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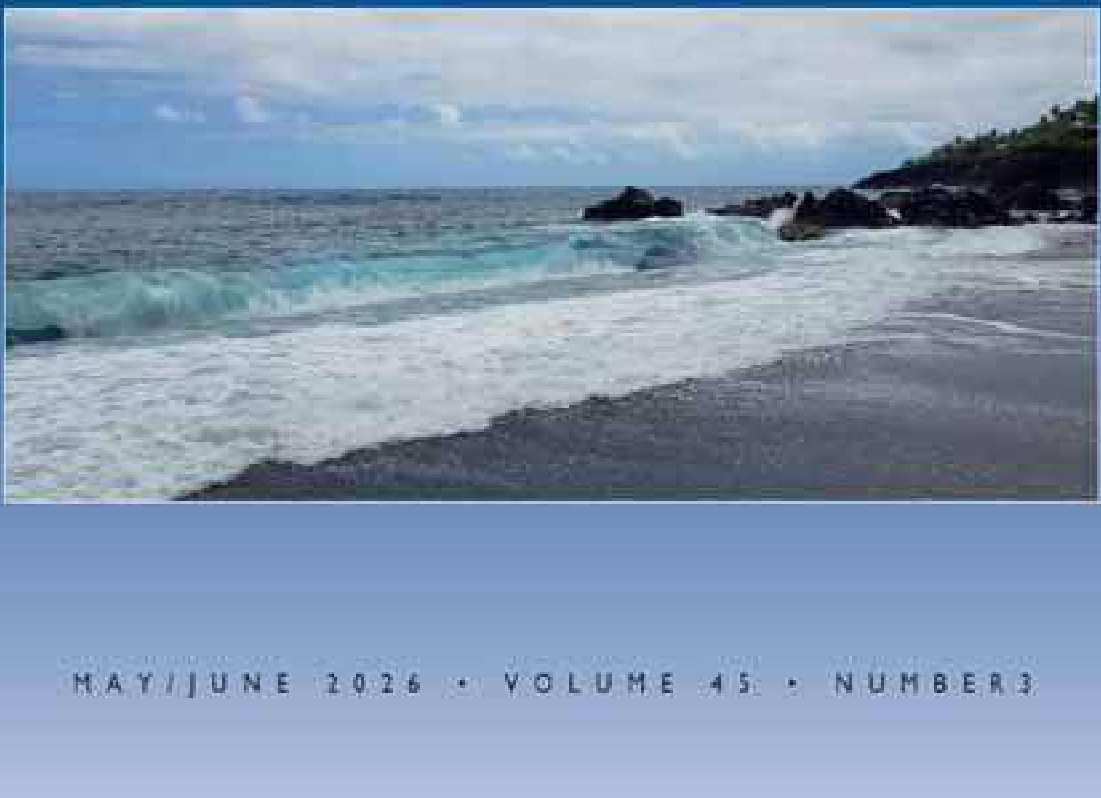

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