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Original Article

Monte Carlo Modeling of Air Conditioner Condensate Water Quality and Its Reuse Potential in Iranshahr, Iran

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Abstract
Introduction: In dry areas like Iranshahr, traditional water sources cannot meet the growing needs of people. Reusing water from sources like air conditioner condensate is important. Since there is little information about its quality and safety for irrigation or drinking, evaluating the water's quality and safety for reuse through advanced methods like Monte Carlo simulation is essential.
Methods: Samples were collected in triplicate from 30 air conditioning units to enhance reliability of the data. Chemical analyses measured pH, total dissolved solids (TDS), electrical conductivity (EC), hardness, and specific ions (chloride, sodium (Na), calcium (Ca), magnesium (Mg)). SPSS alongside Monte Carlo simulation were utilized to assess variability and potential risks associated with water reuse.
Results: The water quality analysis of the condensate revealed an average chloride concentration of 51.91 mg/L, Na at 67.49 mg/L, Ca at 14.37 mg/L, and Mg at 20.01 mg/L. Temporary hardness averaged 127.23 mg/L as $CaCO_3$, permanent hardness 178.38 mg/L as $CaCO_3$, and total hardness (TH) reached 305.62 mg/L as $CaCO_3$. TDS were measured at 196.15 mg/L, EC at 296.74 µS/cm, and the pH was slightly alkaline at 7.13. Based on the histogram of water quality index (WQI), the WQI values of the samples ranged between 32.14 and 126.6. This is equivalent to "Moderate" to "Poor" quality water.
Conclusion: The results indicate high potential for reuse of such a water source, especially for non-potable purposes such as irrigation. Detailed further studies are, however, required to properly evaluate its safety, treatment requirements, and suitability for larger applications.
Keywords: Air conditioner condensate, Water quality index, Monte Carlo simulation, Water reuse, Irrigation potential

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Introduction

The idea of harvesting water from the atmosphere is not new. Evidence of harvesting water from the air in Middle Eastern deserts and Europe dates back at least two thousand years. The ability of living organisms to capture water from the air may have inspired humans to develop methods for collecting condensate water.[1] It has been documented that the air contains billions of cubic meters of freshwater, which can be a remarkable potential water source, especially in humid coastal areas.[2] Initially, fog fences and dew ponds were the most common devices used for harvesting water from the air for various applications such as irrigation, cleaning, and even non-potable uses.[3, 4] While the primary function of air conditioners is to cool the air, they also generate water as a byproduct of the cooling process. During operation, air conditioners remove heat and moisture from indoor air, causing water vapor to condense on the cooling coils. This condensate is typically discharged outdoors or into sewer systems and is often wasted, particularly in tropical regions.[5] To utilize this water efficiently and economically, clear technical guidelines for its collection and reuse are required.[3]

According to the results obtained from many countries located in tropical or semitropical zones, the average relative humidity is more than 50% for most of the year. Therefore, increased access to new technologies and changes in lifestyles have led to rapid growth in the use of air conditioning systems.[6] For instance, a study in Palestine found that air conditioner condensate water generally meets local standards for reuse in irrigation, although it exhibited elevated turbidity and biological oxygen demand

(BOD) levels.[7] Similarly, findings from Sri Lanka indicated compliance with local standards for parameters like pH and total dissolved solids (TDS) suggesting suitability for agricultural use, with further analysis required for portable applications.[8] In Iran, a study conducted in Bandar Abbas evaluated the quantity and chemical quality of condensate water produced by air conditioning systems. The research revealed that each air conditioner generated an average of 36 L of water per day, with TDS, electrical conductivity (EC), and total hardness (TH) falling within acceptable ranges for various municipal and industrial applications.[9] Assuming an office building has 50 air conditioning units, each producing 36 L/d, the daily water production would be 1,800 L and the annual water production would be 657,000 L or 657 cubic meters.[9]

