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Article

A comparative study of the potentials of Oman and UAE in condensate water recovery

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Abstract: Freshwater is essential for everyday activities including drinking, irrigation, farming and many industrial processes. However, freshwater is less than 1% of the total water resources in the planet and, therefore, it is considered a very valuable commodity. Limited resources and growing needs for freshwater triggered global exploration for alternatives to produce enough freshwater for human needs. Today's most widely used methods to produce freshwater is desalination. However, critical appraisal of the desalination procedures raised the alarm about sustainability of desalination and indicated that significant research is needed to develop alternative green resources of freshwater. Countries in the Gulf area such as Oman and UAE experience hot and humid climates and use air-conditioning units to achieve acceptable comfort levels and create a healthier indoor environment. The cooling process release a large amount of condensate water through cooling coils. This amount of water is usually considered as a problem rather than opportunity and, thus, is wasted into municipal sewerage systems via a system of drainage pipes. This alternative source can be utilized in various drainage, irrigation, and cooling applications to reduce the use of considerable amount of municipal potable water. This source not only takes part in controlling the water scarcity, but also in saving energy and to reducing the carbon footprint. This paper focus on highlighting the opportunities for Oman and UAE to utilize the condensate water from air-conditioning process, as a viable alternative source of green fresh water. It provides a comparison of the potentials of both countries to collect condensate water, based on meteorological data, location and climate. It was concluded that both countries have great potentials and opportunities to utilize this wasted resource.

Keywords: freshwater; condensate water; metrological data; air temperature; relative humidity; solar radiation; sunshine hours; Oman; UAE

1. Introduction

Water is considered one of the most important plentiful resources on earth but freshwater, which is needed for human everyday needs, is considered a rare commodity. Salty water covers three fourths of the globe's surface and, accounts for a massive 97% of all water resources on earth. Unfortunately, this salty water cannot be used in most activities such as drinking, irrigation, farming livestock and many industrial processes. Freshwater, on the other hand, is essential for human needs, but its amount is very limited, as it accounts for 3% of the total water on earth. Furthermore, the available freshwater is actually less than 1% of the total water resources in the planet, as about 70% of the existing freshwater is not readily available [1–4].

The World Health Organization (WHO) reported that only 2.1 billion people gained access to safely managed drinking water between 2000 and 2022 [5]. Accordingly, only one out of four people have access to safe drinking water, but three quarters of the world population do not.

In 2018, the Population Division of The United Nations reported that the world population is increasing and could approach ten billion by 2050, as can be seen in **Figure 1**. About half of the current world population lives in highly dense cities, particularly in developing countries with high demand of water. It is projected that the population of these countries will be more than two-thirds the world population in the next two decades, leading to further increase in the demand for fresh water [6].

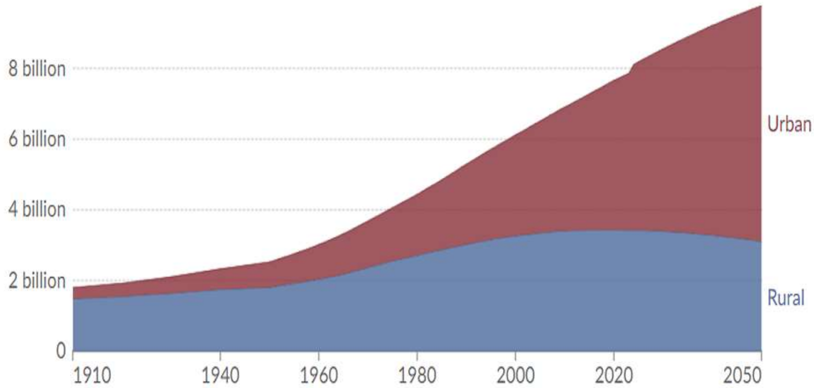

Figure 1. Projection of urban and rural population, to 2050 (UN Population Division).

As the global demand for freshwater is increasing, many countries are facing severe shortage of freshwater supply or even encountering water stress [7]. The concept of water stress is widely used to present the case when demand for water excessively exceeds available amount of water or when water usage is restricted due to poor water quality. Many countries in the Middle East, Gulf region and North Africa are facing water stress [8,9]. These countries confront numerous issues including water shortages, unsustainable water consumption and over exploitation of already limited groundwater [10]. This situation is not expected to get any better because many of these countries are projected to become even drier, as one of the consequences of global warming.

Several countries in the Gulf area, including Oman and UAE (The United Arab Emirates) are among the countries with limited water resources and facing severe shortage of fresh [11–13]. Therefore, managing their water resources and exploring new methods and alternatives to produce enough freshwater are crucial for these two countries to achieve water security. In another word, to cover the gap between supply and demand of freshwater.