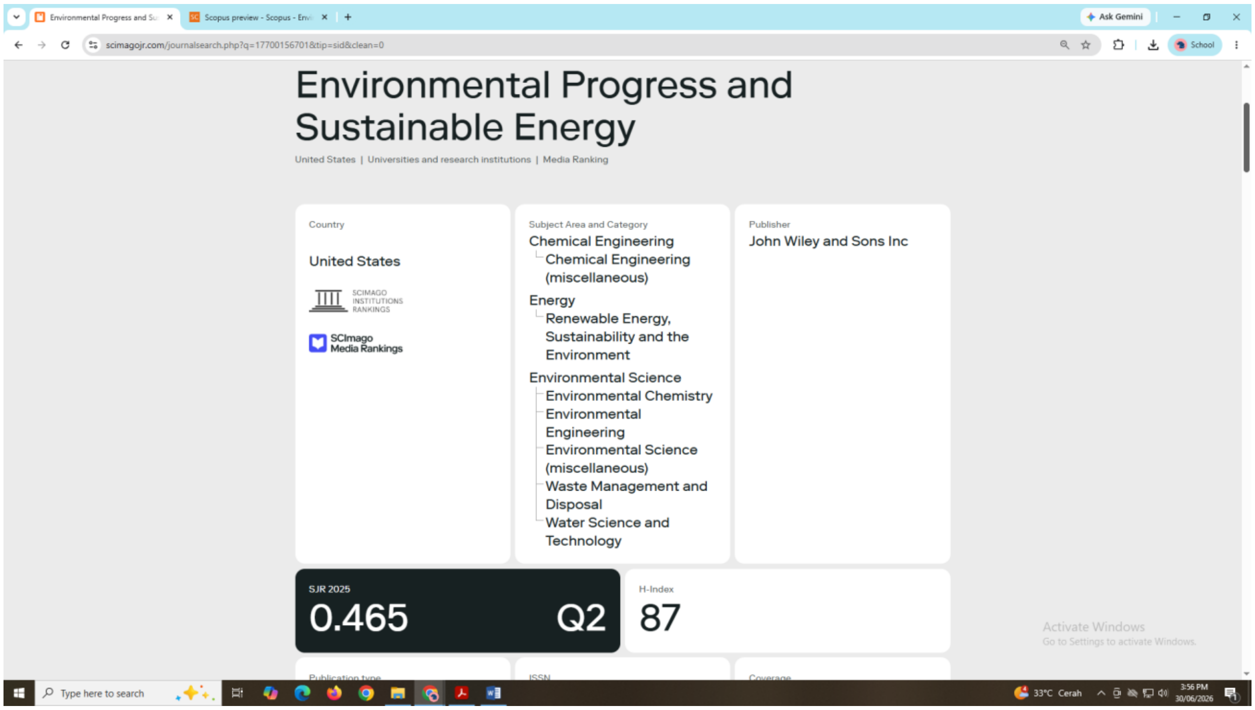

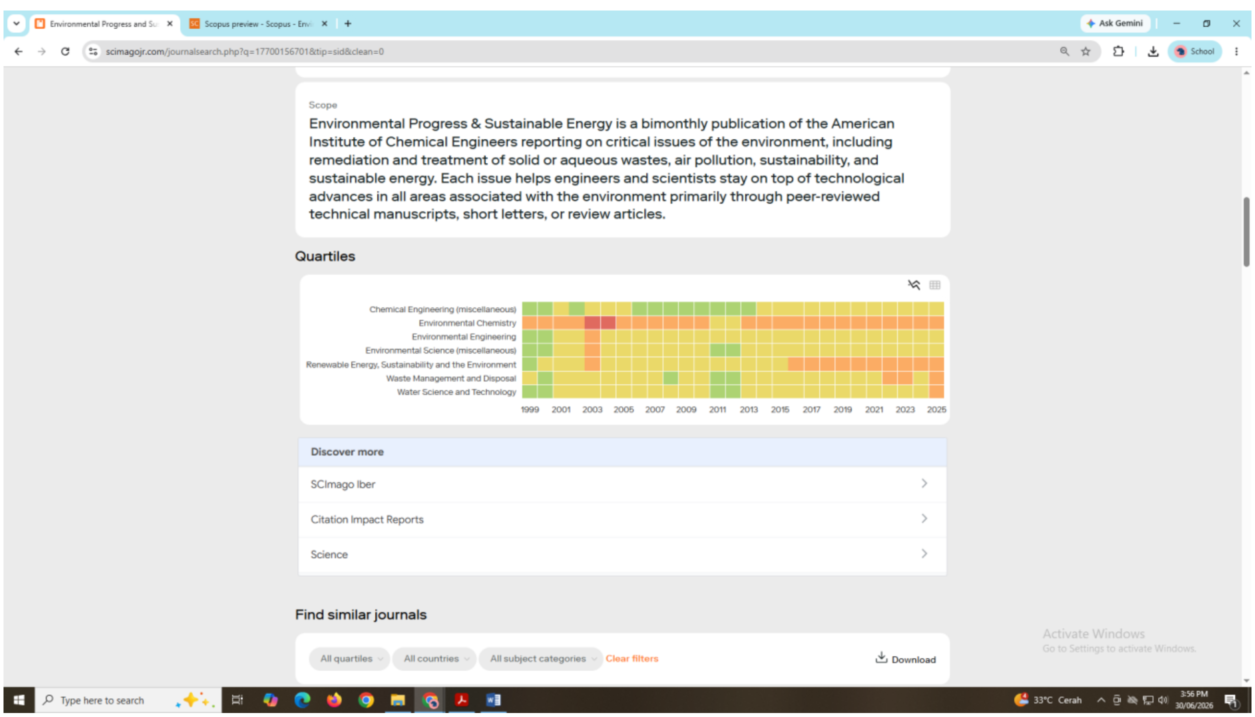