This indicates that significant volumes of usable water could be harvested from air conditioners in this coastal city, which is crucial given the region's water scarcity.[8] In Sri Lanka, a research in 2024 revealed that the condensate water met local standards for irrigation and agricultural use, with parameters such as pH, TDS, and turbidity showing good compliance with safety standards.[10] Also, another study in Dhaka, Bangladesh in 2023 showed that the quality of condensate water from air conditioning systems is suitable for non-potable applications. It assessed various physicochemical parameters and finds that the condensate water quality is generally high, making it suitable for uses such as irrigation and cooling towers.[11]

Under current conditions, traditional water sources are unable to meet the growing demands of populations in arid regions such as Iranshahr. Therefore, the adoption of new technologies that focus on water reuse—particularly the recovery of condensate from air conditioning systems—has become necessary. However, limited information is available regarding the chemical quality of this water, its suitability for irrigation or drinking purposes, and the potential effects of environmental fluctuations on its quality. Consequently, comprehensive chemical analysis and quality assessment, including the application of modeling tools such as Monte Carlo simulation, are essential. To the best of our knowledge, this study is the first to employ Monte Carlo simulation to evaluate the quality of condensate water generated by split air conditioning systems.

Materials and Methods

Study Area

Location of Iranshahr county in Sistan and Baluchestan province has been showed in Figure 1. This city has an extremely hot and dry climate, with a record high temperature of 50.0 °C and an annual average temperature of 27.3 °C. The mean daily maximum in July reaches 44.4 °C. Annual precipitation is very low at 103.9 mm, with only about 13 days of measurable rain per year. Also, average annual relative humidity is 27.2%, ranging from a low of 18.0% in June to a high of 44.0% in January. The water supply of this county is provided annually by 1,042 wells, 13 qanat channels, and several spring channels, with a combined yield of 5.95 million cubic meters, in addition to the Kajo rivers, which contribute approximately 500 million cubic meters on average each year.[12]

Sample Collection

Water samples from the air conditioner units were collected according to a planned procedure and in compliance with standard protocols: in June of last year, 30 samples were collected from various split-type AC units. One day prior to sampling, the purpose, procedure, and conditions of sample collection were clearly explained to the shopkeeper or homeowner. Upon receiving their consent and cooperation, samples were collected the following day. Before sampling, all laboratory equipment and containers were thoroughly washed with an acid-wash solution (0.1 N HCl) and rinsed with distilled water to prevent contamination. Water samples were collected in 1-liter HDPE bottles. Immediately after collection, samples were stored at low temperatures in an icebox and transported promptly to the chemistry laboratory

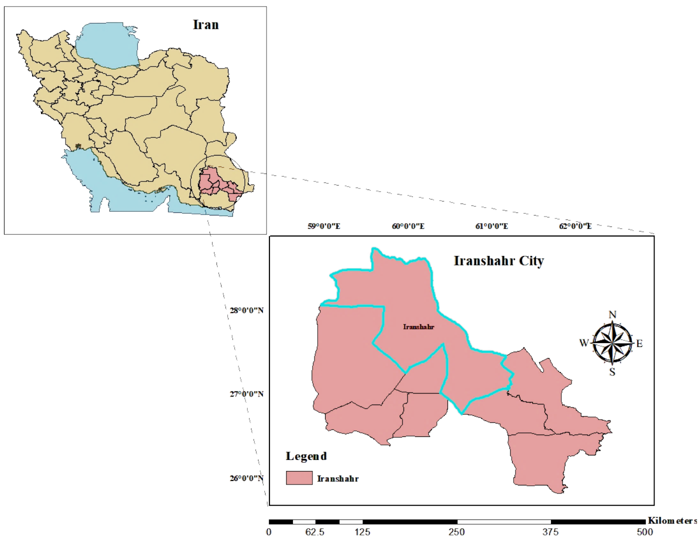

Figure 1. Location of Iranshahr County in Sistan and Baluchestan Province

refrigerator to preserve their chemical integrity until analysis. Each sample was clearly labeled with relevant information, including sample name/code, air conditioner type, date of collection, and sampling point. Before any analytical procedures were conducted, the pH meter and other measurement devices were calibrated according to the manufacturer's instructions to ensure accuracy and reliability of results.

