

Condensate as a water source in terrestrial and extra-terrestrial conditions

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ARTICLE INFO

Keywords:

Condensate
Water recovery
Circular management

ABSTRACT

A condensate generated from air in air conditioning (AC) units is a reliable, and a stable source of water possible to be reused in different forms. This study focuses on condensate recovery from heating ventilation air conditioning (HVAC) systems maintaining ambient or indoor air. The database of experiments conducted in outdoor air is much larger than those conducted in indoor air. The experiments conducted in greenhouses, plant factories, vertical farms, and space systems and applications come with assistance. The latter include facilities such as the International Space Station and closed analog ecosystems simulating future space bases. In these locations, condensate is mainly recovered for crew needs (consumption, hygiene, etc.). From these studies it is possible to derive knowledge of what treatment processes are required to obtain water of high quality. In general, the most important parameters affecting the quantity and quality of recovered condensate are climate zone and associated climate parameters, building type, building use, and supply air volume. Additionally in case of indoor air recovery, the most important parameters are the climatic conditions, people activity, plant types grown, and whether the system has to operate in a closed loop. Other important parameters influencing condensate composition is construction and material of the HVAC system and the condensate capture system. The growing interest in the market for vertical farms and closed-loop grow chambers is observed globally. Thus, this study will favor future research on condensate recovery from these facilities. This paper deepens the look at the problem of HVAC condensate recovery by including previously not considered places such as closed ecological systems, where condensate is used for drinking water purposes.

1. Introduction

Water stress and climate change are one of the major current problems of humanity [1]. Rapid population growth is accompanied by widespread globalization, industrialization, and modernization of developing countries resulting in freshwater scarcity, which slowly becomes not only a regional but also a global problem [2]. Already, global water demand is estimated to increase at a rate of 1% year to year associated with an increasing demand for water for industrial and domestic use [3].

Only 0.76% of the Earth's water is available and accessible to human activities [4]. Two-thirds of freshwater is unavailable for human consumption because it is preserved as ice phases in ice caps, glaciers, and permanent snow. In addition, an intensive exploitation of groundwaters causes the congestion of available aquifers thereby forcing the use of appropriate treatment processes [5,

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6]. Growing population, intensive industrialization and urbanization coupled with climate change are exacerbating the problem of a hollow food production chain, thereby further increasing the demand for water for agricultural reasons.

The need to look for new sources of water recovery can be seen in The Sustainable Development Goals (SDGs). These are hidden in SDG 2, which requires zero hunger, SDG 3, which is ensuring healthy lives, SDG 6, which is an access to safe drinking water and adequate sanitation for all, and protecting water resources from pollution, among others. It is also evident in SDG 14.1, which demands to reduce marine pollution, explicitly mentioning nutrient pollution. All these goals should be achieved by 2030 [7]. Ensuring future water security requires broad community support, as well as changes in policy, practice, and technology to increase the committed provision of alternative water resources [8].

Many technologies are already in use for water recovery and reuse of wastewater. Examples include desalination (e.g., through evaporation, reverse osmosis, electrodialysis), solar distillation, cloud seeding, atmospheric water vapor harvesting, and water recovery from wastewater streams (e.g., through membrane techniques, or conventional techniques for e.g., rainwater) [1,9].

Another potential source is worth noting – the air (both indoor and outdoor), which can contain a large amount of water. The potential of the water recovery from the air is already noted and reviewed in earlier studies [10,11]. This source of water is expected to be more popular since the global Heating, Ventilation, Air Conditioning (HVAC) market is predicted to grow nearly 6% by 2023 compared to the last 5 years [12]. The use of air conditioning systems is rapidly increasing worldwide and is now almost a necessity, in parallel with the widespread demand for thermal comfort, which until recently was a luxury [12]. Both thermal and cooling comfort provisions involve the possibility of water recovery through HVAC equipment. There are a few air conditioning related technologies where such recovery would be possible:

- Vapor compression units [11].
- Recuperators (crossflow, counterflow) [13,14].
- Indirect evaporative exchangers operating in a condensation variant [15].
- Sorption desiccant systems [10].

A key process is condensation, which allows for obtaining the condensate obtained to be used for various applications, thus striving to create a closed water cycle. Additionally, current knowledge regarding condensate recovery from HVAC might be supplemented with space research experience. This data is important because typically these systems operate in a closed-loop system e.g., the atmosphere inside the space object must be regenerated without an access to fresh ambient (atmospheric) air for obvious reasons. Moreover, considering the need for the water recovery, condensate is usually used for potable purposes. Thus, condensate management in space application is one of the most demanding examples of such a recovery system.

The data of condensate management systems has been available from the previous years, from space missions in stations such as MIR [16,17], and from recent times, due to the continued operation of the International Space Station [18–21]. A special case is the condensate recovery from plant cultivation growth facilities (implemented in closed analog systems e.g., Lunar Palace, NASA Biomass Production Chamber etc.) [22–29]. Plants transpire large amounts of water into the air, which can be successfully recovered. Fortson et al. (1994) [23] presented detailed data on condensed water transpiring from the Biomass Production Chamber (BPC) of a NASA closed ecosystem. This chamber had a volume of 113 m³ and when growing wheat its daily condensation rates ranged from 23 to 84 L/d. By analyzing the data obtained from the BPC, the species of crop grown can affect the composition of the condensate [30]. For example, the condensate from the chamber where wheat was grown had higher concentrations of potassium, calcium, and zinc compared to the experiments where potatoes were grown.

The analysis of data regarding the composition of recovered condensate from greenhouses is particularly important because of the growing popularity of vertical soilless farms applied in terrestrial condition. An increasing number of new installations being built is indicative of the growing popularity of these solutions [31]. An interesting project which combines water recovery and vertical

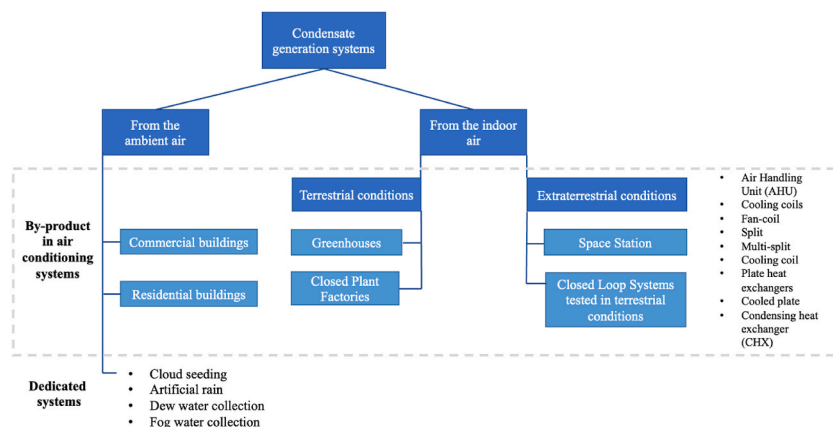


Fig. 1. General division in condensate generating systems.

Table 1

Review on chosen condensate generation system from ambient air.

Place, where condensation occurs		Device	Main findings	References
Commercial building	Institutional Building, Doha, Qatar	HVAC	15,443 L/month per one unit with nominal cooling capacity equal 63.303 kW (one unit considered from 25 units). - It is very important to plan a separate condensate pipeline already at the water and sewage design stage for the new buildings. - Suggested applications of condensate collection systems are irrigation of plants around the building, and as make-up water in cooling towers.	Bryant et al. [40]
	University building, Birmingham, Alabama, USA	Air Handling Unit (AHU)	55.27 million liters of condensate was collected over 17 months (about 3.25 mln L/month). - Savings of \$63 000 mainly due to reduced water consumption. Energy savings for recirculating condensate to the refrigeration system at that time were the equivalent of \$29 000. - Water quality analysis of the condensate data showed no significant contamination in the water. The water quality was good, but disinfection is still recommended to avoid the presence of biological content, such as bacterial and fungal forms. - The multiple regression models developed in this study provide more than 90% accuracy in estimating condensate production based on weather parameters alone.	Kajale [41]
	Hotel building, Mexico	HVAC	- The experiments were carried out in November (ambient temperature equal to 27.3 °C and relative humidity equal to 86%) collecting 56,400 L/month of condensate. - Based on the experimental and simulation results, a payback period of up to 2.5 years was estimated.	Cattani et al. [42]
Residential building	Bandare-Abbas (BA), Iran	HVAC	66 samples were collected over a nine-month period in four BA clusters based on distance from the coast, population, and vehicle traffic. - The quality of the water is suitable for many municipal applications and due to the large amount, it would be economically viable to plan to use this substantial amount of free water. - The average water extracted per unit in the four regions is approximately 36 L/d. - To ensure the microbiological safety of the condensed water, the recommended amount of 5 g/m³ of perchlorate powder should be added to the water.	Alipour et al. [43]
	Dhaheeran, Saudi Arabia	AC split	The highest average daily water production 70.1 L/d, was recorded in the wet month of August with air flow rate at 0.135 m³/s.	Al-Farayedhi et al. [44]
	Single Family House, Apartament, Bourne, MA, USA	HVAC	- The two main challenges of HVAC condensate collection are estimating the amount of condensate production and understanding the chemical composition of the condensate. - Therefore, this study tested a method for estimating the amount of condensate production and analyzed the chemical composition of condensate samples from three separate HVAC units in different residences. - Measured condensate production rates ranged from 12 to 25 percent of the predicted values, and water chemistry results showed the presence of both metals and organic compounds. - Considering the production volume in the summer months, 8.6, 39.3 and 3.9 L/d for units A, B and C respectively, irrigation or non-potable reuse at home (i.e., toilet flushing) are currently the best options for reusing condensate.	Reuter [45]
	The West Bank, Palestine	HVAC	Condensed water has generally been found to be of good quality which is in line with Palestinian standards for re-irrigation water, except for turbidity, biological oxygen demand (BOD) and chemical oxygen demand (COD) measurements.	Siam et al. [46]

