

Use of condensed water from air conditioning equipment as a strategy to face the global scarcity of freshwater: a review

Uso de agua condensada de equipos de aire acondicionado como estrategia para enfrentar la escasez mundial de agua dulce: una revisión

Aproveitamento da água condensada dos equipamentos de ar condicionado como estratégia para enfrentar a escassez mundial de água doce: uma revisão

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Para citar este artículo:
Dalmora, A., Civeira, M., De Campos, S. & Hernández, H. (2023). Use of condensed water from air conditioning equipment as a strategy to face the global scarcity of freshwater: a review. *LADEE*, 3(2), 35–44. <https://doi.org/10.17981/ladee.03.02.2022.4>

Keywords: Condensed water recovery; water reuse; sustainable use of water; sustainable development

Palabras clave: Recuperación de agua condensada; reutilización del agua; uso sostenible del agua; desarrollo sostenible

Palavras-chave: Recuperação de água condensada; reúso de água; uso sustentável da água; desenvolvimento sustentável

Abstract

Introduction: The increase in the world's demand for water has become one of the most relevant topics on environmental sustainability and the conservation of water resources. As a result of the scarcity of potable water, processes such as the use of water through practices, techniques, and technologies for its efficient use have become essential for future generations. Among the possibilities for using water, air conditioning systems stand out, due to the formation of condensed water during operation. The world's population is increasingly concerned about environmental issues, showing that it is necessary to seek alternatives to recycle water, whether for use in gardening, sewage systems, washing sidewalks, and cars, among others. The present study carried out a review of primary articles published in the Scopus and Web of Science databases between the years 2013 to 2022. The terms used for the search were water reuse, condensed water, and air conditioning. **Objective:** The objective of this literature review was to reflect on the theme of reuse of condensation water from air conditioners, raise awareness and preserve, pointing to the waste of water from air conditioners. It is important to point out that the potability parameters for the reuse of this water must be determined, aiming at a proposal for its use. In addition, physical-chemical and bacteriological analyzes are essential to define the classification of use of condensed water. This strategy for the sustainable use of water resources can generate savings of up to 100% in water consumption in medium and large enterprises, such as shopping malls and industries, and enhance the future of planet Earth.

Resumen

Introducción: El aumento de la demanda mundial de agua se ha convertido en uno de los temas más relevantes sobre la sostenibilidad ambiental y la conservación de los recursos hídricos. Como consecuencia de la escasez de agua potable, procesos como el aprovechamiento del agua a través de prácticas, técnicas y tecnologías para su uso eficiente se han vuelto imprescindibles para las futuras generaciones. Entre las posibilidades de aprovechamiento del agua destacan los sistemas de climatización, debido a la formación de agua condensada durante su funcionamiento. La población mundial está cada vez más preocupada por los temas ambientales, demostrando que es necesario buscar alternativas para reciclar el agua, ya sea para uso en jardinería, alcantarillado, lavado de aceras, automóviles, entre otros. Metodología: El presente estudio realizó una revisión de artículos primarios publicados en las bases de datos Scopus y Web of Science entre los años 2013 a 2022. Los términos utilizados para la búsqueda fueron agua reutilizada, agua condensada y aire acondicionado. **Objetivo:** El objetivo de esta revisión bibliográfica fue reflexionar sobre el tema de la reutilización del agua de condensación de los acondicionadores de aire, sensibilizar y preservar, apuntando al desperdicio de agua de los acondicionadores de aire. Es importante señalar que se deben determinar los parámetros de potabilidad para la reutilización de esta agua, visando una propuesta para su aprovechamiento. Además, los análisis físico-químicos y bacteriológicos son fundamentales para definir la clasificación de uso del agua condensada. Esta estrategia de uso sostenible de los recursos hídricos puede generar ahorros de hasta el 100% en el consumo de agua en medianas y grandes empresas, como centros comerciales e industrias, y potenciar el futuro del planeta Tierra.