Chemical Analysis

The water samples were tested as per Standard Methods for the Examination of Water and Wastewater (APHA, 23rd edition).[13] The concentrations of ions: Cl, Na, Ca, and Mg were measured using titration methods or atomic absorption spectroscopy (AAS); HCO_3 and CO_3 ions were determined by acid-base titration. Also, TDS and EC were determined using the Aqualytic CD24 device; TH was measured by titration and Merck kit; and pH was measured using an Elmetron pH meter, model CP-501.

Water Quality Index (WQI) Method

In this study, a common and basic formula called the WQI was employed. To calculate the WQI, various water quality parameters measured, including EC, pH, HCO_3, CO_3, TDS, TH, Cl, Ca, Mg, and Na, were used. The World Health Organization (WHO) standards were also considered. Parameters with low significance were assigned a weight of 1, while those with high importance were assigned a weight of 5. The WQI calculation was performed based on specific equations (1-4).[14, 15]

$$W_i = \frac{w_i}{\sum_{i=1}^{n} wi} \quad (1)$$

$$q_i = \frac{C_i}{S_i} \times 100 \quad (2)$$

$$SI_i = W_i \times q_i \quad (3)$$

$$WQI = \sum_{i=1}^{n} SI_i \quad (4)$$

where, W_i is the relative weight, wi is the weight of each parameter, n is the number of parameters, qi is the water quality rating, C_i is the measured concentration of each parameter, S_i is the drinking water standard for each parameter (mg/L), and SI_i is the sub-index of the i-th parameter (Table 1). Water classification based on WQI has been showed in Table 2.[15]

Sodium adsorption ratio (SAR)

SAR expressed as equation 5 is a measure of irrigation water quality and soil effect. The parameter quantifies the relative sodium (Na) content to calcium (Ca), magnesium (Mg) in water and enables one to predict the risk of Na accumulation in the soil, leading to such problems as reduced soil permeability.[17]

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{+2} + Mg^{+2}}{2}}} \quad (5)$$

where, SAR is sodium adsorption ratio. Na, Ca, and Mg represent the concentrations of sodium, calcium and magnesium ions (meq/L), respectively. Water classification based on SAR and EC has been showed in Table 3.

Data Analysis

Data obtained from the chemical analyses were statistically analyzed using SPSS (Statistical Package for the Social Sciences). Descriptive statistics, including means and standard deviations, were calculated for each parameter. Monte Carlo simulation was employed to model and predict potential variations in water quality and quantity under different scenarios. Moreover, sensitivity analysis was conducted to identify the most influential factors affecting the water quality and to assess the robustness of the simulation results.

Results and Discussion

Analysis of Chemical Quality of Condensate Water

In this study, the average age of the air conditioners was 2.81 years. The water quality analysis of the condensate revealed an average concentration of chloride, Na, Ca, and Mg was 51.91, 67.49, 14.37 and 20.01 mg/L, respectively. Temporary hardness averaged 127.23 mg/L as $CaCO_3$, permanent hardness 178.38 mg/L as $CaCO_3$, and TH reached 305.62 mg/L as $CaCO_3$. TDS were measured at 196.15 mg/L, EC at 296.74 µS/cm, and pH was slightly

Table 1. Comparison of water quality parameters with WHO standards and calculation of it WQI[16]

Parameter	Concentration		
	Weight (w_i)	Relative weight	WHO standard
Cl (mg/L)	3	0.097	200
Na (mg/L)	2	0.071	200
Ca (mg/L)	2	0.077	75
Mg (mg/L)	2	0.083	50
HCO_3	1	0.045	500
CO_3	4	0.190	500
TDS (mg/L)	5	0.294	1000
TH	4	0.333	500
EC (µs/cm)	4	0.500	300
pH	4	1.000	6.5-8.5