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Table 1 (continued)

Place, where condensation occurs	Device	Main findings	References
		• The presence of heavy metals in the collected condensed water does not present any particular risk to drinking water or reused irrigation standards, apart from 0.19 mg/L manganese in one sample. • From a single unit, large amounts of water were observed, amounting to approximately 259 L and 453 L per month, in the cities of Ramallah and Jericho, respectively. These figures should alert policymakers and decision-makers to the introduction of strict technical guidelines to be followed in the event of potential reuse of condensate at local level. • Only 36.47% of HVAC users reused the condensate.	

farming is the SUSKULT project. It assumes the spatial integration of wastewater treatment plants with food production in vertical farm with soilless systems [32]. Their vision is to combine urban wastewater treatment systems and efficient agricultural production systems in densely populated urban areas.

Thus, it can be predicted that the potential for condensate utilization will only increase. Therefore, it is reasonable and appropriate to perform a review relating to the prediction models of volume of condensate, stream parameters, possible treatment methods and management, with special focus on condensate stream gained from plants cultivation chambers.

This paper aims at compiling the data available in the literature regarding the quantitative and qualitative parameters of water recovered from liquefaction in conventional systems – terrestrial HVAC, and in space, closed-loop systems. The factors that may influence the parameters of the resulting condensate are analyzed, as well as possible uses, and technologies for management and treatment of this stream. This approach will outline opportunities for the integrated design of HVAC systems optimized for water production in addition to air treatment in terrestrial systems.

This paper deepens the look at the problem of HVAC condensate recovery by including previously not considered places such as closed ecological systems, where condensate is used for drinking water purposes.

2. Classification of condensate generating systems

A general division prepared for the purpose of this study is presented in Fig. 1. Water in the form of water vapor can be recovered from both ambient and indoor air. Systems generating condensate from the ambient air can be also divided into those in which the condensate is a by-product (usually in the vapor compression-based air-conditioning systems), and those in which condensation is specially induced to collect the condensate (the same, chillers, sorption systems, thermoelectric modules, etc.). The second source of obtaining water is the air exhausted. Generally, the facilities where high humidity is required present the highest potential – in particular greenhouses or plant factories.

In extract air heat recovery condensate is a by-product in recuperative or evaporative exchangers (this happens if the appropriate configuration is used). Often, this water is not used and is directed to the sewage system. Nevertheless, striving for a closed circuit, it is worth referring to the facility such as the ISS, in which there is no possibility of draining the “unwanted” condensate to the sewage system. On the contrary, it is a source of water for cosmonauts.

3. Condensate characteristics

3.1. Condensate recovery from ambient air

There are systems where the primary purpose is to recover water from outdoor air (e.g., cloud seeding or artificial rain, dew water collection and fog water collection). A detailed review on this topic was described by Shafein et al. [10], Kandeal et al. [33], Raavesh et al. [34], and Wang et al. [35]. In this chapter, the study focuses on condensate generated as a byproduct from the ambient air maintenance.

The collection of condensate depends on several factors; however, the air parameters such as temperature and humidity ratio hence the dew point temperature and the cold contact surface temperature are the main factors that determine the amount of condensate generated from HVAC equipment [36]. Geographical location (temperature and humidity ratio of the air) as well as the type of building and its style of use are also important factors influencing the production of condensate. For example, the areas with a cold climate will have less condensate recovery potential from the ambient air than areas with a tropical and humid climate. Similarly, a typical production building, equipped with machinery and lighting, and intensive human activity will burden air conditioning more than an empty building, which will increase condensate production from the indoor air [37]. As the amount of generated condensate is also related to the size of the air stream supplied to the air-conditioning unit, therefore, it will be generated less in single-family buildings than in large multi-family or commercial buildings. In humid climates, more water can be recovered in laboratory and clinical buildings which require 100% outdoor air in each air exchange process, while other buildings generally recirculate some of the conditioned air along with the outdoor air [38,39].

Some cities have decided to legally resolve the issue of condensate accumulation. For example, San Antonio (USA) requires all new commercial buildings (with a total cooling capacity of 10 refrigeration ton (35 kW) or more) to design drain lines that trap condensate from air conditioning systems and discharge this water to one location in the building [38,39]. This encourages the reuse of condensate and its management in the most optimal way, which in turn helps to alleviate the growing demand for limited water resources and the city's water infrastructure [39]. The examples of the amount of generated condensate from commercial buildings in the city are 946 and 5184 L/d from the mall and library, respectively [38,39].

A collective list of systems generating condensate from the ambient air with the division into commercial and residential buildings is presented in Table 1.

The authors Siam et al. and Alipour et al. show the need for changes on the legal level, as well as social education, so that the reuse

Table 2

Review on chosen theoretical studies on condensate generation system from ambient air maintained in cooling coils.

Place, where condensation occurs	Main findings	References
Hot and humid areas: Jeddah, Saudi Arabia	- The use of evaporator coils as collecting surfaces for water in hot and humid areas appears to be cost effective only in a range of air inlet velocities close to the design speed of the cooling system. - Based on actual climatic data, the estimated monthly average water yield in August and February was 509 and 401 kg/m², respectively, for an air speed of 2.25 m/s.	Habeebullah [47]
Laboratory, Houston, Texas, USA	The results show savings of up to 13% in energy (when condensate is used as pre-cooling the exhaust air) and 37% in water by using condensate as make-up water to the chiller condenser loop.	Eades [48]
Laboratory, San Antonio, Texas, USA	- The annual condensate production was 7.15 million L, which provides a complete annual demand for sanitary and urinal water (6.12 million L). - The authors suggest using the excess as irrigation water or in a cooling tower.	Paintner et al. [49]
Theoretical review on commercial building	- The analysis shows that the production of condensate from six large AHU is sufficient for an effective use in the energy recovery process with 9.3% savings in the absence of a heat pipe and 10.9% savings using the heat pipe strategy. - Condensate can offset from 52.3% up to 55.3% of total make-up water requirements, when using heat pipe strategy.	Licina et al. [50]
Condensate recovery model for any region using factors such as hourly weather data, load in TR, and sensible heat factor (SHR). Abu-Dhabi, United Arab Emirates	- Authors developed a theoretical model in Microsoft Excel to predict condensate recovery for any region using the factors such as hourly weather data, load in TR, and sensible heat factor. - With decreasing sensible heat factor, the amount of condensate increased in a non-linear fashion. - Authors performed an economic and environmental feasibility study of the CRS which was conducted in the city of Abu Dhabi, United Arab Emirates (UAE), analyzing the initial costs and TR of the air conditioner.	Hassan and Bakry [51]
Residential building G+20 floors, Dubai, United Arab Emirates	- Condensate production of 2600 L/d with average summer outdoor conditions. - Authors estimated reduction in carbon dioxide emissions by 0.54284 kg CO₂ per kWh, resulting in a lower carbon footprint. - Condensate is suggested to be reused in a variety of drainage and irrigation applications to reduce consumption of municipal drinking water and save energy.	Khan et al. [52]
Different 31 locations, different building types	- The authors provided estimated amounts of condensate for selected 31 cities. By differentiating based on population and location, production elsewhere can be predicted. - For example, for the same airflow in the ventilation unit of a large building in Singapore, 1 million liters more of condensate will accumulate per year than for the same parameters in Saudi Arabia.	Loveless et al. [53]
Typical ground + 15 floors apartment building in Abu Dhabi, United Arab Emirates	The condensate production rate is estimated on the level 368.64 L/h and used to pre-cool the associated recirculating air conditioning equipment.	Khan et al. [54]
Hotel, Abu Dhabi, United Arab Emirates	It has been estimated that in the summer months such an integrated system could collect around 10,200 L of water per day, which could cover more than 24% of the hotel's annual water needs.	Magrini et al. [55–57]

Table 3

Review on chosen condensate generation system from indoor air. T – terrestrial, E – extraterrestrial.