Today's most widely used methods to produce freshwater is desalination. However, Badr [14] scrutinized desalination processes and provided critical appraisal of its sustainability from input to output. The author raised the alarm and recommended that significant research is needed to develop alternative green resources of freshwater.

Capturing condensate water from air is an interesting alternative method that is gaining more attention from researchers around the globe. There are several techniques to capture condensate water, either as the main product such as in direct air capture of moisture processes (DAC) or as by-product as in condensate water from air-conditioning systems. The DAC processes include variety of different methods.

Broadly there is two main types including fog water collection and dew water collection [15–18]. Further details of each DAC process is given elsewhere [18]. This research focus on condensate water produced as by-product from air-conditioning systems, as a viable alternative source of green fresh water. The aim is to investigate the opportunities for Oman and UAE environmentally and economically. A case study of a typical residential house is used to highlight the potential,

2. Geography and climate

Geographically, Oman and UAE are located on the southeastern coast of the Arabian Peninsula in Western Asia. Oman lies between latitudes 26°12′ and 17°1′ North, and longitudes 52° and 60° East. UAE share 450 km southeast border with Oman. It is located between latitudes 25°47′ and 24°12′ North, and longitudes between 51° and 56°25′ East [19]. Summary of the location and climate zone of Oman and UAE is given in **Table 1**.

Oman and UAE are in the arid tropical zone, as can be seen **Figure 2**, which shows that the climate of Oman and UAE can be classified as BWh climate [20]. It is described as subtropical dry, hot desert climate with low annual rainfall, very high temperatures in summer and can be as high as 48 °C.

Table 1. Location and climate zone of Oman and UAE [19].

	Oman	**United Arab Emirates**
Climate zone	Subtropics to tropics	Subtropics to tropics
Latitudes	26°12′ N to 17°1′ N	25°47′ N to 24°12′ N
Longitude	52° to 60° East	51° to 56°25′
Distance to equator	1900–2900 km	2700–2900 km