Resumo

Introdução: O aumento da demanda mundial por água tornou-se um dos temas mais relevantes sobre sustentabilidade ambiental e conservação dos recursos hídricos. Em decorrência da escassez de água potável, processos como o aproveitamento da água por meio de práticas, técnicas e tecnologias para seu uso eficiente tornaram-se essenciais para as gerações futuras. Dentre as possibilidades de aproveitamento da água, destacam-se os sistemas de ar condicionado, devido à formação de água condensada durante o funcionamento. A população mundial está cada vez mais preocupada com as questões ambientais, mostrando que é preciso buscar alternativas para reaproveitar a água, seja para uso em jardinagem, esgoto, lavagem de calçadas, carros, entre outros. O presente estudo realizou uma revisão de artigos primários publicados nas bases de dados Scopus e Web of Science entre os anos de 2013 a 2022. Os termos utilizados para a busca foram reúso de água, água condensada e ar condicionado. **Objeto:** O objetivo desta revisão de literatura foi refletir sobre o tema reaproveitamento da água de condensação dos aparelhos de ar condicionado, conscientizar e preservar, apontando para o desperdício de água dos aparelhos de ar condicionado. É importante ressaltar que os parâmetros de potabilidade para o reúso dessa água devem ser determinados, visando uma proposta de seu uso. Além disso, análises físico-químicas e bacteriológicas são essenciais para definir a classificação de uso da água de condensação. Essa estratégia de uso sustentável dos recursos hídricos pode gerar economia de até 100% no consumo de água em empreendimentos de médio e grande porte, como shoppings e indústrias, e potencializar o futuro do planeta Terra.

DOI: 10.17981/ladee.03.02.2022.4

Fecha de recibido 12/11/2022. Fecha de aceptado 14/12/2022

1. Introduction

The twenty-first century has been confronted with a global concern: the scarcity of potable water. According to William et al. (2015), when we consider the seasonal climate changes and the corresponding changes in the amount of potable water, more than 5 billion people, or three-quarters of the world's population, suffer from partial water scarcity. Approximately, 800 million people worldwide suffer from severe water shortages throughout the year. At the same time, it is not considered that the atmosphere to our north is saturated with water, which may meet the needs of nearly all people on Earth (Kumar & Yadav, 2015). The water in the atmosphere can be classified into three types (Kim et al., 2017): cloud cover at various altitudes above sea level; fog near the surface of the earth; and, finally, water vapor, which is always present in the atmosphere. One important feature is that the water extracted from the atmosphere is clean and hence suitable for use in a variety of agricultural and domestic needs (Bergmair et al., 2015).

The importance of extracting water from the air is undeniable, particularly in arid regions where there are no other sources of freshwater (Woods, 2014). This applies to both permanent water supply and water supply in natural disaster-affected areas (Bergmair, 2015; Yin et al., 2014; Bui et al., 2016). Apart from the relevant characteristics of water extraction from the air, it should be noted that this method of water extraction is decentralized in nature, making it practically indispensable in the provision of potable water in poor and underdeveloped countries (Bui et al., 2017). More than 2 million deaths are caused each year by poor hygiene and a lack of sanitation due to a lack of clean water (Magrini et al., 2015a; Dalai et al., 2017). The availability of clean water is a factor in the economic development of areas far from conventional water sources, such as rivers, lakes, and springs. In many of these areas, annual precipitation is minimal (Joshi et al., 2017; Liu et al., 2017; Zhang et al., 2017). These areas' freshwater supply technologies must be both feasible and economically viable. There are two approaches: desalination of salty water or direct gathering of fresh water from the atmosphere. Distillation, dew evaporation, reverse osmosis, and electrodialysis are the basic technologies for desalination of salt-containing water (Gürsoy, Harris, Carletto et al., 2017; Gürsoy, Harris, Downing et al., 2017). Small-scale water desalination facilities, on the other hand, are not economically viable since they require the existence of saltwater close to the sources and the employment of qualified employees to handle production. The items listed above significantly limit the possibilities for using desalination systems to provide clean water (Park et al., 2016; Gürsoy, Harris, Downing et al., 2017; Shang et al., 2017). In this regard, the methods for obtaining sweet atmospheric water are more versatile (Gido et al., 2016).