Place, where condensation occurs	Device	Main Findings	References
Greenhouse (T)	Cooling plate/Forced ventilation in combination with a heat exchanger	- The authors tested three dehumidification systems. The energy savings were compared to the conventional method using natural ventilation. - The most promising method is a forced ventilation with heat exchanger. - In greenhouses with higher insulation, the system saves even more energy than in a normal single-glazed greenhouse.	Campan et al. [59]
Space Station (E)	Condensing heat exchanger (CHX)	- Condensate recovery rate is approximately 2.27 kg/day per crewmember. - Two-stage process is used for obtaining condensate. - A complex treatment process is applied to meet drinking water standards.	[16,19–21,60]
Closed Plant Production Chamber (T/E)	HVAC	- Condensate is collected on the cold-water coils used in the ducting of heating, ventilation, and air conditioning (HVAC) systems. - Condensation can peak at a rate of up to 100 L/d for each chamber, although the average rate of condensation for plant growth experiments are around 40–50 L/d, up to 60 L/d, depending on plant variety is cultivated. - During the experiments, it was noticed that the species of the cultivated plant may have an influence on the composition of the condensate - This water is then filtered and deionized before being stored for later use. - Other uses for this water include a reserve for additional humidification, a solvent for concentrated media solutions to be added to the media tanks, a diluent for nitric acid to control the pH of the media and use in a bioreactor mixer.	Fortson et al. [23]
Analog Closed Ecosystem Biosphere 2 (T/E)	Dedicated system	- The largest analog, closed system of 7 biomes (ocean, freshwater and saltwater marshes, tropical rain forest, savanna, desert, intensive agriculture, and human habitat) attempt to mimic the biomes of Earth, or Biosphere 1. - A water recirculation system is used, using pathways for evapotranspiration, condensation, and wastewater treatment in wetlands. The processes are mechanically supported by forced air movement. - Condensation takes place in each biome in two different places: on the cooling coils of air-conditioning units and on the hermetic glazing of Biosphere 2. - The condensate was subjected to two-stage filtration down to 0.1 µm and ultraviolet sterilization for drinking water tanks. - It was used for both utility and food purposes. For analytical purposes, it was additionally treated with the reverse osmosis process.	Nelson et al. [61,62]
Analog Closed Ecosystem BIOS-3 (T/E)	Cooling coil	- Closed system inhabited by humans and equipped with soilless cultivation of plants. - Condensate was collected and recycled, mainly for plant fertilization, but also for washing and general cleaning. - Drinking water was additionally purified using ion-exchange filters. Small amounts of potassium iodide and fluorides were also added to this drinking water, and potassium chloride and other salts improved the taste.	Salisbury et al. [25]
Analog Closed Ecosystem Closed Ecology Experiment Facilities (CEEFF) (T/E)	Not mentioned	- The experimental system consisted of two people, two goats and a crop (growing area: 150 m²). - Condensate collection of 818–938 L/d. - The condensate was recirculated as water replenishment to compensate for the loss of liquid fertilizer through transpiration.	Tako et al. [24]
	HVAC	Condensate production at the level of 12.9 L/d.	

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Table 3 (continued)

Place, where condensation occurs	Device	Main Findings	References
Analog Closed Ecosystem Small Closed Ecosystem (SCE) (T/E)		The condensate was assessed for its suitability as drinking water. Due to the lower pH level and the low concentration of minerals compared to the norm, the authors recommend adjusting its composition before consumption.	Tikhomirov et al. [26]
Analog Closed Ecosystem The Lunar Palace 1 (T/E)	AHU	- Lunar Palace 1, a ground-based experimental bio-regenerative life support system experimental facility, was developed by our team, and a large-scale 105-day bio-regenerative life support system experiment was conducted at this facility with multiple crew members. - The collection of condensate was 270.4 kg/d. - The condensate was collected in a tank equipped with a UV lamp. - The treatment system consisted of PP column prefiltration, activated carbon adsorption column and ultrafiltration. The purified water was stored in a clean water tank for daily use by crew members and irrigation of the plants - Purified condensed water (pure water) can meet China drinking water quality standard (GB5749-2006).	Xie et al. [63]
Analog Closed Ecosystem The Controlled Ecological Life Support System (CELSS) (T/E)	Cooling coil	- Experiment of 4-person 180-day in closed ecosystem. - Collection of about 917 L/d condensate water. 95% was reused as plant nutrient solution after ultraviolet (UV) disinfection, the rest was used as the raw water for the domestic water supply needs.	Zhang et al. [64]
Analog Closed Ecosystem The Lunar Palace 365 (T/E)	HVAC	- The condensate was collected from Plant cabin I, II, and Comprehensive Cabin from the temperature-humidity control system. - Treatment was conducted in an aerobic membrane bioreactor. Treated stream was stocked inside a clean water tank equipped with a UV lamp. - Condensate served as sanitary water for crewmembers and to produce liquid fertilizer for plant cultivation in Plant Cabin I and II. It was used for potable purposes as well, but with further purification by a cartridge filter and an ion exchanger.	Zhao et al. [22]

of condensate becomes more popular [43,46]. A detailed analysis of the next steps before implementing the condensate recirculation was presented by Siam et al. [46].

Theoretical models are one of the helpful tools in assessing the feasibility and profitability of a condensate capture and reuse installation. However, the theoretical model may differ significantly from actual measurements. For example, in Lawernce et al. [36] study condensate volume was predicted using a model that was based on the climate conditions of their location study and tonnage of the system. The observed values of condensate were 30% higher than the predicted values; the difference in estimation was mainly attributed to an error in measurement of the relative humidity and the supply air flow rate [36].

Chosen research is shown in Table 2.

3.2. Condensate recovery from indoor air

The condensation process can also be carried out with the use of indoor air from such places as greenhouses, closed plant production chambers or halls, Space Stations, and other closed ecosystems. Extensive review on dehumidification process in greenhouses, including condensate recovery was conducted by Soussi et al. [58].

A collective list of systems generating condensate from the indoor air is presented in Table 3.

The case of the International Space Station is particularly interesting because the collection of condensate takes place in micro-gravity conditions [19]. The maintenance of appropriate environmental parameters requires the removal of both the sensible heat and the water vapor generated inside space station. To achieve this condensing a heat exchanger is installed onboard ISS [18]. The current system uses a two-step process including condensation in a heat exchanger, and further a two-phase air-water mixture separation in a rotary separator. Before the stream reaches a separator, it is passed through the particle filter. Further condensate treatment includes catalytical oxidation, multifiltration process with catalysts, sorbents, and ion exchange resins and ion exchange. The purified water is mineralized with inorganic salts and preserved with ionic silver for potable purposes.

Other, non-obvious places from which it is possible to gain knowledge about condensate recovery are closed ecosystems mainly used to simulate space missions on Earth. It is worth noting that the papers describing production of condensate by the systems

intended to work ultimately in extraterrestrial conditions do not precisely describe the condensate generation technology. It is essential, since in those experiments it is assumed that it is necessary to create closed or closely closed loops of all consumables (such water, energy, nutrients etc.). The water recovered from condensate is used for liquid fertilizer production, but also for potable purposes. Thus, it also shows necessary treatment chain to achieve good quality. This also gives a perspective that can also be faced by humans in earthly conditions in the future.

There are some theoretical studies on condensate generation system from indoor air including greenhouses, and closed plant factories. A list of selected studies is presented in Table 4.

Despite the small amount of theoretical research on this subject, an increase in modeling the possibilities of water recovery in plant factories or vertical farms is expected to extend, considering the growing popularity of these forms of intensive agriculture [69,70]. More importantly, numerical simulations and theoretical models will help design effective systems at such facilities. However, in order to create a precise mathematical model, basics knowledge of mass and heat transfer is required, but also plant physiology and processes taking place in them.