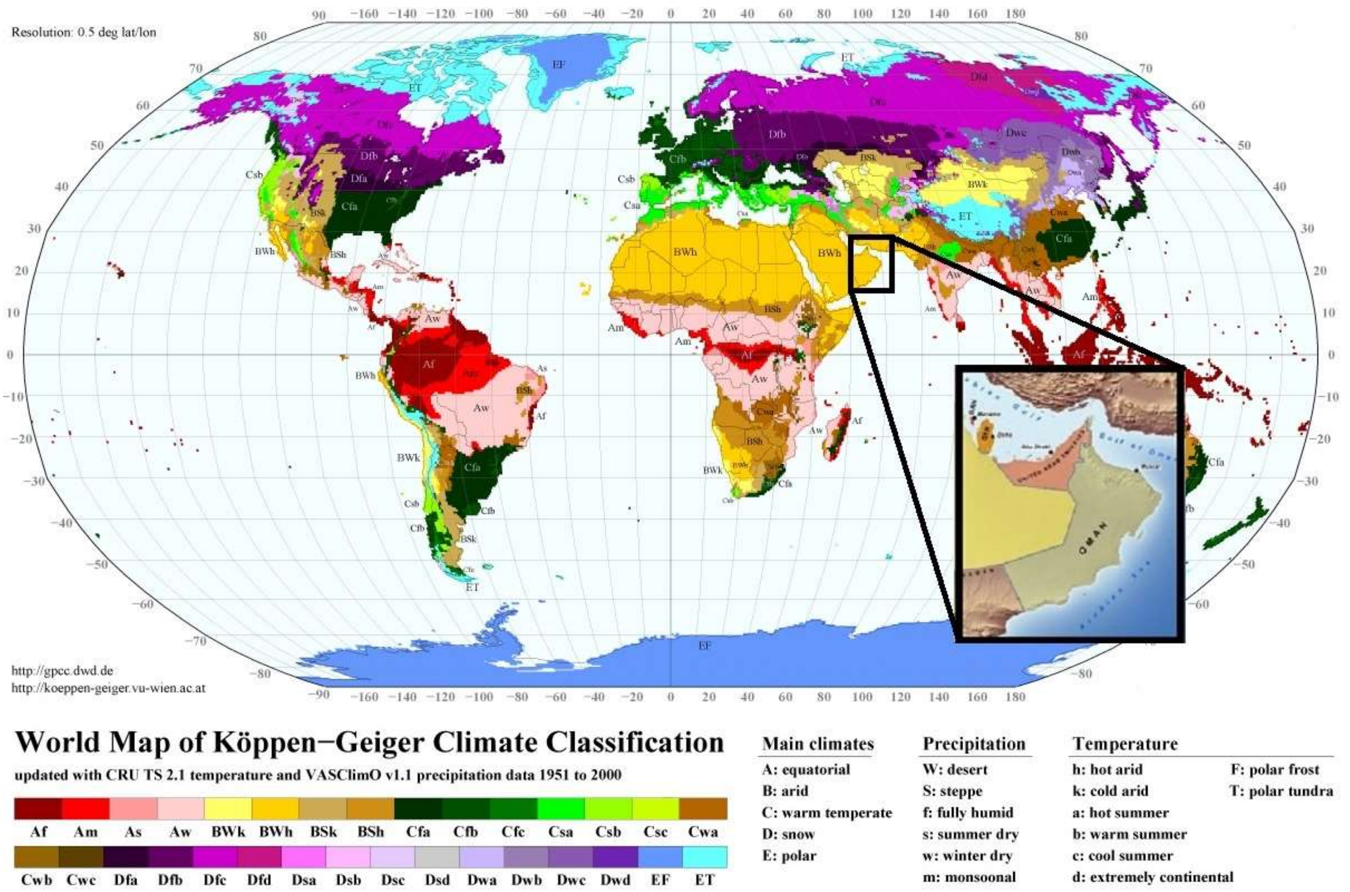

Figure 2. Location of Oman and Koppen-Geiger climate classification map, adapted from [20].

3. Water resources in Oman and UAE

The main water resources in Oman include 1400 MCM (Million Cubic Metres) of underground and surface, 440 MCM from desalination of seawater and 100 MCM from wastewater treatment. Representing 70%, 23% and 5% of annual freshwater production per year, respectively. In addition, there is a small amount of fog harvesting water [21].

According to the UAE state of environment report 2020, UAE produces annually 2.52 BCM (Billion Cubic Metres) of underground water, 2.02 BCM of desalinated seawater and, 0.53 BCM of treated wastewater used. Thus, the main water resources in UAE includes groundwater (50%), desalinated water (40%) and treated wastewater (10%).

In their effort to reduce the demand of energy environmental impact of desalinations, both countries are increasingly using solar energy to power Distillation plants. This subject is out of scope of the current paper and is addressed by many researchers elsewhere [22–23]. It has been mentioned earlier that the author, Badr [14], critically appraised the sustainability of desalination and highlighted the pressing need for alternative green resources of freshwater.

4. Analysis of meteorological data

The geographical location determines the climate of a country, city, district, or a property. Tropical and humid regions have a high potential for condensate recovery. The amount of condensate water captured from the moisture in the atmosphere during the operation of an air-cooling unit is directly proportional to the value of humidity. The potential decreases as the humidity decrease and, thus, places with low humidity levels have low potentials and might not be suitable for condensate collection if humidity drops under certain limit. Therefore, meteorological data should be considered and analysed to decide on the feasibility of using this technique as an alternative method of collecting condensate water in a specific location, city or country.

The air temperature and its humidity are interrelated. The hotter the air, the more water it can accommodate, as hot air expands and offer more space for the moisture. For example, when the air temperature is 30, a cubic meter of air could have 26 grams of moisture. Five more degrees will facilitate about 3 more grams of moisture, that represents an increase of more than 10%. In fact, the term absolute humidity is rarely used. Rather, the term relative humidity (RH%) is commonly used, which gives the air humidity as a percentage value relative to the temperature-dependent maximum value. Therefore, information about the air temperature is vital in predicting the potential of collecting condensate water.

The amount of the by-product condensate water collected during a full cycle of one day depends also on two more factors. The first is the difference between the hot atmospheric temperature outside the property and the required cool temperature inside the closed place. The second is the number of operating hours of the cooling unit [24]. the longer the exposure to sunshine the longer the cooling unit are required to work to maintain the same level of comfort inside a specific property. The number of sunshine hours per day is more in summer than winter and varies according to the location and geography of a place. Therefore, the potential of harvesting the by-product condensate water from cooling systems is greater for locations exposed to longer hours of sunshine.

Oman and UAE have long coastlines with high relative humidity due to their geographical location. They are also exposed to a very high solar radiation and long hours of sunshine during the day, particularly in summer months. The meteorological data for these two countries is analysed in the following section around the year (annual values) and within the cycle of one day (daily) to appreciate the potential of harvesting condensate water from cooling units, in each country.

Table 2 shows a summary of average annual values of the most significant meteorological parameters for Oman and UAE, including daytime maximum temperature, daily low temperature, humidity, precipitation, rain days and hours of sunshine (World Meteorological Organisation).

Table 2. Average annual values of meteorological data, in Oman and UAE.

Average annual values	Oman	United Arab Emirates
Daytime maximum temperature	34.10 °C	34.40 °C
Daily low temperature	23.10 °C	23.10 °C
Humidity	65 %	61 %

Table 2. (*Continued*).