The air-cooling process through the coils promotes water condensation, generating liquid water as a by-product (Barbosa & Coelho, 2016).

Scalize et al. (2018) concluded that condensed water has a quality level between distilled water and Milli-Q water and that it has the potential to replace distilled water in the activities of the Laboratory of the Federal University of Goiás, Brazil.

The water that leaks from the appliance is made of the moisture in the air, which the air conditioner condenses when it cools the interior air. The current study aims to give a literature review on the viability of installing a drenching system in air-conditioning equipment to recycle water, with the goal of presenting a long-term solution for water use.

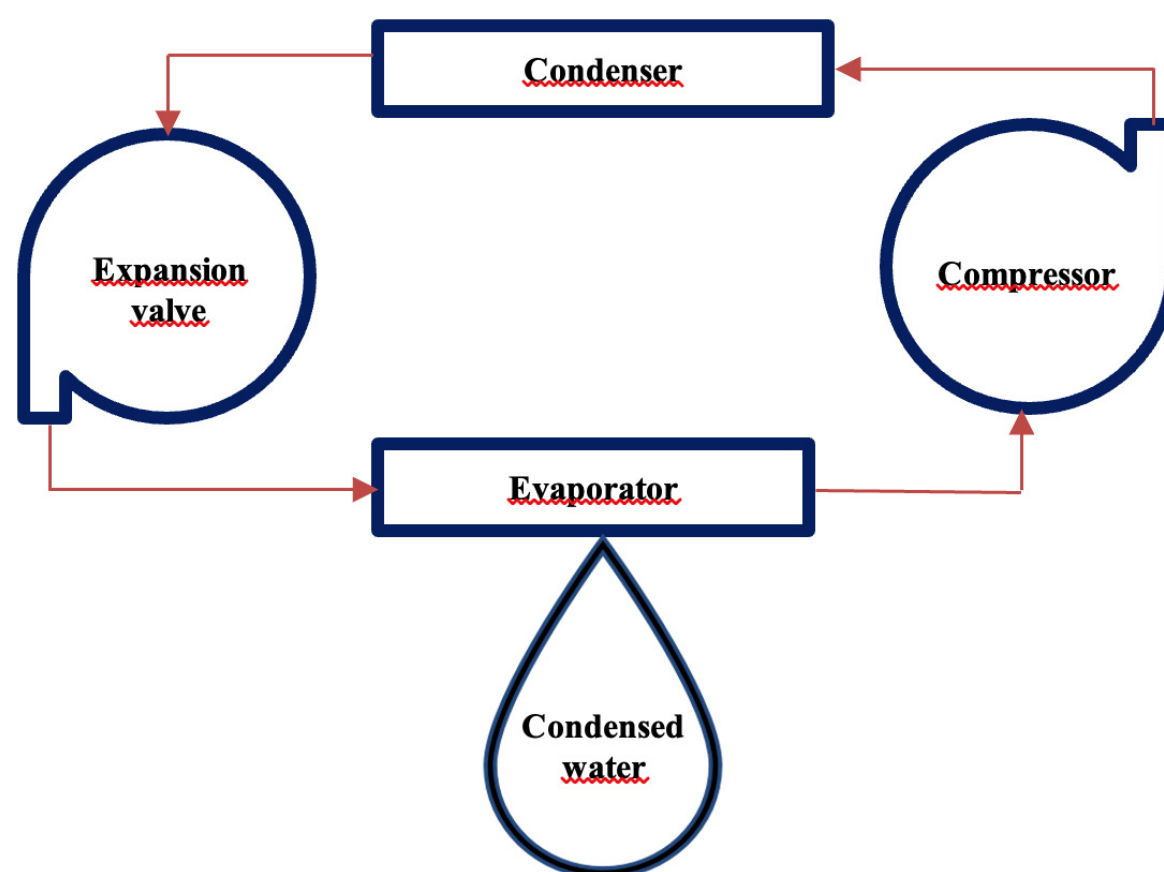
2. Condensate water collection potential an impact on water quality

There is no dispute about the high value and urgent need for water retrieved from the atmosphere (Beysens et al. 2007). However, the practical use of systems for obtaining water from the atmosphere on an industrial scale has not yet found widespread application, which is a significant impediment to the development of such systems.