4. Condensate quality and management

The quality of the condensate is a very important indicator due to the fact that the purpose of the condensate recovery is to use it for another use. It can be as simple as make-up water in cooling towers, providing 15% to even 45% of the required make-up water for a cooling tower for typical commercial buildings and specialist buildings such as laboratories [37]. Other common applications are the use of condensate for flushing toilets, irrigation of green areas as process water [38,39]. During analog and actual space missions condensate is used mainly for potable purposes and for fertilizer production [19].

The air entering the AHU (both ambient and indoor) is one of the sources of contamination in the condensate. Preliminary air filtration allows for the removal of contaminants suspended in the air, however, particles not captured will pass further into the condensation water. This is especially seen in closed facilities such as the International Space Station, where it is reported that the

Table 4

Review on chosen theoretical studies on condensate generation system from indoor air. T – terrestrial, E – extraterrestrial.

Place, where condensation occurs	Device	Main findings	References
Greenhouse (T)	A fan and pad evaporative cooling system	- The case study showed that a water recovery system using water from an evaporative cooling tank as a source of chilled water can be integrated into greenhouse cultivation in semi-arid conditions. - Validation done in Eurofresh Farms (Willcox, Arizona, USA), which operates 100 ha of greenhouse hydroponic crop production. - In pre-monsoon and monsoon seasons, the overall simulated amount of condensate water increased when water flow rate in the cooling coil increased from 0.003 to 0.006 m³/s in each condenser regardless of bypass factor.	Lovichit et al. [65]
Greenhouse (T)	Heat Pump/Evaporative cooling system	- The authors developed a dynamic model to predict energy and mass exchange in a greenhouse. - Estimated water recovery reaches 1.17 kg/day·m² in summer, which is comparable to the amount of transpiring water.	Yildiz and Stombaugh [66]
Closed Plant Factory (T)	–	- The authors compared total energy consumption between greenhouses and plant factories. - They compared total energy consumption between greenhouses and plant factories. - The model illustrates the energetic distribution of sensible heat and latent heat and the corresponding transpiration production from soilless lettuce cultivation. - The model made is easy and does not require detailed empirical data, therefore it can be used for any production installation. - The authors showed that the plant transpiration process can be used as a design parameter that helps to estimate the overall energy profile and possible water yield in plant factories.	Graamans et al. [67]
Closed Plant Factory (T)	Cross-flow heat exchanger	- The authors simulated condensate recovery potential in a cross-flow heat exchanger from air removed from an indoor vertical farming facility located in Wrocław (Poland) in 2012–2019. - The condensate recovered from the system was used for production of the liquid fertilizer for plants. - For a cultivation area of 522 m², the condensate recovery as high as 100%. - Authors proved that exhaust air, which has constant parameters throughout the year, is a stable source of water recovery.	Pacak et al. [68]

dissolved organics, ammonia, ions, and microorganisms are present in captured stream [63]. Condensate is cleaner in places where the human presence is combined with plants cultivation [63]. This was the case of Lunar Palace 1, where transpiring water reduced the level of contamination, but at the same time increased the amount of wastewater generated (270.4 kg/d versus 2.27 kg/d condensate produced per crewmember in ISS). More importantly, Goto [30] observed the crop variety also affects the composition of the condensate. For example, the condensate from the wheat-growing chamber had higher concentrations of potassium, calcium, and zinc compared to the experiments where potatoes were grown. In addition to metal contamination, small amounts of bacteria were another questionable parameter. The composition of the water recovered from plant transpiration in the future extraterrestrial colony will therefore depend on the size and type of cultivation, plant species and the type of system used.

The second source of contamination is the surface on which condensate is generated (e.g., cooling coils) and the entire remaining condensate handling system (e.g., transport lines, collection tanks, etc.). Since condensate is usually slightly acidic and contains not completely dissolved solids [39], it tends to react with surfaces to form metal ions and other chemical contamination, and thus requires further handling. This was visible in the closed growth chamber with soilless cultivation, where higher concentrations of copper, cadmium and zinc were associated with the direct leaching of these elements from the condensation system, in which copper condensation coils and cadmium and tin solder were used [30].

A condensate storage tank is necessary in most cases due to the time buffer between collection and re-use. Inside the tank and in pipeline biofilm may grow on the walls, which might result in microorganisms' development. Microbial contamination of condensate than would be dependent on thickness and composition of biofilm, and also flow velocity. Thus, when water is reused for human use, a microbiological control is required to detect possible pathogenic microorganisms.

As it can be seen various factors may affect the quality of the condensate, and its composition may vary depending on the type of air used (ambient/indoor).

Summary of condensate quality gathered from ambient air and indoor air are shown in Tables 5 and 6, respectively.

It can be seen that typically the pH of the outdoor air condensate is lower than the pH of the indoor air condensate. According to Alipour et al. [43] lower pH of the condensate may be related to the presence of gases, especially carbon dioxide in the air. Overall, however, the pH of the condensate samples is quite close to the EPA standard values.

The EC of water can be defined as the ability to conduct electricity by the presence of electrolytes producing cations and anions [71]. Alipour et al. [43] observed that in the quayside areas the mean EC and TDS of condensate is higher than in offshore areas. The

Table 5

Condensate quality and composition data gathered from systems generating condensate from ambient air.

Reference	Alipour et al. [43]	Al-Farayedhi et al. [44]	Reuter [45]	Glawe et al. [38,39]	Siam et al. [46]
T (°C)				12.80–27.20 (17.20)	15.50–22.50 (18.05)
pH	6.82	6.52	5.00 ± 0.51	5.16–6.92 (6.3)	6.40–7.59 (7.12)
Biological Oxygen Demand (BOD) (mg/L)					1.00–6.00 (2.23)
Chemical Oxygen Demand (COD) (mg/L)					18.00–150.00 (101.71)
Electrical conductivity (EC) (µs/cm)	42.50				30.00–220.40 (79.40)
Dissolved Oxygen (DO) (mg/L)					0.36–5.90 (2.52)
Turbidity (NTU)	2.43	2.01			0.55–6.69 (1.97)
Total Dissolved Solids (TDS) (mg/L)	31.70	27.00		10.00	15.20–76.40 (42.48)
Alkalinity (mg/L)	36.30		20.00 ± 7.07		
N-NO ₃ (mg/L)		1.71	0.14 ± 0.08		
K (mg/L)			<0.005		
Mg (mg/L)		0.93	<0.005	0.059	
Ca (mg/L)		5.08	0.054 ± 0.005		
Na (mg/L)		0.43	<0.05	11.30	
Cl (mg/L)		0.70	0.10 ± 0.10		
P (mg/L)			0.004 ± 0.002		
S-SO ₄ (mg/L)		5.38	0.051 ± 0.072		0.001–0.006 (0.0033)
Acetate (mg/L)			55.6 ± 13.59		
Al (mg/L)			0.004 ± 0.003	0.226	0.0734 ± 0.01
Cr (mg/L)			0		0.0605 ± 0.0587
Cu (mg/L)		0.019		0.23	0.968 ± 0.638
Fe (mg/L)			0.05 ± 0.029		0.0694 ± 0.0241
Pb (mg/L)			0.001 ± 0.0008	0.543	
Mn (mg/L)		0.007	0.05 ± 0.0039		0.0595 ± 0.0635
Ni (mg/L)			19.2 ± 6.74		
Sn (mg/L)			0.002		
Sr (mg/L)		0.023	<0.000627		
Zn (mg/L)			0.283 ± 0.230	0.18	0.213 ± 0.205
Si (mg/L)			0.350 ± 0.107		
Co (mg/L)			0.364 ± 0.447		
Ba (mg/L)		0.01	0		0.113 ± 0.178
B (mg/L)			0.242 ± 0.263		
Formate (mg/L)			19.2 ± 6.73		

Table 6

Condensate quality and composition data gathered from systems generating condensate from indoor air in closed ecosystem experiments both in terrestrial and extraterrestrial conditions.