Average annual values	Oman	United Arab Emirates
Precipitation	117 mm	77 mm
Rain days	10.8 days	12.0 days
Hours of sunshine	2263 h	3066 h

4.1. Air temperature

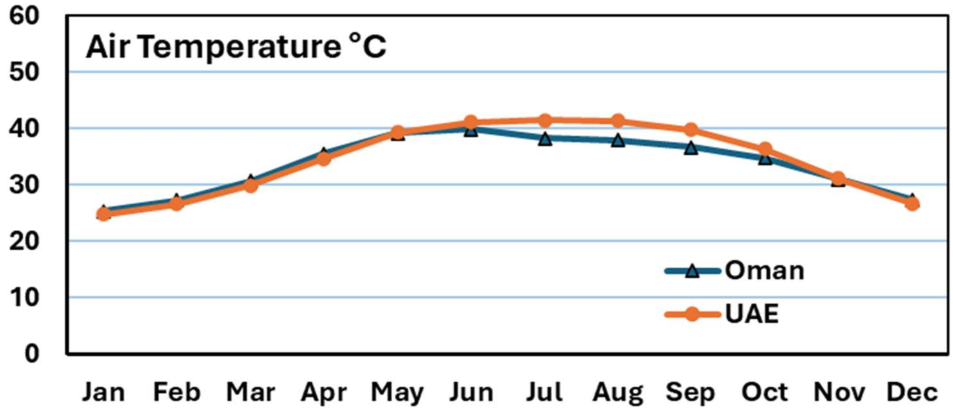

Figure 3. Daily maximum temperatures in a full year, in Oman and UAE.

It has been shown earlier that Oman and UAE shares borders, location and are in the same climate zone. They are both classified as BWh climate, which is described as subtropical dry, hot desert climate with low annual rainfall. It is, therefore, not surprisingly that the curves of the daily maximum temperatures are almost the same for a full year, as can be seen from **Figure 3**. The highest daytime temperature in Oman is about 41 °C and it is recorded in June, which is the hottest month in Oman. Although the maximum temperature in the UAE is the same as that of Oman (41 °C) it occurs on several months from June to August, inclusive.

The coldest month in both countries is January. The recorded coldest temperature in both counties is almost the same of about 25 °C.

The comfortable temperature for most people is between 24 °C and 26 °C, therefore, the common operating temperature for air-conditioning units is 24 °C. For a viable collection of condensate water there should be a significant difference between the temperature of the outside air and the operating temperature of air-conditioning units. Studying **Figure 3** reveals that the method would be effective for more than 6 months of the year from April to September. The potential decreases either side of these months in March and October; and might be ceased from November to January, inclusive.

Judging by the results of the analysis of the daily maximum temperatures in a full year, it could be suggested that both Oman and UAE have the same potential for collecting condensate water as by-product from air-conditioning units, provided that all other variables are similar.

4.2. Air humidity

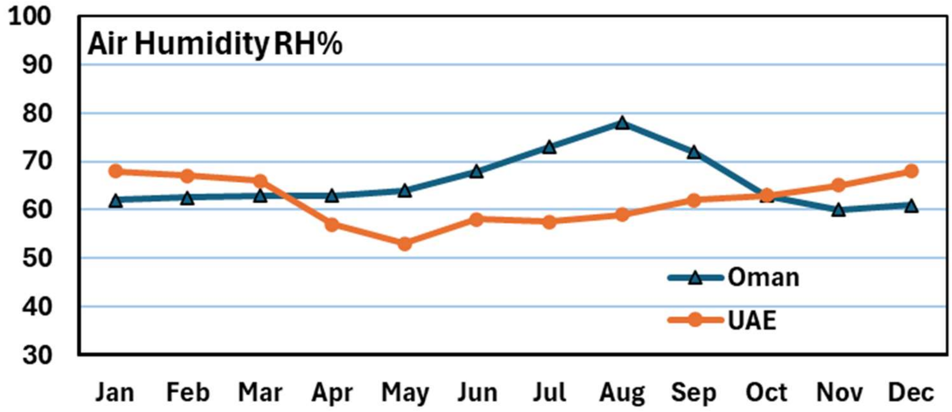

Figure 4. Daily maximum RH% in a full year, in Oman and UAE.

The relative humidity (RH%) is a commonly used expression that gives air humidity as a percentage value relative to the temperature-dependent maximum value. **Figure 4** presents the annual average relative humidity RH% in both countries. The RH% in both countries is very high and almost flat around the year with a band of less than 20%. However, the RH% in the UAE is about 10% less than that of Oman. The latter has an average RH% of about 66% compared to 62% for the UAE. Oman has a minimum value of 60% and a maximum of 78%. The corresponding values in the UAE are 53% and 68%. The higher RH% in Oman indicates that the potential for collecting the by-product condensate water is slightly better in Oman than in the UAE.