Table 2. Water classification based on WQI[15]

WQI value	Water quality	Purpose of Uses
0-25	Excellent	Drinking, irrigation, and industrial
26-50	Good	Drinking, irrigation, and industrial
51-75	Moderate	Irrigation and industrial
76-100	Poor	Irrigation
>100	Very poor	Proper treatment required

alkaline at 7.13. These values represented typical water quality parameters of air conditioner condensate water. Notably, the samples from Evvoli air conditioners showed significantly elevated sodium (287 mg/L) and chloride (220.77 mg/L) levels, which exceed acceptable drinking water standards and may pose potential health risks (Table 4).

The values of pH, TH, EC, and chloride obtained in this study differed significantly from those reported in similar investigations conducted in various countries (Table 5). Our findings were partly consistent with those reported by Miranzadeh et al, who performed in Kashan, Iran, where AC condensate exhibited an average TH of 13.67 mg/L as $CaCO_3$, TDS ranging from 8 to 42.5 mg/L, an average chloride concentration of 21.4 mg/L, and a slightly acidic pH of approximately 6. However, concentrations of certain heavy metals, such as lead (0.03–0.036 mg/L) and arsenic (0.04–0.046 mg/L), exceeded the WHO and Iranian limits, making the water unsuitable for drinking.[19] These differences indicate the influence of regional factors,

Table 3. Classification of water quality based on salinity and sodicity levels[18]

Water Classification	Salinity amount EC (µs/cm	Sodicity SAR	Water application
Excellent	Up to 250	Up to 10	Suitable for all irrigation and drinking.
Good	250-750	10 to 18	Acceptable; caution for sensitive crops
Fair/medium	750-2000	18 to 26	May cause salinity issues; needs management.
Poor/bad	2000-3000	>26	Unsuitable for agriculture and drinking

Table 4. Water parameters of various air conditioner samples

Sample	Age (year)	Type of Air conditioner	Cl (mg/L)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	Temporary hardness (mg/LCaCO$_3$)	Permanent hardness (mg/LCaCO$_3$)	Total Hardness (mg/LCaCO$_3$)	TDS (mg/L)	EC (µs/cm)	pH
1	5	LG	16.30	21.20	24	19.2	140	260	400	17.2	93.2	7.6
2	4	General	47.58	61.86	8	21.6	110	150	260	176.8	272	7.7
3	1.5	Evvoli	47.40	61.63	8	18	95	120	215	176.2	271	6.7
4	4	Samsung	39.53	51.40	20	21.6	140	160	300	148	226	6.2
5	3	Evvoli	220.77	**287.0**	28	31.2	200	430	630	**822**	1262	7.2
6	1	Haier	70.67	91.88	12	16.8	100	160	260	236	404	7.5
7	3	Hisense	32.38	42.10	12.8	19.2	112	155	267	162	185.1	7
8	3	Evvoli	37.78	49.12	8	25.2	125	140	265	143	216	7.39
9	3	LG	40.93	53.22	12	19.92	113	135	248	139	234	6.95
10	2	Samsung	28.34	36.84	16	22.08	132	145	277	112	162	7.2
11	3.5	GREE	30.79	40.03	14	19.68	117	147	264	126	176	7.22
12	0.5	GREE	35.39	46.01	16	24	140	162	302	159.7	202.3	7.44
13	3	Evvoli	26.94	35.02	8	1.62	130	155	285	132	154	6.6
Mean	2.81	------	51.91	67.49	14.37	20.01	127.23	178.38	305.62	196.15	296.74	7.13
SD	1.2	-------	50.3	65.4	6.1	6.4	25.5	79.3	102.3	186.7	287.7	0.4

Table 5. Comparison of Key Water Quality Parameters in Air Conditioner Condensate Across Different Studies and Regions