To comprehend the many methods of extracting water from the atmosphere, it is required to rely on thermodynamic fundamentals and analyze the efficacy of various methods of extracting water from the atmosphere. A method of getting water from the atmosphere, such as the sorption method, can also be estimated. Any system for extracting fresh water from the atmosphere can be divided into two stages: the capture of water vapor from the air and the condensation of this vapor to the state of liquid humidity.

The examination of water sustainability in buildings and Heating, Ventilation, and Air Conditioning (HVAC) systems is essential because water is one of the world's most valued resources. Fig. 1 presents a scheme of water production in air conditioning equipment.

Fig. 1. Scheme of an air conditioner producing water.



Source: Authors.

The amount of condensed water obtained from an air conditioning system is affected by variables such as humidity, temperature, and system running hours (Lawrence et al. 2010). Furthermore, tropical, and humid regions have the greatest potential for recovering condensates because they require a relatively small number of operating hours to achieve high condensate recovery potential. The high humidity level in the air is useful due to the possibility of producing a substantial amount of condensed water in a short period of time when an air conditioner is functioning.

Lawrence et al. (2010) proposes a model for calculating the amount of condensate that can be used in both existing and new buildings. Data from a common surface method of reflection installed at the University of Georgia in 2009 was used to validate the model. During the validation, the amount of collected condensate, the relative temperature and humidity of the outside and recirculated air, and the caudal of the supply air were all considered.

The accuracy of the prediction was highly dependent on the relative humidity sensors used. The potential condensate that could be harvested for non-potable condensate use is calculated as follows (equation 1):

$$q_{cond} = q_{air} d_{wlb} / v_{da} \quad (1)$$

Where:

q_{cond}	=	The condensate produced at a rate of liters per minute.
q_{air}	=	The airflow measured in cubic meters per minute.
d_{wlb}	=	The difference, is the specific humidity.
v_{da}	=	The specific volume of air.

Other authors believe that recycling air condensation saves energy and water, as demonstrated by Bastos and Calmon (2011), who used a system that used recycled water from air conditioner evaporators and alternative sources such as wetlands. Each evaporator produces 4.8 L of water per hour; assuming 10 h of daily use, the volume accumulated for each unit would be 48 L per day; multiplying this by the sum of all 137 units yields a daily volume of 4298 L, which corresponds to 77.72% of the daily demand for medical supplies, which is 5.530 L.

The amount of water required for sanitation-related discharges is very close to the amount of water captured by the drip system of the evaporators, resulting in a significant reduction in the amount of potable water utilized for virtually all operations. Furthermore, the project employs clean, renewable energy by utilizing a solar pump installation that converts the continuous electricity generated by solar panels into heat.

Water is a vital resource everywhere in the world, but it is especially crucial in warm, dry countries with limited water supplies (Loveless et al., 2013). The economic and political conditions in many locations make it tough for sweet water subministrators. The importance of technologies that can produce sweet water at a cheaper cost is growing, and these technologies have the potential to have a substantial impact on sustainable development and emergency water supply.

The collection of condensed water from huge air-conditioning units is one potential solution to the water shortage problem.

Loveless et al. (2013) used the findings of a climate model that examined data collected from 2000 to 2010 to select the geographical regions with the greatest potential for data collection. Because of their tremendous condensation potential, coastal towns become strategically essential places for exploiting the condensation created by conditioned air, as proven by this review.

Mahvi et al. (2013) characterized the chemical and microbiological quality (turbidity, suspended solids, alkalinity, total hardness, electrical conductivity, bacterial and fungal counts) of condensed water from air conditioners in Bandar-e-Abbas, southern Iran. The presence of gases in the air, such as CO₂, is most likely to blame for the condensate's slightly acidic and near-neutral pH. The turbidity averaged 2.55 Nephelometric Turbidity Units (NTU) in a densely populated area far from the shore and 2.35 NTU in a sparsely populated area near the coast. The turbidity of the captured condensate was expected to be near zero, like that of pure water, yet the results revealed sustained turbidity values. This was most likely caused by the city's presence of car emissions and suspended smog particles. Total electrical conductivity, total hardness, total turbidity, and the alkalinity of extrapolated water were all low.