4.3. Daily sunshine hours

Combining the outcome of the results of the analysis of the daily maximum temperatures and RH% in a full year for Oman and UAE, both countries have great potentials for collecting condensate water as by-product from air-conditioning units. This is attributed to the fact that Oman and UAE have experience high temperatures and high RH% around the year due to their geographical location and climate.

In addition to the high air temperature and RH%, Oman and UAE are also exposed to very high solar radiation and long hours of sunshine during the day, particularly in summer months. As a result, the air-conditioners will be operating longer periods during summer days. The number of sunshine hours per day in Oman and UAE is plotted in **Figure 5**.

The actual amount of condensate water that could be collected during a full cycle of one day depends on the operating hours of the cooling unit [24].

Once again, with more than 3,000 hours of sunshine per year, the UAE comes on top for potential air-conditioning operating hours. Most days in the UAE has more than 8 hours of sunshine with a maximum of 9.9 hours recorded in June. Although the average hours of sunshine in Oman looks inferior to those in the UAE, they are still high with an average of 6.6 hours and a maximum of 8.5 hours. The annual value is a decent total of more than 2200 hours of sunshine per year.

The daily and total hours of sunshine in Oman and UAE indicate great potential for both countries to get huge quantities of collected condensate water due to the long operating hours of air-conditioners. However, once again, the longer operation hours indicates that the potential in the UAE is higher.

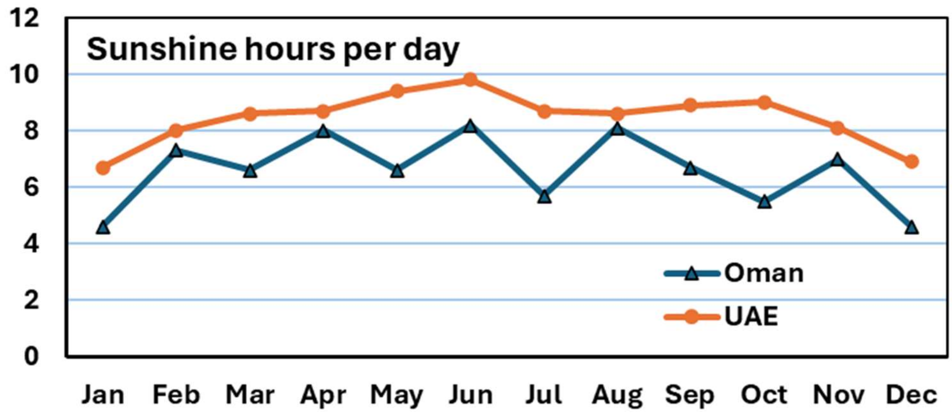

Figure 5. Sunshine hours per day, in Oman and UAE.

5. Condensate production

Most air-conditioning units are designed to not only cool the air but also to dehumidify it as well. In fact, some air-conditioners are primarily designed as dehumidifiers or make the dehumidification mode the default mode of operation of air-conditioners. Furthermore, some air-conditioners are designed with extra features that allow users to adjust the levels of dehumidification and cooling, separately.

During the cooling process, the hot air passes over the cooling coils of an air-conditioner, the temperature of the air is lowered below its dew point, causing moisture in the air to condensate on the coils. Lowering the humidity level in the air by removing excessive moisture improves the comfort level and creates a healthier indoor environment by preventing bug growth. However, condensate water is naturally produced as a by-product of the of an air-conditioning process.

Various types of air-conditioning units (AC) are used for cooling and conditioning domestic and commercial buildings. These are Window AC, Split AC, Chiller based Air Handling Units (AHUs), Fan Coil Units (FCUs). These machines generate considerable amounts of condensate water during cooling and dehumidification process at the cooling coil [10]. However, Split AC is the most common type used in Oman and UAE for residential buildings and small commercial enterprises.

Regardless of the type of the air-conditioner, the by-product condensate water has the potential to be a valuable alternative source of freshwater. It can be utilized in various drainage, irrigation, and cooling applications to reduce the use of similar amounts of municipal potable water. This source not only takes part in controlling the water scarcity, but also in saving energy and to reducing the carbon footprint.

6. Condensate production rates

The quantity and quality of recovered condensate from outdoor air are influenced by parameters such as climate zone and associated climate parameters, the type of building, how it is used, and the volume of the supply air. In general, these factors could be grouped in four main categories including but not limited to:

- Installed air-conditioner: Type, capacity, and efficiency.
- Outside air parameters: Air temperature, humidity, and sunshine hours per day.
- Building parameters: Building type, design, area, personnel density, and usage.
- Indoor conditions: Fresh air volume, indoor temperature, and humidity.