References	Quality Parameters pH	TH (mg/L)	EC (µS/cm)	TDS (mg/L)	Cl (mg/L)
Present Study	7.13	305.61	296.73	196.15	51.9
Okeyinka et al (2021, Nigeria)[21]	5.82	84	17.2	22.5	11
Siam et al (2019, Palestine)[7]	6.4–7.59	-	-	-	-
Uddin et al (2019, Bangladesh)[23]	6.30	-	-	25.04	-
Matarneh et al (2024, Jordan)[20]	-	-	-	-	5.23
Bryant & Ahmed (2008, Doha)[24]	6.5	-	86	-	1.2
Siriwardhena & Ranathunga (2012, UAE)[25]	5.5–6.5	-	60–100	-	1–3.2
Loveless et al (2013, Saudi Arabia)[26]	5.7	-	63.7	-	-
Mahvi et al (2013, Iran)[9]	6.6–6.9	-	6.6–6.9	-	-
Amer et al (2015, Qatar)[27]	6.5–8.5	-	0–400	-	0–250

types of air conditioners, and environmental conditions on the quality of condensate water.[7, 20, 21] Similarly, a study in Jeddah, Saudi Arabia, found that condensate from split and window AC systems produced substantial volumes of water, with maximum monthly outputs of 2,274 L for split ACs and 1,146 L for window units, strongly correlated with humidity levels ($r = 0.77$ for split ACs, $r = 0.73$ for window ACs; $p \leq 0.01$). The physicochemical parameters of Jeddah AC condensate—including pH, TDS, EC, COD, phosphates, chlorides, sulfates, and heavy metals—were generally within the WHO guidelines, and microbial contamination was limited to a few non-pathogenic *Bacillus* strains.[22]

Analysis of Condensate Water Quality Based on Monte Carlo Simulation

The Monte Carlo simulation-based sensitivity analysis showed that Ca^{2+} and Mg^{2+} ions had the greatest impact on WQI of condensate water. Mg accounted for approximately 42% of the WQI sensitivity, accounted for about 35%, whereas other parameters such as bicarbonate, chloride, TH, TDS, carbonate, and pH had lesser effects. These results highlight the importance of precise monitoring and control of these two hardness-causing ions for optimal management of condensate water quality, as even small changes in their concentrations can noticeably affect the physical and chemical properties of the water and lead to issues such as scaling and equipment corrosion (Figure 2a). Besides, the histogram of WQI values in the samples ranged from 32.14 to 126.6, with the highest frequency observed in the range of 60 to 80. As seen in Table 2, which classifies water quality based on WQI values, this range corresponds to "Moderate" to "Poor" water quality.[15] Specifically, WQI values between 51 and 75 indicate moderate quality, suitable for irrigation but requiring treatment before drinking, while values between 76 and 100 are considered poor and need attention for irrigation use. The data distribution is relatively normal with considerable dispersion, reflecting the influence of various variables, especially Ca and Mg, on water quality. These findings emphasize the need for improved treatment processes and precise management of hardness ions to maintain desirable water quality and prevent negative environmental and operational impacts