	Zhao et al. [22]		Bobe et al. [18]		Fortson et al. [23]	Mudget et al. [16]
	<i>Tank-I CW</i>	<i>Tank-II CW</i>	<i>SM condensate</i>	<i>US LAB condensate</i>	<i>Wheat experiment WP882</i>	<i>Average MIR Phase 1 Results</i>
pH	7.23 ± 0.41	7.76 ± 0.55			6.5	7.2
TOC (mg/L)			60–160	115–350		
COD (mg/L)	1.92 ± 1.13	25.12 ± 30.68				
EC (µS/cm)	52.29 ± 71.96	92.98 ± 48.52				252
N-NH ₄ (mg/L)	3.61 ± 1.90	14.07 ± 4.75	10–20	30–88		25.7
N-NO ₂ (mg/L)	0.10 ± 0.09	0.10 ± 0.20				0.01
N-NO ₃ (mg/L)	0.29 ± 0.44	0.57 ± 1.67			0.02	0.5
K (mg/L)	0.1 ± 0.14	0.39 ± 0.30			7.31	1.70
Mg (mg/L)	0.02 ± 0.02	0.03 ± 0.04			0.09	0.60
Ca (mg/L)	0.34 ± 0.33	0.63 ± 0.80			1.26	1.00
Na (mg/L)						8.30
Cl (mg/L)	0.13 ± 0.16	0.39 ± 0.41				1.70
P-PO ₄ (mg/L)	0	0.06 ± 0.28				0.40
S-SO ₄ (mg/L)	0.07 ± 0.18	0.30 ± 0.57				6.30
Methanol (mg/L)			6–10	3–6		
Ethanol (mg/L)			40–105	30–125		
Other alcohols (mg/L)			3–12	2–44		
Ethylene glycol/Propylene glycol (mg/L)			3–15	30–135		
As (mg/L)					0.06	<0.001
Cd (mg/L)					0.049	0.027
Cr (mg/L)					0.01	0.012
Cu (mg/L)					0.96	0.0164
Fe (mg/L)					0.08	0.108
Pb (mg/L)					0.02	0.041
Mn (mg/L)					0.08	0.064
Ni (mg/L)					0.02	1.4
Se (mg/L)					0.03	0.0005
Zn (mg/L)					1.86	1.26

reason for the increased content is probably the dissolution of sea salt in the air. The soilless plant cultivation experiments had a similar salinity, which could in turn be related to the evaporation of the saline nutrient solution [22].

Alipour et al. [43] predicted that the turbidity of the condensate may be greater in the case of the outside air than in the case of the inside air, due to the greater pollution caused by, for example, the emission of particles from vehicles.

COD appeared to be higher in condensate originated from ambient air, than from indoor air. However, it should be noted that activities undertaken indoors can significantly affect the quality of the condensate in terms of COD. For example, Zhao et al. [22] noted large differences between COD in condensates collected from different rooms. The authors state that the reason for the differences is straw chopping conducted by the crew members in the storage room connected with Plant Cabin II, which caused straw powders discharge into atmospheric environments. This is especially important when designing condensate recovery in vertical cannabis farms, where the process of processing plant material can also cause such effects.

The main nutrients (N, P, K) are present in rather small amounts, except in a few cases. The highest nitrogen concentrations were found in the condensate from the ISS, which is caused by the source of the condensate itself, i.e., sweat and moisture exhaled by the crew [18]. Potassium content was especially visible in condensate from wheat experiment in NASA's Biomass Production Chamber and onboard MIR Station [16,23]. This was not the case in experiments using ambient air, where potassium content was close to 0.

Magnesium, calcium, and chloride content were similar for both condensate sources. Slightly higher values of Mg and Ca were noticed in Al-Farayedhi study [44], and Cl in Mudget study [16] compared to the other studies shown in Tables 5 and 6.

Except for the case of the MIR station [16] and the Glawe study [39], where higher sodium concentrations were reported (8.30 and 11.30 mg/L) the other cases had negligible sodium content. A similar relationship was noted for sulfate. Only Al-Farayedhi [44] and Mudget [16] study observed higher values (5.38 and 6.30 mg/L).

Generally, the presence of microelements (i.e., Fe, Mn, etc.) in condensate allows for using it as a supplementation to liquid fertilizers used for growing plants. The lack of certain nutrients will limit plant growth and quality, which is a particular problem in closed systems [72].

Acetate and formate are volatile constituents of many cleaning compounds and are present in other consumer products and hence may appear in the condensate [45]. This is important as acetate and formate can corrode the copper radiator coils, which can lead to premature coil aging or even complete deterioration [73]. Additionally, as electron donors they can create biological control problems and biofilm can form in the system [45].

Glawe [39] explains the presence of aluminum and copper by the fact that these metals are the basic materials that make up the

cooling coils. On the other hand, iron and nickel can come from a galvanized steel tank, as well as from transport pipes. Reuter noticed those constituents, as well as the content of organic substances, low alkalinity and pH might be the biggest challenge regardless of the chosen method of treatment [45]. Precipitation of copper and aluminum compounds can be a problem.

In general, the choice of condensate treatment methods will depend on the intended use of the reclaimed water. Non-human contact applications (e.g., cooling towers) will have lower requirements than those where human contact may occur (such as landscape watering, toilet flushing and flat surface cleaning). If the condensate will be used as drinking or hygienic water, it must meet all potable water standards. Such a variant occurs primarily in experiments relating to closed loops space systems. Examples of process sequences include, but are not limited to:

- processes such as filtration, catalytic oxidation and ion exchange are used in ISS [18];
- PP column prefiltration, activated carbon adsorption column, ultrafiltration, and UV disinfection in first experiments in Lunar Palace analog [63];
- nitrification process in aerobic membrane biological reactor (MBAR) and further collection in tank equipped with UV lamp in further Lunar Palace experiments [22];
- two-stage filtration down to 0.1 μm and ultraviolet sterilization in Biosphere 2 [28,61,62].

Similar processes (including ion exchange resins and electrochemical processes) were used in terrestrial systems using ambient air for condensate recovery for potable purposes [53]. When the condensate was used to produce liquid fertilizer, the authors typically used UV disinfection [64].

5. Challenges regarding condensate systems

According to literature reports, it is crucial for earth systems to include a condensate capture and management system already at the design stage of new buildings. This would greatly facilitate its management, etc. Proper commissioning of the system would allow potential faults to be caught earlier. In addition, scheduled inspections and maintenance are critical to maintaining continuous efficient operation of the system.

Glawe [39] presented the main challenges and recommendations facing condensate capture for terrestrial systems with HVAC:

- Appropriately designed storage tanks (in terms of size, material). Combination of condensate with other on-site sources of reclaimed water to optimize return of investment.
- Poor maintenance of HVAC system, condensate management system and storage tanks might result in major failures.
- Since any condensate use system in a building must be able to be supplemented with tap water, a measurement of the amount of condensate and tap water must be implemented.
- Algae and biofilm growth in the condensate system, which in turn can clog pipes and components further downstream. An additional threat is pathogenic microorganisms such as *Legionella*.

In the context of closed-loop systems designed for space applications, the case is somewhat different. The issues shown above are equally important. However, reduced or microgravity conditions are an additional challenge, which must be considered at the design stage. Additionally, the systems must be reliable, which is why synthetically created condensate is often used for long-term testing [74]. This approach can also be used to test condensate management systems and treatment methods.

Another essential factor is cost of the system. It is sad that condensate recovery systems add approximately 3–5% to the total cost of mechanical engineering for a new building [75]. Upgrade costs of addition of such system to the existing buildings are slightly higher, but still reasonable [75].

Kajale [41] summarized initial cost of installation of condensate recovery system in the University of Alabama at Birmingham Condensate Recovery System. Depending on the building cost was in the range of 2475–29,965\$. The variation in the installation cost was due to the varying number of air handlers in the buildings, sharing of the 500-gallon storage tank, and also its location, with final total cost of 148,460\$. Other examples shown by the author is Winship Cancer Institute of Emory University (45,000\$), and EPA's Science and Ecosystem Support Division (SESD) (24,000\$) [41]. The recovered water is used in a cooling tower to reduce the make-up water requirement.

Considering the challenges facing municipal water infrastructures due to a climate change, intensive urbanization, and globalization, it is necessary to look for alternative water sources. The condensate obtained from the air, as a relatively stable and predictable, not heavily polluted source of water, should be considered already at the design stage of the building alongside other solutions such as rainwater harvesting. Such solutions were presented, among others, by Jurga et al. [76], Niloy [77], Ghimire et al. [78].

6. Summary and conclusions

Summary of this study could be concluded in following sentences:

- Outdoor air water recovery via HVAC from commercial and residential buildings is more discerned than indoor air water recovery. Experience gained from experiments relating to space missions can be useful in future research.