Considering the factors affecting the recovery of AC condensate water, it is very difficult to predict the condensate rate of the collection prediction, due to the variability of each factor. However, the effect of each factor could be predicted assuming that the other variables are constant for a specific case or at one point of time. For example, for air-conditioners with similar power and efficiency, the main factor controlling the collection potential depends on the difference between the outside humidity and the desired one inside. Vice versa, the AC power and efficiency will be the main factors if the meteorological factors are constant.

Therefore, the potential of condensate recovery should be assessed on a case-by-case basis, including cases for whole countries, cases for specific regions, cases for particular property or facility.

In many of the cases reported in the literature, the amount of recovered condensate is sufficient to cover all or part of the water demand for plant watering, or toilet flushing [25]. There are cases in which the recovered amount of condensate water exceeded the water demand of the building [26]. In a full-scale experiment conducted by the University of Birmingham, in Alabama USA, the amount of condensate water was 55.27 million L recovered in 17 months. The collection rate was not constant over time, with the largest output of condensate water was collected in June and represented about 6.5% of the total water demand. The results provided encouraging indication of the great water-saving potential [27].

However, in all cases when air-conditioning is needed to mitigate hot temperature and humidity, the condensate water collected is a naturally by-product produced during the air-conditioning process, with no additional cost.

7. Quality of condensate water

Theoretically, the quality of the condensate water should be as pure as droplets of water condensate on leaves in the early mornings (**Figure 6**). However, due to the existence of metal, plastic and fabric parts and particles within any AC unit, there could be some contamination or pollution during the condensation process, collection, and transportation of the condensate water.

Several researchers conducted chemical analysis, physical tests, and bacterial tests on released drain-water collected from different types of cooling air-conditioner in experiments conducted around the world. Recently, Moosa et al. [11] reported that freshwater collected directly from air-cooling units as a byproduct was almost distilled water with very low electrical conductivity and a pH of about 7. They, therefore, concluded that the collected by-product condensate water is almost pure.

As would be expected, there could be a possibility of contamination with some types of bacteria because there are some types of bacteria that exist naturally in the moisture of the atmosphere. However, such contaminated water could be easily disinfected using solar disinfection by raising the water temperature above 60 ℃. Moosa et al. [11] recommend that the temperature of the contaminated water must reach a range of 60 °C to 65 °C to guarantee completion of the disinfection by solar energy.

Figure 6. Droplets of water condensate on leaves in the early mornings.

Uddin et al. [28] collected condensate water samples from different locations. After conducting a full analysis of the collected samples, they found that the collected condensate water was good for drinking according to WHO standard. Since using the condensate water has no potential risk for drinking it is will be safe and suitable for washing and other household purposes, irrigation, and fisheries purposes.

8. Applications of condensate water

Condensate water could be used directly in many applications without any treatment, including toilet flushing, landscaping, gardening, green roofs, water features, and roof ponds. It could also be utilized in several other applications with some sort of treatment. Furthermore, with proper treatment and disinfection it could even be used for drinking. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [29] conducted a study to investigate reusing condensate water for non-potable purposes and concluded that a typical office building could offer significant savings by using it in applications such as landscaping and irrigation.

The best choice of applications should be decided on the actual needs of the location where it is collected. However, any amount of condensate water used instead of using municipal potable water will have an equal value to the municipal water, in addition to the extra benefit of reducing the sewerage flow by the same amount of water.

Examples of applications for AC condensate water that could contribute to water security in Oman and UAE and minimize the dependence on municipal water include:

8.1. Applications without pre-treatment

8.1.1. Toilet flushing

Condensate water can be effectively utilized without any treatment in toilet flushing. However, it is suggested that condensate water could be mixed with suitable dye to distinguish it from potable water supplied to sinks, kitchens, and bath hubs in the same building [24,26].

8.1.2. Landscaping and gardening

Landscape and gardening irrigation is an ideal application to use condensate water effectively without any treatment. Gardens could be provided with self-watering systems including piping network connected to a storage tank that is supplied with condensate water. The quantity of condensate water produced in a specific building will probably be more than enough to provide the water required for gardening and the surrounding landscape in the same property.

8.1.3. Water features

Fountains and similar water features are similar applications to landscaping and gardening but would require less amount of condensate water, as the system works by circulating the same amount of water for a relatively longer time before the need to change or top-up. Therefore, these could be ideal for smaller buildings with low number of occupants and fewer air-conditioning units.

8.1.4. Green roofs

Green roofing is a nice landscaping and a habitat for birds. It also offers a cheap passive cooling system for the top floor of any facility. The quantity of condensate water produced in a specific building could be enough to provide the water required for its green roof. The main components of a green roof include root barrier layer, a growing medium, vegetation, a drainage layer and an irrigation system [30]. Similar to the application of gardening it could be provided with self-watering systems including piping network connected to a storage tank that is supplied with condensate water.