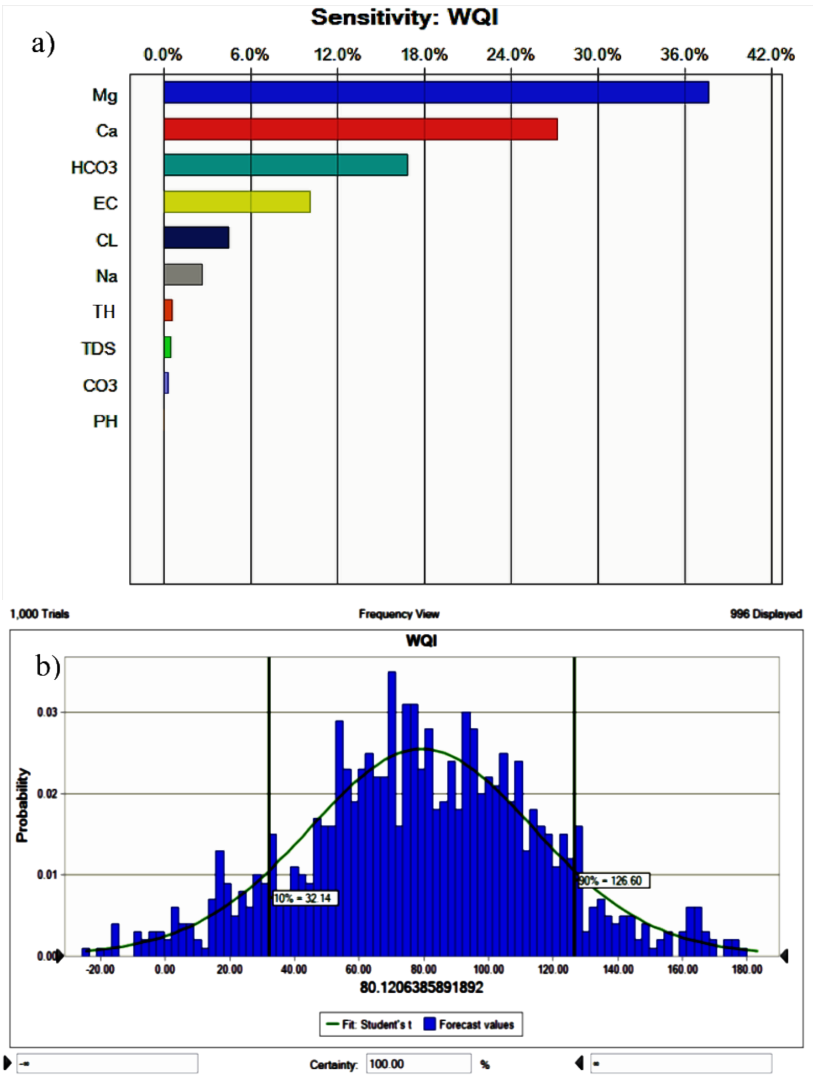

Figure 2. (a) Sensitivity of WQI to major ions, highlighting Ca and Mg; (b) Distribution of WQI values for condensate samples in Iranshahr based on Monte Carlo simulation

(Figure 2b). Integrating Monte Carlo simulation with the WQI offers a probabilistic approach to assess condensate water quality more accurately. Unlike the traditional WQI, which provides a deterministic result, this method accounts for sampling uncertainties and natural variations by generating a range of possible water quality scenarios. This enables the identification of high-purity condensate sources, highlights key factors influencing quality, and supports risk-informed management. Combined with simple polishing treatments, this approach could help establish condensate water as a safe and practical supplementary water resource.[28, 29]

Quality of Condensed Water From Air Conditioners Based on the SAR and EC Indexes

Condensate water can be used to irrigate gardens and green spaces, often without the need for treatment. By installing proper piping systems, gardens can be designed for automatic irrigation using this water source. The volume of condensate produced by large central air conditioning systems is typically sufficient to meet the irrigation needs of surrounding green areas.[30] However, certain parameters, such as the SAR and EC, must be measured. An undesirably high SAR deteriorates the physical structure of soil, as sodium adheres to soil particles and significantly reduces water permeability.[18, 31] Probabilistic analysis provides an effective framework for evaluating the irrigation suitability of air-conditioner condensate water based on SAR and EC distributions. Based on 1,000 Monte Carlo simulations, the mean SAR was 17.07, with approximately 81.86% of the simulated values falling below 36.89 (Figure 3). According to standard water quality classification (Table 3), most samples fell within the "Good" range (SAR between 10 and 18), which is suitable for most agricultural uses, although caution should be taken for sodium-sensitive crops.[18] Modeling EC as a normally distributed variable with a mean of 296.74 µS/cm and a standard deviation of 287.7 µS/cm revealed that 69% of EC values belonged to the "Excellent" class ($EC \leq 250$ µS/cm). This indicates that most samples exhibit very low salinity and pose a minimal risk of salt accumulation in soils, a particularly important advantage in arid and semi-arid regions.[32] The integration of cumulative distribution functions (CDFs) with standard water quality classifications allows for a more reliable assessment of irrigation suitability by quantifying the probability of samples falling into specific quality classes. Similar probabilistic and CDF-based approaches have been successfully applied in water quality assessment to improve classification accuracy and decision support.[33] Overall, the predominance of samples in the "Excellent" and "Good" categories confirms the high potential of air-conditioner condensate water for irrigation reuse. However, the occurrence of higher SAR values in a fraction of the simulations highlights the need for continuous monitoring and appropriate soil and crop management practices to ensure sustainable use.