- The quantity and quality of recovered condensate from outdoor air will be 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 contrast, for indoor air recovery, the main parameters are the purpose of the building, and required climate parameters, whether people live in it, whether crops are grown, if so, which crops, whether the system is to operate in a closed loop.
- The amount of recovered condensate depends on the capacity of the installed air conditioning equipment and the outdoor or exhaust air parameters. In many of the cases analyzed, the amount of recovered condensate is sufficient to cover all or part of the water demand for plant watering, cooling tower feed or toilet flushing. There are cases in which the recovered amount of condensate exceeds the water demand of the building (sanitary and urinal water) Paintner et al. [49]. Therefore, the validity of condensate recovery could be considered on a case-by-case basis already during the design of the building's internal systems. Condensate can be used both as part of water and energy savings when used for ventilation air pre-cooling or as feed water for evaporative cooling equipment. Of the cases analyzed, the largest amount of condensate per day 10,200 L was obtained by analyzing the recovery in a hotel building in Abu Dhabi Magrini et al. [55–57]. In Alabama, at the University of Birmingham, an experiment was conducted in which 55.27 million L of condensate was recovered in 17 months. It should be noted that the condensate flux is not constant over time and depends on, among other things, the parameters of the air from which the water is recovered.
- Condensate pH values vary in the range 5.0–7.76. Higher values are observed in indoor experiments. Condensate EC vary in the range 30–220.4 $\mu\text{S}/\text{cm}$. The greater the salt content of the air (due to e.g., close proximity to the beach, or evaporation of salt-rich fertilizers), the greater the EC of the condensate. COD appeared to be higher in condensate originated from ambient air (18–150 mg/L), than from indoor air (1.92–25.12 mg/L). The main macro-nutrients (N, P, K) are present in rather small amounts (<2.0 mg/L). Exception is N-NH_4 in indoor experiments (3.61–88 mg/L). Mg, Ca, and Cl content is similar for both sources, indoor, and ambient (0.02–0.933 mg/L, 0.054–1.26 mg/L, 0.10–1.70 mg/L for Mg, Ca, and Cl respectively). Except for the two cases where higher sodium concentrations were reported (8.30 and 11.30 mg/L) the other studies had negligible sodium content. A similar relationship was noted for sulfate (5.38 and 6.30 mg/L). Micronutrients presence is visible. The highest values are observed for Zn (1.86 mg/L), Cu (0.96 mg/L), and Ni (1.40 mg/L), each in indoor experiments. Other constituents that may appear in the condensate are acetate, formate, methanol, other alcohols.
- Due to the increasing need for intensive agriculture such as vertical farms and plant factories, future research directions should focus on the recovery of condensate from these sites and more on combining various growth parameters with water recovery, energy balance, and higher crop yields. Systems that use both condensate and rainwater appear to have great potential for future studies.

7. Recommendation for future research and perspectives

The use of condensate recovery systems in the future may become a necessity. There is a need to include the political bodies that establish the law in the discussion. There is also a need for more education of the community responsible for urban planning and architecture, as well as making the public aware of the positives of introducing such solutions. It is also advisable to introduce probabilistic risk-based assessment models to support decision-making in water system risk management (e.g., as in Ref. [79]) combined with detailed cost analyses of recovery systems. According to the authors, the review performed demonstrates one of the future perspectives of the direction of research development which is condensate recovery in closed cultivation halls (i.e. urban farming, vertical farming, aquaponic farms). Future theoretical and experimental research should include such places.

Funding

This research was funded by Polish National Center for Research and Development, program Lider X, agreement number U/0180/666/2019 and by the European Regional Development Fund, Industrial research and development works conducted by enterprises., under the competition 1/1.1.1/2021 Fast Track of the Intelligent Development Operational Program 2014–2020. Agreement number 11IR/0011/2021” and by Polish National Agency for Academic Ex-change (Bekker program), agreement number BPN/BEK/2021/2/00014/U/00001/A/00001.

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.

Data availability

No data was used for the research described in the article.

References

- [1] F.A. Canales, J. Gwoździej-Mazur, P. Jadwiszczak, J. Struk-Sokołowska, K. Wartalska, M. Wdowikowski, B. Kaźmierczak, Long-term Trends in 20-day Cumulative Precipitation for Residential Rainwater Harvesting in Poland, Water (Switzerland), 2020, p. 12, <https://doi.org/10.3390/w12071932>.

