the nation (WIIN) grants to address emerging contaminants.

Haldar et al. demonstrated the efficacy of MOFs in terms of both water efficiency and water safety (Haldar, 2020). MOFs are promising materials for the removal of arsenic, fluoride, and iron from drinking water. This review article discusses the recent developments in MOF-based water purification technologies.

Distributed drinking water systems are a critical technology for providing safe and reliable access to water in developing and underdeveloped countries, both in times of peace and in times of crisis (Peter-Varbanets, 2009).

This paper will focus on distributed drinking water with the most economical and ecological engineering technology for fulfilling the SDGs (Sustainable Development Goals).

Water is a food as defined in section 20 L(f) of the US Federal Food, Drug, and Cosmetic Act (2 L USC 32 L(f) (US FDA, 2022). Water should be declared on the label as an ingredient when used as an ingredient of a fabricated food, including water used to reconstitute concentrated or dried ingredients (US FDA, 2022).

According to the WHO (World Health Organization), water is a major food input from primary production through all stages in the food value chain to consumption (WHO, 2019). In other words, we cannot live without water.

Water is considered an essential nutrient because the body cannot produce enough water itself, by metabolism of food, to fulfil its need (Bourne, 2007). Water, a vital nutrient, has numerous critical roles in the human body (Jéquier, 2010). Water, an essential nutrient, is often ignored in reports of dietary surveys and nutrition (Rush, 2013). Without sufficient fluid in the body, dehydration can occur (Jéquier, 2010). It can be life threatening, especially to babies, children, and the elderly.

Up to 60% of the adult human body is water and newborn babies have the most at about 78% (USGS, 2019). Water has a number of functions that are essential for our survival: (1) it is a vital nutrient for all cells and acts as a building block; (2) it regulates internal temperature through sweating and breathing; (3) the carbohydrates and proteins that our bodies use as food are stored in the bloodstream; and (4) it is a source of energy for the body. 4) it helps to flush waste products, mainly through urination, (5) it acts as a shock absorber for the brain, spinal cord, and fetus, (6) it forms saliva, and (7) it lubricates joints (USGS, 2019).

Water is important to the human body, but water is often unavailable during natural disasters. Therefore, this paper focuses on sustainable and resilient drinking water supply in disasters.

In the conventional water supply system, rainwater stored in dams and lakes is treated and disinfected at water purification plants. The purified water is stored at a higher elevation or pumped to increase the water pressure. And then, drinkable water is distributed to each household. Wastewater or sewage in each household is transported to a sewage treatment plant where it is either recycled or discharged into the river or ocean.

We must know the important fact that the existing water infrastructure is vulnerable to earthquakes because of the extensive network of above and below ground pipelines, pump stations, tanks, administrative and laboratory buildings, reservoirs, chemical storage, and treatment facilities (EPA, 2018).

The centralized water infrastructure is also vulnerable to typhoons, floods, drought, and freezing (OECD, 2021). The conventional water infrastructure is also vulnerable to human-induced disasters including poisoning by terrorism (Shandler et al., 2021; Maiolo et al., 2018).

Although we're in the midst of a COVID-19 pandemic in the world, contamination by SARS-CoV-2 coronavirus in water and wastewater systems poses a new problem for us (Bogler et al., 2020; Tran et al., 2021; Fuschi, 2021). Decentralized drinking water can be generated with the proposed MOF (Metal–Organic Framework) technology. However, cost-effective decentralized technology is needed for wastewater management.

With the current centralized water supply system, it is difficult to manage a safe water supply. Centralized systems are responsible for the vulnerabilities of water infrastructure, including earthquakes, typhoons, floods, droughts, freezing, and poisoning drinking water by terrorism (Shandler et al., 2021; Maiolo et al., 2018).

This paper introduces the state-of-the-art decentralized system and technology in order to mitigate the vulnerabilities of the conventional water system. The water technology is called water alchemy.

According to the proceeding of US army (Richard et al., 2009), in fiscal year 2007 (FY07), the Army Environmental Requirements and Technology Assessments (AERTA) process identified sustainable water use as its top-ranked priority. A user need was identified for the capability to recycle/reuse available water through a variety of innovative ideas and practical applications within buildings and processes including cascade recycling and water harvesting, with the ultimate purpose of increasing available supply (Richard et al., 2009).

Hanikel et al. reviewed on MOF water harvesting (Hanikel, 2020). They reviewed the latest progress in MOFs for extracting water from air and designing atmospheric water harvesters. Productivity and stability of MOF water harvesters should be monitored for several months. Protection against environmental contamination may increase longevity and comply with health regulations. A detailed assessment of maintenance costs is necessary to demonstrate readiness for long-term field operation and potential to address the global water shortage crisis.

Liu et al. concluded on MOF water harvesting that MOFs are promising materials for energy-efficient applications in humidity control and heat reallocation. They have high working capacities and can absorb and release water vapor at low relative pressures and moderate temperatures. Future research should focus on improving the stability of MOFs in humid conditions and cyclic operation, as well as developing new applications for MOFs.