Conclusion

The widespread use of AC equipment in tropical regions generates substantial amounts of condensate water. Monte Carlo sensitivity analysis revealed that water quality was strongly influenced by the hardness ions Ca^{2+} and Mg^{2+}, which contributed the most to changes in the WQI. Even minimal variations in their concentrations can lead to operational issues such as scaling and equipment corrosion. Sample analysis indicated that most condensate water fell within a "moderate" to "poor" WQI range, emphasizing the need for consistent monitoring and precise treatment protocols. Regarding irrigation suitability, the SAR suggests this water is generally appropriate for most crops, though caution is advised for sodium-sensitive varieties. Furthermore, EC values showed that most samples were of "good" to "excellent" quality, indicating low salinity risk. To safely optimize this water resource, effective management of hardness ions, proper maintenance of AC

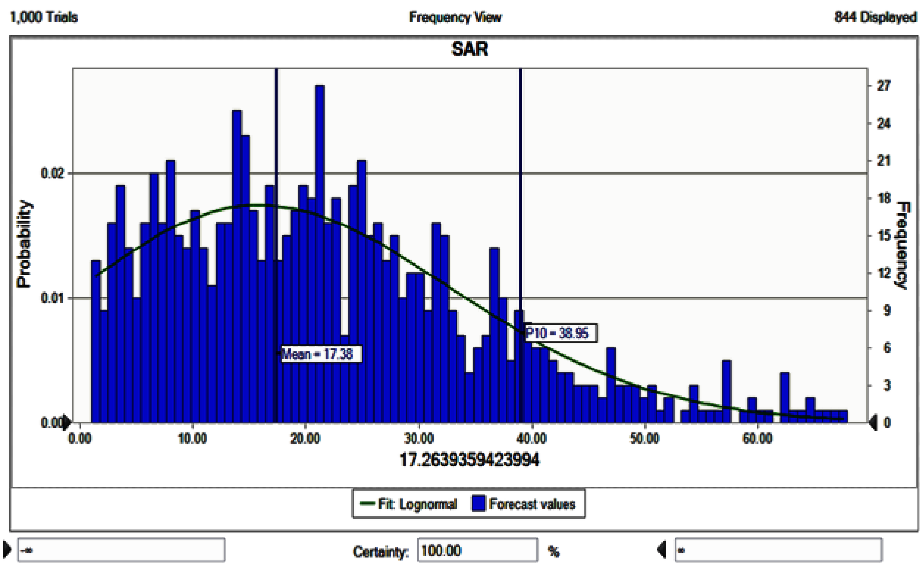

Figure 3. SAR distribution of condensate water with a mean of 17.38; most samples were suitable for irrigation

systems, and targeted treatment are essential. This study has certain limitations, including a restricted geographical range for sample collection, potential variability in condensate quality due to differing AC system designs, and a lack of long-term data to assess seasonal or operational fluctuations. Focusing on these in future research would strengthen the findings' reliability and comprehensiveness. Finally, employing Monte Carlo simulation techniques, an approach not yet widely used in this specific field, is highly recommended for future studies. This method can effectively handle data uncertainty, provide a probabilistic assessment of water quality, and noticeably enhance the depth of analysis, offering valuable data for comparative research.

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Competing Interests
None.

Ethical Approval
This study was approved by the Ethics Committee of the Research and Technology Deputy of Iranshahr University of Medical Sciences (Ethical Code: IR.IRSHUMS.REC.1402.003).

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