To ensure the microbiological safety of the captured condensate, 5 g of chlorine per m³ of air was advised. The water quality is adequate for many municipal applications, including irrigation, gardening, swimming pools and aquatic parks, water for putting out fires, building constructions, and washing autos, according to testing. Furthermore, Mahvi et al. (2013) discovered that condensate does not need to be treated before being used in activities such as irrigation, gardening, and aquatic parks.

Milani et al. (2014) show that producing water from atmospheric vapor is a renewable source of water that includes more water than all the world's sweet water sources combined. The scientists estimate that the earth's atmosphere contains more than 12.9×10^{12} m³ of renewable water. This amount exceeds the total amount of sweet water found in the world's oceans, humectants, and rivers.

The generation of water from atmospheric air is regarded as a renewable source of water and has been mentioned in the literature on occasion. Because of the high-water content of the air in coastal regions, the capture and condensation of this resource—which can be done using either domestic or industrial technologies, such as air conditioners—can create a substantial amount of water.

Al-Farayedhi et al. (2014) established the importance of relative humidity and temperature for conditioned air condensate collection. The amount of condensation was discovered using the software Engineering Equation Solver in an experimental study on condensation collection in a split-type air conditioning system in Dhahran, Saudi Arabia, where relative humidity and bulb temperature were varied from 15% to 90% and 25°C to 50°C, respectively.

It is vital to examine the quality of the collected water while determining the potential uses for condensed water. Al-Farayedhi et al. (2014) determined the quality of condensed water from air conditioners in several places in Saudi Arabia. The authors showed that the quality of the condensed water was very good. That had a purity comparable to distilled water, and it could readily achieve drinkable water quality using low-cost purifying techniques such as ion exchange resins and electrochemical procedures. Because of the high quality that may be produced utilizing several low-cost treatment procedures, these findings suggest the use of condensed air as a possible source of drinkable water.

Researchers have developed many designs to recover energy and water from HVAC systems (Magrini et al., 2015a; Magrini et al., 2015b; Magrini et al., 2017; Eades, 2018; Tu & Hwang, 2019; Cuvilla-Suárez et al., 2021). Cattani et al. (2018) developed an integrated HVAC system to produce water. They also ran a simulation of a year's worth of water savings to evaluate the performance of this integrated system. The life cycle research demonstrated that condensate recovery and rainfall collection are realistic options for meeting the water needs of urban buildings (Ghimire et al., 2019; Arden et al., 2020).

Tan et al. (2018) discovered that combining membrane distillation with a thermoelectric cooler lowered energy usage due to the cooling supplied by the membrane, and that the condensate increased due to an increase in thermoelectric efficiency.

Magrini et al. (2015b) investigated the feasibility of extracting water from air by comparing a standard HVAC system to an integrated HVAC system installed in an Abu Dhabi hotel. According to the writers, collecting and treating condensed water from air conditioning systems saves energy and water.

The integrated HVAC system was designed with two objectives in mind: to produce cooled air and water. This system lowered overall water costs by 19% while meeting 56.4% of the hotel's daily water requirements. Furthermore, the savings from this approach may be enough

to cover the additional cost of the integrated HVAC system. If any form of water treatment is required, the cost of potable water will be reduced by 7%.

De Souza and Cordeiro (2022) carried out a quantitative study of the hourly, daily and monthly flow in a teaching institution in Brazil. The authors showed a high potential for reusing water from air conditioners, which would result in an average savings of US\$ 65 per month for the institution.

Studies on water recovery from HVAC systems are available, but many issues still need to be evaluated due to possible condensate contamination and storage (Algarni et al., 2018; Scalize et al., 2018).