Zaman et al. concluded that water splitting is a pollution-free way to produce hydrogen (Zaman, 2021). Metal-organic frameworks (MOFs) are multifunctional resources with high surface areas, tunable porosity, and easy modification. MOFs and their derived materials are used as electrocatalysts for water splitting. Their review summarized the advancement in MOF materials and their role in water splitting.

2 Harvesting water from air

Atmospheric Water Harvesting is a new technology harvesting water from air (Xingyi et al., 2020). Metal-Organic frameworks (MOFs) play a key role in harvesting water from air. MOFs can capture and release water using only sunlight and require no additional energy. Water can be collected in 24-hour cycle of low and high temperatures to produce water in MOFs.

If the lower critical solution temperature (LCST) is higher than the current temperature (T), then MOFs can capture water from air. If $LCST < T$, then MOFs can release captured water. LCST is determined by the characteristics of the MOF.

MOFs are organic-inorganic hybrid crystalline porous materials that consist of a regular array of positively charged metal ions surrounded by organic 'linker' molecules (Michael, 2009). The metal ions form nodes that bind the arms of the linkers together to form a repeating, cage-like structure. Due to this hollow structure, MOFs have an extraordinarily large internal surface area (Michael, 2009).

Pioneered in the late 1990s "Design and synthesis of an exceptionally stable and highly porous metal-organic framework" by Prof. Omar Yaghi at UC Berkeley, MOFs have become a rapidly growing research field (Michael, 2009). Their device is capable of harvesting 2.8 L of water per kilogram of MOF daily at relative humidity levels as low as 20% (Hyunho et al., 2017). The same team can produce one liter per kilogram of MOF per day at relative humidity levels as low as 10%.

In 2021, under humid conditions, a polymer-MOF lab prototype yielded 17 L (4.5 gal) of water per kg of MOF per day without added energy (Yilmaz et al., 2020).

Alexandros reported that moisture harvesting rate is based on the order of 10 L/day/kg of MOF-801.

Zirconium-based MOF is at $160 per kilogram, while aluminum-based MOF costs $3 per kilogram as of 2019 (Julianne, 2019).

MOFs have a very high porosity and surface area, which can be as large as 7,800 m^2/g. In other words, the surface area of one gram of MOF covers an entire soccer field (Prometheanparticles, 2021).

3 Discussions

Khan et al. discussed the synthesis methods of MOFs and MOFs-based heterostructures, their applications in photocatalytic degradation of pollutants, and strategies to improve their photocatalytic performance (Khan, 2022). Fast recombination of electron-hole pairs is a challenge for effective photocatalysis. Future studies should focus on improving the overall characteristics of MOFs and MOFs-based heterostructures as visible light active materials (Khan, 2022).

A stable and pure-phase nanocomposite can promote the growth of secondary crystals that are less stable and difficult to synthesize, but offer more functionalities (Poonia, 2023). The thermal and chemical stability of MOFs primarily in water still need to be explored. These stability parameters get affected by the extension of pore sizes. The presence of a type of porosity significantly affects the diffusion and approachability of the bulky molecule to actively adsorb on the surface. Subsequently, the generation of pore size regimes in MOFs should be in accordance with the targeted molecule. The wide-scale synthesis of MOFs-based hierarchical composites are rare, and the researchers are still on the way to going for cost-effective and industrial-scale applications.

The application of MOFs as microbial fuel cell (MFC) electrode materials is still far from being fully understood because the vast quantities of MOFs consist of inactive organic ligands, and they are electrical insulating (Zhang, 2023). It is currently possible to improve the electrical conductivity of MOFs by using carbonization strategies.

The application of MOF materials in large-scale water processing is still a challenge due to their high cost (Kaur, 2023). Additionally, more research is needed to explore water-stable MOFs for potential functional applications. The effects of radiation on the strength of MOFs have not been well-studied, and more information would be valuable. Additionally, many MOFs are made from expensive ligands, so more economical options are needed. The long-term durability of MOFs and their recyclability are also challenges, as they could lead to secondary pollution. MOFs that are resistant to structural degradation caused by moisture, oxidants/reductants, acids/bases, and radiation are promising candidates for future research. Overall, further research is needed to promote the potential of MOFs for practical applications.

Metal-organic frameworks (MOFs) are promising materials for water harvesting from air. The MOFs technology can mitigate the vulnerabilities of the current water infrastructure by converting centralized system to decentralized system. MOFs not only can harvest water but also extract pesticides in food samples.

According to the U.S. National Academies of Sciences, Engineering, and Medicine, an adequate daily fluid intake is: about 3.7 L of fluids a day for men while 2.7 L water a day for women is needed (Mayoclinic, 2020). In other words, the inexpensive MOF technology can be used in times of disaster and can be feasible in daily life without the current water infrastructure.

MOFs may be able to transform the current centralized water system into a decentralized system, reducing the vulnerability of the system to natural and human-induced disasters.

MOFs technology has the potential to reduce COVID-19 virus contamination in water and wastewater systems because of its decentralized infrastructure.