8.1.5. Roof ponds

Condensate water could be utilized in roof ponds to provide passive cooling system in the most effective way by using water as an ideal thermal mass. This application is particularly beneficial in places characterised with rare rainwater or hot dry environment. At night, the insulation is removed to expose the wate in the roof bond, so it loses significant amounts of heat by radiation to atmosphere [24].

8.2. Applications with little pre-treatment

8.2.1. Agriculture Irrigation

This application is similar to gardening irrigation but needs huge quantities of condensate water that could be collected from a city, district or several residential quarters. For edible crops, it may be a good idea to periodically analyse samples and pre-treat the condensate water before using in fruit and vegetable farms. For flowers and decoration plants, the condensate water could be used without pre-treatment.

8.2.2. Livestock farming

With little pre-treatment, condensate water could be used for livestock farming, including raising animals and birds. Animals could be raised for their meat, such cattle, sheep, goats, horses, buffalo, and camels. Similarly, it could be used for raising birds commercially or for domestic use for their meat or eggs, chickens, turkeys, ducks and geese.

8.3. Applications with pre-treatment

Drinking

Moosa et al. [11] reported that freshwater collected directly from air-cooling units as a byproduct has very low electrical conductivity and a pH of about 7 and, therefore, concluded that the collected by-product condensate water is almost pure. However, the collected water could be contaminated with some types of bacteria because that exist in the atmosphere. It is, thus, recommended to use solar disinfection by raising the water temperature to 65 °C to guarantee completion of the disinfection.

9. Conclusions

This study conducted a comparison between the potentials of Oman and UAE to utilize the condensate water from air-conditioners as a viable alternative source of green freshwater. Meteorological data, location and climate of both countries were used to investigate the potential of each country. The following conclusions could be made:

- Oman and UAE, have great potentials for collecting condensate water as a by-product from air-conditioning units, as both countries experience high temperatures and high RH% around the year due to their geographical location and climate.
- The relative humidity (RH%) in the UAE is about 6% less than that of Oman. The latter has an average RH% of about 66%, whereas the corresponding value in the UAE is 62%, indicating that the potential for collecting the by-product condensate water could be slightly higher in Oman than in the UAE.
- In addition to the high air temperature and RH%, Oman and UAE are also exposed to long hours of sunshine during the day, particularly in the UAE. As a result, the actual amount of condensate water that could be collected in the UAE could be more than that in Oman, due to longer operating hours of the cooling units.
- Considering all the analysed meteorological data, it could be suggested that both countries have similar great potentials for collecting condensate water from air-conditioners.
- Collecting condensate water in Oman and UAE will be effective for more than 6 months of the year from April to September. The potential decreases either side of these months in March and October; and might be ceased from November to January, inclusive.
- Any amount of condensate water produced in both countries and used instead of using municipal potable water will have an equal economical value to the municipal water, in addition to the extra environmental benefit of reducing the sewerage flow by the same amount of water in Oman and UAE.

10. Recommendations

For countries with great potential for collecting and using condensate water from air-conditioners and cooling systems, such as Oman and UAE, it is recommended to:

- Encourage private sector to investment in condensate water recovery and reuse systems, both at national and local facilities. The increases in water demand and high cost of wastewater treatment indicate that such investment could be very cost-effective.
- Propose, approve, and implement polices that require all new residential and commercial buildings that install certain number of air-conditioners or cooling systems to include a properly designed separate drainage systems to collect condensate water and reuse it within the facility until a national system is constructed.
- Invest in designing and construction of national system to collect reusable water resources, including rainwater and condensate waters among others.

Conflict of interest: The author declares no conflict of interest.