According to the findings of Siam et al. (2019), air conditioning systems can generate a large amount of condensed water. In the Palestinian towns of Ramallah and Jericho, respectively, 8.63 L and 15.1 L per day of water were measured from the capacity of a single air conditioner. According to the authors, to preserve Palestinian environmental sustainability and reduce freshwater usage and dependency on freshwater resources, these amounts of water must be collected and reused (Siam et al., 2019).

Algarni et al. (2018) have investigated the possibility of using the water or condensation produced by climate control systems, particularly those with air conditioning, as a source of potable water. In addition, condensation produced by heating, ventilation and air conditioning systems has been found to be a potential source of clean water that is normally wasted.

According to Hermes (2013), even though many studies on the characterization of condensed water revealed a high quality, which makes it possible to use it as drinking water, it is essential to use appropriate sterilization techniques (such as ozone, hypochlorite) to minimize the risks of contamination by microorganisms.

Relevant water quality parameters are total hardness, turbidity, dissolved solids, alkalinity, electrical conductivity, heavy metal content, chlorides, dissolved oxygen, pH, chemical oxygen demand, total suspended solids, biological oxygen demand, and corrosivity. Abdullah and Maursalin (2021) evaluated the parameters of condensed water from an air conditioning unit in Bangladesh. The results revealed that the pH of the condensed water was close to neutral, and that the other parameters are all within the permissive ranges of the study region.

Several condensate generation and water collection technologies have been proposed in the development of efficient industrial air conditioning methods (Zheng et al., 2010). All these methods necessitate additional energy expenditures. Although the first condensate formation methods were proposed in the 1930s, they did not become widely used until the 1980s, with the widespread adoption of efficient industrial mechanical air-cooling methods.

Water condensation technologies are extensively utilized in locations where there is not only a scarcity of potable water, but also where the quality of that water is poor. Active water condensation devices operate similarly to conventional dehumidifiers. There are works that indicate very high energy consumption of water condensation systems among the works that study the possibility of employing water condensation methods (Raveesh et al., 2023). However, as evidenced by the analysis of these works, this is due to a poor heat exchange process and the small amount of water received by small installations.

When we look at air conditioning systems in the summer, we can see that the air is usually cooled below the dew point. That is, air conditioning systems generate a lot of condensed water, which is often discarded. In other words, the condensed water simply enters the city's sewage system. However, if the air conditioning system and the water collection system are combined, two problems —cooling the air and obtaining drinking water— will be solved at

the same time, and energy costs will remain within the same limits. As a result of taking ventilation, heating, and air conditioning systems into account, you can acquire free fresh water from the air.

It is evident that collecting and utilizing air conditioner condensate benefits in energy and water savings. This has a favorable effect on the condensation from air conditioners, which can be handled adequately and used for human consumption in this scenario.

3. Final considerations

Air conditioning systems are employed for indoor climate management because they provide a large volume of untapped condensed water that may be used for irrigation, flushing toilets, washing machines, automobile batteries, radiator water, and industrial washing machines. Given the scarcity of water resources, condensed water can be viewed as an alternate source of this resource, which can be critical in supplying water when fresh water becomes rare.

Condensed water should be tested for physical, chemical, and microbiological water quality to ensure it meets local, regional, or national guidelines for its intended application.

The environmental benefit must surely be considered. The goal of the United Nations 2030 Agenda of rational resource use and universal socio-environmental awareness are both compatible with the implementation of sustainable ways.

Such a strategy is feasible due to the amount of water that the air conditioner produces per hour, and that this water on a large scale, that is, in places such as condominiums, commercial and residential buildings, schools, colleges and other institutions who use several air conditioners can obtain a large volume of water and that it can be used. For developments that use an air conditioning system with cooling towers, directing reuse water can bring significant gains, especially in the summer.

Credit author statement

Adilson Celimar Dalmora: Methodology, Writing-Reviewing, and Editing.

Matheus da Silva Civeira: Conceptualization, Methodology, Data curation, Writing.

Samuel do Nascimento de Campos: Original draft preparation, Writing Reviewing.

Hugo Gaspar Hernández Palma: support in analyzes, Visualization, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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