- [2] T. Distefano, S. Kelly, Are we in deep water? Water scarcity and its limits to economic growth, *Ecol. Econ.* 142 (2017) 130–147, <https://doi.org/10.1016/J.ECOLECON.2017.06.019>.
- [3] A. Boretto, L. Rosa, Reassessing the projections of the world water development report, *NPJ Clean Water* 2 (2019), <https://doi.org/10.1038/s41545-019-0039-9>.
- [4] P. Vasistha, R. Ganguly, Water quality assessment of natural lakes and its importance: an overview, *Mater. Today Proc.* 32 (2020) 544–552, <https://doi.org/10.1016/J.MATPR.2020.02.092>.
- [5] F. el Yaouti, A. el Mandour, D. Khattach, J. Benavente, O. Kaufmann, Salinization processes in the unconfined aquifer of Bou-Areg (NE Morocco): a geostatistical, geochemical, and tomographic study, *Appl. Geochem.* 24 (2009) 16–31, <https://doi.org/10.1016/J.APGEOCHEM.2008.10.005>.
- [6] S. Tweed, M. Leblanc, I. Cartwright, G. Favreau, C. Leduc, Arid zone groundwater recharge and salinisation processes; an example from the Lake Eyre Basin, Australia, *J. Hydrol. (Amst.)* 408 (2011) 257–275, <https://doi.org/10.1016/J.JHYDROL.2011.08.008>.
- [7] D. Mara, B. Evans, The sanitation and hygiene targets of the sustainable development goals: scope and challenges, *J. Water, Sanit. Hyg. Dev.* 8 (2017) 1–16, <https://doi.org/10.2166/washdev.2017.048>.
- [8] A.J. Dean, K.S. Fielding, J. Lindsay, F.J. Newton, H. Ross, How social capital influences community support for alternative water sources, *Sustain. Cities Soc.* 27 (2016) 457–466, <https://doi.org/10.1016/J.SCS.2016.06.016>.
- [9] J. Struk-Sokolowska, J. Gwozdziej-Mazur, P. Jadowiczak, A. Butarewicz, P. Ofman, M. Wdowikowski, B. Kazmierczak, The quality of stored rainwater for washing purposes, *Water (Switzerland)* (2020) 12, <https://doi.org/10.3390/w12010252>.
- [10] N. Shafeian, A.A. Ranjbar, T.B. Gorji, Progress in atmospheric water generation systems: a review, *Renew. Sustain. Energy Rev.* 161 (2022), 112325, <https://doi.org/10.1016/J.RSER.2022.112325>.
- [11] S. Algarni, C.A. Saleel, M.A. Mujeebu, Air-conditioning condensate recovery and applications—current developments and challenges ahead, *Sustain. Cities Soc.* 37 (2018) 263–274, <https://doi.org/10.1016/j.scs.2017.11.032>.
- [12] L. Cattani, A. Magrini, P. Cattani, Water extraction from air by refrigeration- experimental results from an integrated system application, *Appl. Sci.* (2018) 8, <https://doi.org/10.3390/app8112262>.
- [13] S. Anisimov, A. Jedlikowski, D. Pandelidis, Frost formation in the cross-flow plate heat exchanger for energy recovery, *Int. J. Heat Mass Tran.* 90 (2015) 201–217, <https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2015.06.056>.
- [14] A. Pacak, A. Jedlikowski, M. Karpuk, S. Anisimov, Analysis of power demand calculation for freeze prevention methods of counter-flow heat exchangers used in energy recovery from exhaust air, *Int. J. Heat Mass Tran.* 133 (2019) 842–860, <https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2018.12.144>.
- [15] D. Pandelidis, A. Cichoń, A. Pacak, S. Anisimov, P. Drag, Performance comparison between counter- and cross-flow indirect evaporative coolers for heat recovery in air conditioning systems in the presence of condensation in the product air channels, *Int. J. Heat Mass Tran.* 130 (2019) 757–777, <https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2018.10.134>.
- [16] P.D. Mudgett, J.E. Straub, J.R. Schultz, R.L. Sauer, D.E. Williams, L.S. Bobe, V.M. Novikov, P.O. Andreichouk, N.N. Protasov, Y.E. Sinyak, V.M. Skuratov, Chemical Analysis and Water Recovery Testing of Shuttle-Mir Humidity Condensate, 1999, <https://doi.org/10.4271/1999-01-2029>. SAE Technical Paper . 1999-01–2029.
- [17] C.M. Ott, R.J. Bruce, D.L. Pierson, in: *Microbial Characterization of Free Floating Condensate Aboard the Mir Space Station*, *Microb Ecol.* 2004, pp. 133–136, <https://doi.org/10.1007/s00248-003-1038-3>.
- [18] L. Bobe, M. Samsonov, L. Gavrilov, V. Novikov, M. Tomashpolskiy, P. Andreychuk, N. Protasov, Y. Synjak, V. Skuratov, Regenerative water supply for an interplanetary space station: the experience gained on the space stations “Salut”, “Mir”, ISS and development prospects, *Acta Astronaut.* 61 (2007) 8–15, <https://doi.org/10.1016/j.actaastro.2007.01.003>.
- [19] M.S. Anderson, M.K. Ewert, J.F. Keener, S.A. Wagner, Life Support Baseline Values and Assumptions Document, 2018, <https://doi.org/10.2172/841250>.
- [20] M.M. Hasan, L. Khan, V. Nayagam, R. Balasubramaniam, Conceptual design of a condensing heat exchanger for space systems using porous media, in: *SAE Technical Papers*, SAE International, 2005, <https://doi.org/10.4271/2005-01-2812>.
- [21] A.O. Kohlhasse, N. Porth, J. Doyé, Operational engineering of the COLUMBUS thermal and environmental control system: achievements, optimizations, in: *SpaceOps 2010 Conference Delivering on the Dream Hosted by NASA Marshall Space Flight Center and Organized by, AIAA*, 2010.
- [22] T. Zhao, G. Liu, D. Liu, Y. Yi, B. Xie, H. Liu, Water recycle system in an artificial closed ecosystem – Lunar Palace 1: treatment performance and microbial evolution, *Sci. Total Environ.* (2022) 806, <https://doi.org/10.1016/j.scitotenv.2021.151370>.
- [23] R.E. Fortson, J.O. Bledsoe, J.C. Sager, Condensate Recycling in Closed Plant Growth Chambers, 1994, <https://doi.org/10.4271/941543>. SAE Technical Paper. 941543.
- [24] Y. Tako, S. Tsuga, T. Tani, R. Arai, O. Komatsubara, M. Shinohara, One-week habitation of two humans in an airtight facility with two goats and 23 crops – analysis of carbon, oxygen, and water circulation, *Adv. Space Res.* 41 (2008) 714–724, <https://doi.org/10.1016/j.asr.2007.09.023>.
- [25] F.B. Salisbury, J.I. Gitelson, G.M. Lisovsky, Bios-3: siberian experiments in bioregenerative life support, *Bioscience* 47 (1997) 575–585, <https://doi.org/10.2307/1313164>.
- [26] A.A. Tikhomirov, S.A. Ushakova, V. v Velichko, S. v Trifonov, N.A. Tikhomirova, G.S. Kalacheva, A small closed ecosystem with an estimated portion of human metabolism, *Life Sci. Space Res.* 19 (2018) 63–67, <https://doi.org/10.1016/j.lssr.2018.10.001>.
- [27] Escobar Christine, Nabity James, Past, present, and future of closed human life support ecosystems - a review, in: *47th International Conference on Environmental Systems*, 2017. <http://hdl.handle.net/2346/73083>. (Accessed 13 May 2022).
- [28] M. Nelson, W.F. Dempster, J.P. Allen, The water cycle in closed ecological systems: perspectives from the Biosphere 2 and Laboratory Biosphere systems, *Adv. Space Res.* 44 (2009) 1404–1412, <https://doi.org/10.1016/j.asr.2009.06.008>.
- [29] Y.S. Polyakov, I. Musae, S.v. Polyakov, Closed bioregenerative life support systems: applicability to hot deserts, *Adv. Space Res.* (2010), <https://doi.org/10.1016/j.asr.2010.05.004>.
- [30] E. Goto, Environmental control for plant production in space CELSS, in: E. Goto, K. Kurata, M. Hayashi, S. Sase (Eds.), *Plant Production in Closed Ecosystems: the International Symposium on Plant Production in Closed Ecosystems Held in Narita, Japan, August 26–29, 1996*, Springer Netherlands, Dordrecht, 1997, pp. 279–296, https://doi.org/10.1007/978-94-015-8889-8_17.
- [31] A. Roobeek, White Paper on Vertical Horticulture International Overview of Vertical Horticultural Projects, 2018. <https://www.grwnxt.com/wp-content/uploads/2018/11/180718-MMM-White-Paper-Vertical-Horticulture.compressed.pdf>. (Accessed 14 May 2022).
- [32] V. Keuter, S. Deck, H. Giesenkamp, D. Gonglach, V.T. Katayama, S. Liesegang, F. Petersen, S. Schwindenhammer, H. Steinmetz, A. Ulbrich, Significance and vision of nutrient recovery for sustainable city food systems in Germany by 2050, *Sustainability* 13 (2021), 10772, <https://doi.org/10.3390/su131910772>.
- [33] A.W. Kandeal, A. Joseph, M. Elsharkawy, M.R. Elkadeem, M.A. Hamada, A. Khalil, M. Eid Moustapha, S.W. Sharshir, Research progress on recent technologies of water harvesting from atmospheric air: a detailed review, *Sustain. Energy Technol. Assessments* 52 (2022), 102000, <https://doi.org/10.1016/J.SETA.2022.102000>.
- [34] G. Raveesh, R. Goyal, S.K. Tyagi, Advances in atmospheric water generation technologies, *Energy Convers. Manag.* 239 (2021), 114226, <https://doi.org/10.1016/J.ENCONMAN.2021.114226>.
- [35] Y. Wang, S.H. Danook, H.A.Z. AL-bonsrulah, D. Veeman, F. Wang, A recent and systematic review on water extraction from the atmosphere for arid zones, *Energies* 15 (2022) 421, <https://doi.org/10.3390/en15020421>.
- [36] T. Lawrence, J. Perry, A. Peter Dempsey, Capturing Condensate by Retrofi Tting AHUs, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2010. www.ashrae.org.
- [37] K. Guz, Condensate Water Recovery, 2005.
- [38] D. Glawe, M. Wooten, D. Lye, Quality of Condensate from Air-Handling Units, 2016. www.ashrae.org.
- [39] D. Glawe, San Antonio Condensate Collection and Use Manual for Commercial Buildings, San Antonio Water System, 2013.
- [40] J.A. Bryant, T. Ahmed, Condensate water collection for an institutional building in doha, Qatar: an opportunity for water sustainability, in: *Proceedings of the Sixteenth Symposium on Improving Building Systems in Hot and Humid Climates*, 2008.