References

1. Badr A, Venables J. Towards a Sustainable Water Future. ICE Publishing, London, UK. 2021. doi: 10.1680/oicwe.65253
2. Kılıç Z. The importance of water and conscious use of water. International Journal of Hydrology. 2020; 4(5): 239–241. doi: 10.15406/ijh.2020.04.00250
3. El-Dessouky HT, Ettouney HM. Fundamentals of saltwater desalination. Elsevier Publishing. 2002.
4. Kalogirou S. Seawater desalination using renewable energy sources. Progress in Energy and Combustion Science. 2005; 31(3): 242–281. doi: 10.1016/j.pecs.2005.03.001
5. World Health Organization (WHO). The World Health Report. World Health Organization (WHO). 2024.
6. Ritchie H, Roser M. Urbanization; Our World in Data. Available online: https://ourworldindata.org/how-urban-is-the-world (accessed on 2 June 2024).
7. Tzanakakis VA, Paranychianakis NV, Angelakis AN. Water Supply and Water Scarcity. Water. 2020; 12(9): 2347. doi: 10.3390/w12092347
8. Khan SA, Badr A. Energy recovery through air-conditioning machine's condensate. International Journal of Engineering Research & Technology (IJERT). 2014; 3(6).
9. Sherif M, Liaqat MU, Baig F, et al. Water resources availability, sustainability and challenges in the GCC countries: An overview. Heliyon. 2023; 9(10): e20543. doi: 10.1016/j.heliyon.2023.e20543
10. Khan SA, Badr A. Recycling A/C chilled water condensate to reduce water scarcity in Oman. In:Towards a Sustainable Water Future: OICWE2020 Proceedings, London, UK, 2021; 171–187.
11. Moosa IS, Kazem HA, Al-Badi H, et al. Evaluation and analysis of freshwater from atmospheric moisture as byproduct of air-cooling units in Oman. Renewable Energy and Environmental Sustainability. 2021; 6: 19. doi: 10.1051/rees/2021016
12. Pless S, Torcellini P. Net-Zero Energy Buildings: A Classification System Based on Renewable Energy Supply Options. Office of Scientific and Technical Information (OSTI). 2010. doi: 10.2172/983417
13. Garde F, Lenoir A, Scognamiglio A, et al. Design of Net Zero Energy Buildings: Feedback from International Projects. Energy Procedia. 2014; 61: 995–998. doi: 10.1016/j.egypro.2014.11.1011
14. Badr A. Desalination sustainability-The need to think again. In: Towards a Sustainable Water Future: OICWE2020 Proceedings. 2021; 171–187.
15. Webber M, Aliyu A, Jin SH, et al. A techno-economic review of direct air capture of moisture processes: sustainable versus energy-intensive methods. International Journal of Environmental Science and Technology. 2024. doi: 10.1007/s13762-024-05720-7
16. Algarni S, Saleel CA, Mujeebu MA. Air-conditioning condensate recovery and applications—Current developments and

challenges ahead. Sustainable Cities and Society. 2018; 37: 263–274. doi: 10.1016/j.scs.2017.11.032
17. NanNan L, Li J. Prospects of Air Conditioning Condensate Recovery and Utilization Technology. IOP Conference Series: Earth and Environmental Science. 2021; 781(4): 042052. doi: 10.1088/1755-1315/781/4/042052
18. Okeyinka OM, Ogundipe OO, Oloke DA, Adesogan SO. Reclaimed Air-conditioner Condensate as Alternative Source of Water in Hot Humid Region. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE). 2021; 18(6):25–30. doi: 10.9790/1684-1806012530.
19. Wikipedia Geography of the United Arab Emirates Available online: https://en.wikipedia.org/wiki/Geography_of_the_United_Arab_Emirates. (accessed on 2 June 2024).
20. Kottek M, Grieser J, Beck C, et al. World Map of the Köppen-Geiger climate classification updated. Meteorol. Z. 2006; 15: 259-263. doi: 10.1127/0941-2948/2006/0130.
21. Water Resources in Oman. Water of the Middle East and North Africa. Country Report. Water. 2018. https://water.fanack.com/oman/water-resources-oman/
22. Chaichan MT, Kazem HA. Water solar distiller productivity enhancement using concentrating solar water heater and phase change material (PCM). Case Studies in Thermal Engineering. 2015; 5: 151–159. doi: 10.1016/j.csite.2015.03.009
23. Mousa H, Naser J, Gujarathi AM, et al. Experimental study and analysis of solar still desalination using phase change materials. Journal of Energy Storage. 2019; 26: 100959. doi: 10.1016/j.est.2019.100959
24. Lawrence T, Perry J, Dempsey P. Capturing condensate by retrofitting AHUs. ASHRAE Journal. 2010; 52(1): 48–54.
25. Jurga A, Pacak A, Pandelidis D, et al. Condensate as a water source in terrestrial and extra-terrestrial conditions. Water Resources and Industry. 2023; 29: 100196. doi: 10.1016/j.wri.2022.100196
26. Painter FI. Condensate harvesting from large dedicated outside air-handling units with heat recovery. Building Engineering. 2009; (115).
27. Deng X, Shen Y, Yang S, et al. Feasibility of condensate water recycle of split air handling unit in Chinese University buildings. Energy and Built Environment. 2024; 5(2): 309–315. doi: 10.1016/j.enbenv.2022.10.006
28. Uddin S, Omar A, Alam MA. Assessment of quantity and quality of condensate water from air-conditioners. In:Proc. 2nd International Conference on Water and Environmental Engineering (iCWEE2019) 19–22 Jan 2019, Dhaka, Bangladesh.
29. ASHARE. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Available online: https://www.ashrae.org/ (accessed on 2 June 2024).
30. Abdellatif M, Al-Shamma'a A. Review of sustainability in buildings. Sustainable Cities and Society. 2015; 14: 171–177. doi: 10.1016/j.scs.2014.09.002