Tran et al. explain how the virus is transmitted through centralized wastewater systems (Tran, 2021; Fuschi, 2021). Virus-laden aerosols can be created as waste is discharged. In centralized drainage systems, aerosols are transmitted to neighboring apartments and houses through deteriorated U-traps. As long as drainage systems are shared, the

COVID-19 virus will remain airborne, so centralized systems provide more opportunities to spread the virus.

In other words, a decentralized water supply is less likely to be infected with COVID-19 than the current centralized water and wastewater systems.

In decentralized water system, our society will be more sustainable and resilient to natural disasters including earthquakes, typhoons, floods, drought, freezing, and COVID-19. However, we don't have cost-effective technology for decentralized wastewater management for mitigating the pandemic (Tran, 2021; Fuschi, 2021).

Decentralized water systems can minimize the casualties caused by terrorist contamination of drinking water (Shandler 2021).

4 Conclusions

The properties of MOFs (Metal-Organic Frameworks) allow us to efficiently harvest water from air. A polymer-MOF lab prototype yielding 17 L of water per kg of MOF per day may allow people to live without the current water infrastructure in disasters. Zirconium-based MOF is at $160 per kilogram, while aluminum-based MOF costs $3 per kilogram as of 2019. MOFs may be able to transform the current centralized water system into a decentralized system, reducing the vulnerability of the system to natural and human-induced disasters. A decentralized wastewater system is less likely to be infected with COVID-19 than the current centralized wastewater system. However, the further investigation is needed in the economical decentralized wastewater system. A decentralized water supply system with MOFs is also resistant to terrorism. This paper presented novel implications for disaster relief and economically decentralized drinking water systems with MOFs.

Implications to theory and practice:

- Theory: The use of MOFs for water purification and water harvesting has the potential to revolutionize the way we think about water treatment and supply. MOFs are highly porous materials with a large surface area, which makes them ideal for capturing and removing contaminants from water. They are also lightweight and portable, making them well-suited for use in disaster relief efforts and in remote areas.
- Practice: The development of MOF-based water purification and water harvesting technologies could have a significant impact on the lives of millions of people around the world. By providing access to safe and clean water, these technologies could help to improve public health, reduce water-borne diseases, and boost economic development.

Here are some specific examples of how MOF-based water purification and water harvesting technologies could be used in practice:

- Water purification: MOFs could be used to remove a variety of contaminants from water, including arsenic, fluoride, and heavy metals. This would make water safer to drink and would also help to protect the environment.
- Water harvesting: MOFs could be used to harvest water from the air, even in arid regions. This would provide a reliable source of water for drinking, irrigation, and industrial use.
- Disaster relief: MOF-based water purification and water harvesting technologies could be used to provide safe and clean water in the aftermath of natural disasters.

This would help to prevent the spread of disease and would also help to improve the overall health and well-being of affected communities.

Overall, the use of MOFs for water purification and water harvesting has the potential to make a significant positive impact on the lives of millions of people around the world. These technologies are still in their early stages of development, but they have the potential to revolutionize the way we think about water treatment and supply.

Key lessons learnt:

- The use of MOFs for water purification and water harvesting is a promising new technology with the potential to revolutionize the way we think about water treatment and supply.
- MOFs are highly porous materials with a large surface area, which makes them ideal for capturing and removing contaminants from water.
- MOFs are also lightweight and portable, making them well-suited for use in disaster relief efforts and in remote areas.
- The development of MOF-based water purification and water harvesting technologies could have a significant impact on the lives of millions of people around the world.
- By providing access to safe and clean water, these technologies could help to improve public health, reduce water-borne diseases, and boost economic development.

Additional lessons:

- The centralized water supply system is vulnerable to a variety of natural and man-made disasters.
- Decentralized drinking water systems can be more resilient to disasters and can provide a more sustainable source of water.
- MOF-based water purification and water harvesting technologies have the potential to provide safe and clean water in the aftermath of disasters.
- The development of MOF-based water purification and water harvesting technologies is still in its early stages, but these technologies have the potential to revolutionize the way we think about water treatment and supply.

Limitation of this research:

- The research is still in its early stages, and more research is needed to fully understand the potential of MOFs for water purification and water harvesting.
- The cost of MOF-based water purification and water harvesting technologies is still high, and further research is needed to reduce the cost of these technologies.
- The stability of MOFs in harsh environments is still a concern, and further research is needed to improve the stability of these materials.
- The toxicity of MOFs is still not fully understood, and further research is needed to assess the safety of these materials.

Despite these limitations, the research on MOFs for water purification and water harvesting is promising, and these technologies have the potential to make a significant positive impact on the lives of millions of people around the world.

Additional limitations that can be mentioned:

- The research only focuses on the use of MOFs for water purification and water harvesting. Other applications of MOFs, such as in the production of hydrogen and the removal of pollutants from air, were not discussed.
- The research does not consider the environmental impact of MOF production and use. Further research is needed to assess the environmental sustainability of these technologies.
- The research does not consider the social impact of MOF-based water purification and water harvesting technologies. Further research is needed to assess how these technologies will impact people's lives and livelihoods.

Overall, the research on MOFs for water purification and water harvesting is promising, but there are still some limitations that need to be addressed. Further research is needed to fully understand the potential of these technologies and to ensure that they are safe and sustainable.

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Declarations

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