- [41] A. Kajale, ESTIMATION AND FORECASTING OF AIR HANDLING CONDENSATE RECOVERY USING MULTIPLE REGRESSION ANALYSIS AND TIME-SERIES AUTOREGRESSIVE MODELS, 2013.
- [42] L. Cattani, A. Magrini, P. Cattani, Water extraction from air by refrigeration—experimental results from an integrated system application, *Appl. Sci.* 8 (2018) 2262, <https://doi.org/10.3390/app8112262>.
- [43] V. Alipour, A.H. Mahvi, L. Rezaei, Quantitative and qualitative characteristics of condensate water of home air-conditioning system in Iran, *Desalination Water Treat.* 53 (2015) 1834–1839, <https://doi.org/10.1080/19443994.2013.870724>.
- [44] A.A. Al-Farayedhi, N.I. Ibrahim, P. Gandhidasan, Condensate as a water source from vapor compression systems in hot and humid regions, *Desalination* 349 (2014) 60–67, <https://doi.org/10.1016/j.DESAL.2014.05.002>.
- [45] S.J. Reuter, Evaluation of Two Water Reuse Applications: Cooling Tower Makeup Water and Residential HVAC Condensate Reuse, 2016. <https://repositories.lib.utexas.edu/bitstream/handle/2152/72471/REUTER-THESIS-2016.pdf?sequence=1&isAllowed=y>. (Accessed 14 May 2022).
- [46] L. Siam, I.A. Al-Khatib, F. Anayah, S. Jodeh, G. Hanbali, B. Khalaf, A. Deghes, Developing a strategy to recover condensate water from air conditioners in Palestine, *Water (Switzerland)* (2019) 11, <https://doi.org/10.3390/w11081696>.
- [47] B.A. Habeebullah, Potential use of evaporator coils for water extraction in hot and humid areas, *Desalination* 237 (2009) 330–345, <https://doi.org/10.1016/J.DESAL.2008.01.025>.
- [48] W. Eades, Beneficial Use of Air Handling Unit Condensate for Laboratory HVAC Energy and Water Recovery in Hot and Humid Climates, 2018. <https://www.researchgate.net/publication/326408684>.
- [49] F.L. Painter, Condensate harvesting from large dedicated outside air-handling units with heat recovery, *Build. Eng.* 115 (2009).
- [50] D. Licina, C. Sekhar, Energy and water conservation from air handling unit condensate in hot and humid climates, *Energy Build.* 45 (2012) 257–263, <https://doi.org/10.1016/j.enbuild.2011.11.016>.
- [51] N.M. Hassan, A.S. Bakry, Feasibility of condensate recovery in humid climates, *Int. J. Architect. Eng. Construct.* 2 (2013), <https://doi.org/10.7492/ijaec.2013.024>.
- [52] S.A. Khan, S. Naji, M.J. Al-Zubaidy, Conservation of potable water using chilled water condensate from air conditioning machines-shahid, *Int. J. Innovative Technol.* (2013) 3. <https://www.researchgate.net/publication/343064146>.
- [53] K.J. Loveless, A. Farooq, N. Ghaffour, Collection of condensate water: global potential and water quality impacts, *Water Resour. Manag.* 27 (2013) 1351–1361, <https://doi.org/10.1007/s11269-012-0241-8>.
- [54] S.A. Khan, F. Wang, S.N. Al-Zubaidy, Energy recovery through the condensate of air conditioning machines, *Int. J. Eng. Res. Technol.* 3 (2014) 548–555. <http://www.ijert.org/view.php?id=10130&title=energy-recovery-through-air-conditioning-machines->
- [55] A. Magrini, L. Cattani, M. Cartesegna, L. Magnani, Water production from air conditioning systems: some evaluations about a sustainable use of resources, *Sustainability* 9 (2017) 1309, <https://doi.org/10.3390/su9081309>.
- [56] A. Magrini, L. Cattani, M. Cartesegna, L. Magnani, Integrated systems for air conditioning and production of drinking water – preliminary considerations, *Energy Proc.* 75 (2015) 1659–1665, <https://doi.org/10.1016/J.EGYPRO.2015.07.406>.
- [57] A. Magrini, L. Cattani, M. Cartesegna, L. Magnani, Production of water from the air: the environmental sustainability of air-conditioning systems through a more intelligent use of resources. The advantages of an integrated system, *Energy Proc.* 78 (2015) 1153–1158, <https://doi.org/10.1016/J.EGYPRO.2015.11.081>.
- [58] M. Soussi, M.T. Chaibi, M. Buchholz, Z. Saghrouri, Comprehensive Review on Climate Control and Cooling Systems in Greenhouses under Hot and Arid Conditions, 2022, <https://doi.org/10.3390/agronomy>.
- [59] J.B. Campen, G.P.A. Bot, H.F. de Zwart, Dehumidification of greenhouses at Northern latitudes, *Biosyst. Eng.* 86 (2003) 487–493, <https://doi.org/10.1016/J.BIOSYSTEMSENG.2003.08.008>.
- [60] A.O. Kohlhasse, N. Porth, J. Doyé, Operational engineering of the COLUMBUS thermal and environmental control system: achievements, optimizations, in: *SpaceOps 2010 Conference Delivering on the Dream Hosted by NASA Marshall Space Flight Center and Organized by, AIAA*, 2010.
- [61] M. Nelson, L. Leigh, A. Alling, T. MacCallum, J. Allen, N. Alvarez-Romo, Biosphere 2 test module: a ground-based sunlight-driven prototype of a closed ecological life support system, *Adv. Space Res.* 12 (1992) 151–156, [https://doi.org/10.1016/0273-1177\(92\)90021-O](https://doi.org/10.1016/0273-1177(92)90021-O).
- [62] M. Nelson, W.F. Dempster, J.P. Allen, Key ecological challenges for closed systems facilities, *Adv. Space Res.* 52 (2013) 86–96, <https://doi.org/10.1016/J.ASR.2013.03.019>.
- [63] B. Xie, G. Zhu, B. Liu, Q. Su, S. Deng, L. Yang, G. Liu, C. Dong, M. Wang, H. Liu, The water treatment and recycling in 105-day bioregenerative life support experiment in the Lunar Palace 1, *Acta Astronaut.* 140 (2017) 420–426, <https://doi.org/10.1016/J.ACTAASTRO.2017.08.026>.
- [64] L. Zhang, T. Li, W. Ai, C. Zhang, Y. Tang, Q. Yu, Y. Li, Water management in a controlled ecological life support system during a 4-person-180-day integrated experiment: configuration and performance, *Sci. Total Environ.* 651 (2019) 2080, <https://doi.org/10.1016/J.SCITOTENV.2018.10.080>. –2086.
- [65] W. Lovichit, G. Student, C. Kubota, C.Y. Choi, J. Schoonderbeek, *Greenhouse Water Recovery System for Crop Production in Semi-arid Climate*, 2007.
- [66] I. Yildiz, D.P. Stombaugh, Heat pump cooling and greenhouse microclimates in open and confined greenhouse systems, in: B.J. Bailey *Acta Hort* (Ed.), *Proc. IS on Greenhouse Cooling*, vol. 719, ISHS, 2006, <https://doi.org/10.17660/ActaHortic.2006.719.28>.
- [67] L. Graamans, A. van den Dobbelaars, E. Meinen, C. Stanghellini, Plant factories: crop transpiration and energy balance, *Agric. Syst.* 153 (2017) 138–147, <https://doi.org/10.1016/j.agry.2017.01.003>.
- [68] A. Pacak, A. Jurga, P. Drag, D. Pandelidis, B. Kaźmierczak, A long-term analysis of the possibility of water recovery for hydroponic lettuce irrigation in indoor vertical farm. Part 1: water recovery from exhaust air, *Appl. Sci.* 10 (2020) 8907, <https://doi.org/10.3390/app10248907>.
- [69] D.D. Avgoustaki, G. Xydis, Indoor vertical farming in the urban Nexus context: business growth and resource savings, *Sustainability* 12 (2020) 1965, <https://doi.org/10.3390/su12051965>.
- [70] K. Al-Kodmany, The vertical farm: a review of developments and implications for the vertical city, *Buildings* 8 (2018) 24, <https://doi.org/10.3390/buildings8020024>.
- [71] N.R.G. Walton, Electrical conductivity and total dissolved solids—what is their precise relationship? *Desalination* 72 (1989) 275–292, [https://doi.org/10.1016/0011-9164\(89\)80012-8](https://doi.org/10.1016/0011-9164(89)80012-8).
- [72] A. Jurga, K. Janiak, A. Wizimirska, P. Chochura, S. Miodoński, M. Muszyński-Huhajto, K. Ratkiewicz, B. Zięba, M. Czaplicka-Pędzich, T. Pilawka, D. Podstawczyk, Resource recovery from synthetic nitrified urine in the hydroponic cultivation of lettuce (*Lactuca sativa* var. *Capitata* L.), *Agronomy* 11 (2021) 2242, <https://doi.org/10.3390/agronomy11112242>.
- [73] D.M. Bastidas, I. Cayuela, J.M. Bastidas Rull, Ant-nest corrosion of copper tubing in air-conditioning, *Rev. Metal. (Madr.)* 42 (2006) 367–381. <http://hdl.handle.net/10261/2120>.
- [74] C.E. Verostko, C. Carrier, B.W. Finger, *Ersatz Wastewater Formulations for Testing Water Recovery Systems*, 2004.
- [75] K. Siriwardhena, S. Ranathunga, AIR-CONDITIONERS CONDENSATE RECOVERY SYSTEM FOR BUILDINGS, 2012. <http://dl.lib.uom.lk/bitstream/handle/123/8927/SBE-12-53.pdf?sequence=1&isAllowed=y>. (Accessed 27 October 2022).
- [76] A. Jurga, A. Pacak, D. Pandelidis, B. Kaźmierczak, A long-term analysis of the possibility of water recovery for hydroponic lettuce irrigation in an indoor vertical farm. Part 2: rainwater harvesting, *Appl. Sci.* 11 (2020) 310, <https://doi.org/10.3390/app11010310>.
- [77] T.H. Niloy, Integrating rainwater harvesting system and A/C condensate for water efficiency in the commercial building of dhaka city, *Res. Rev.: J. Architect. Des.* 2 (2020) 1–12, <https://doi.org/10.5281/zenodo.4471194>.
- [78] S.R. Ghimire, J.M. Johnston, J. Garland, A. Edelen, X. Cissy, M. Jahne Ma, Life cycle assessment of a rainwater harvesting system compared with an AC condensate harvesting system, *Resour. Conserv. Recycl.* 146 (2019) 536–548, <https://doi.org/10.1016/j.resconrec.2019.01.043>.
- [79] B. Tchorzewski-Cieslak, K. Pietrucha-Urbaniak, M. Eid, Functional safety concept to support hazard assessment and risk management in water-supply systems, *Energies* 14 (2021) 947, <https://doi.org/10.3390/en14040947>.