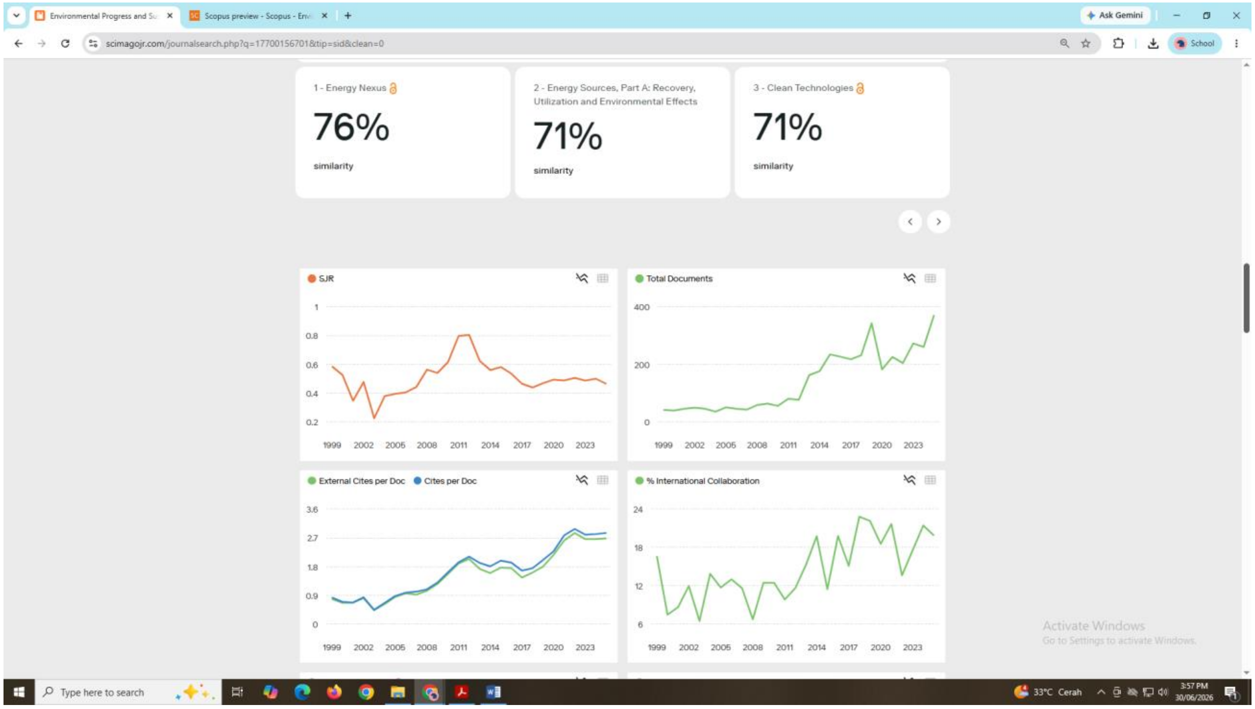
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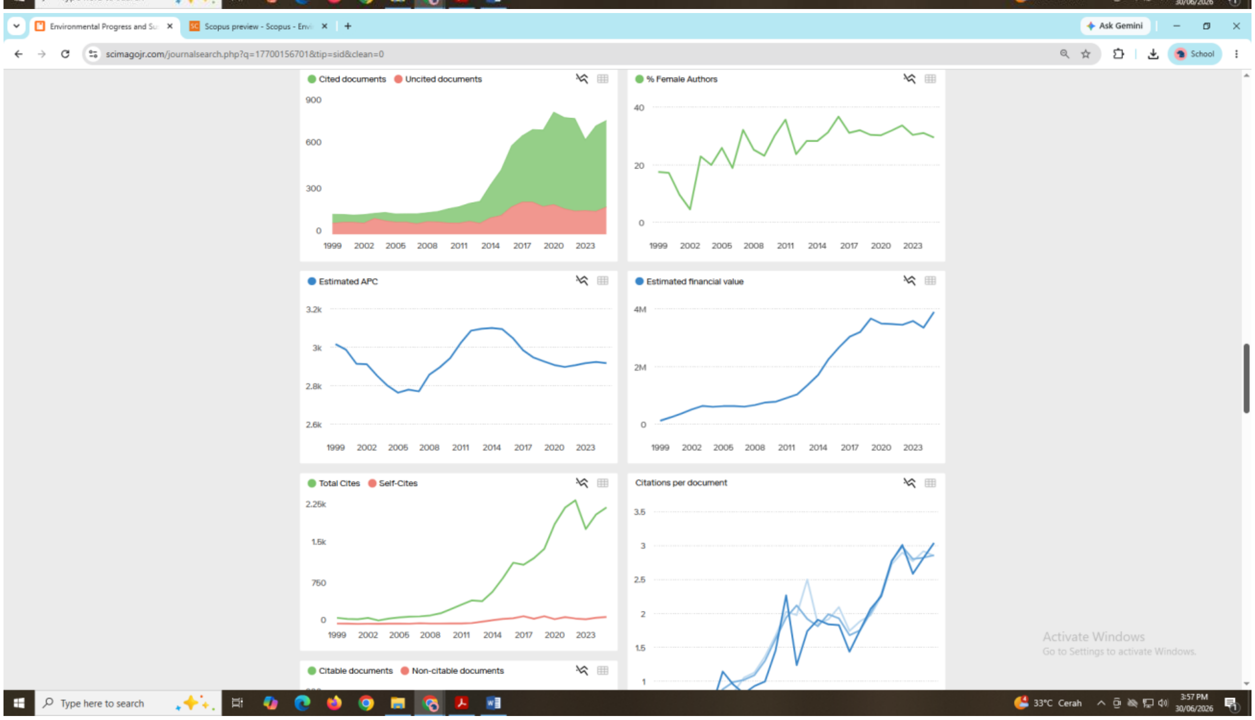
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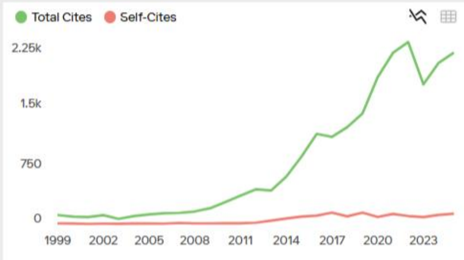

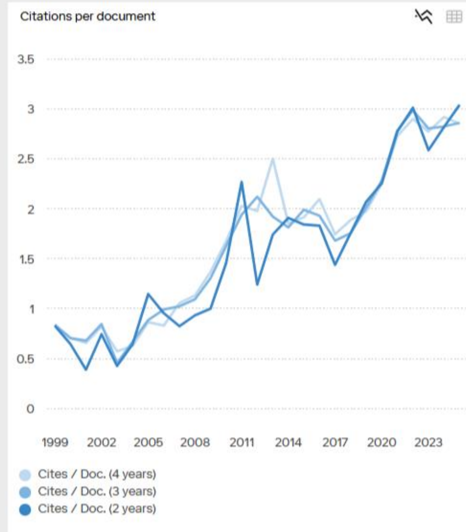

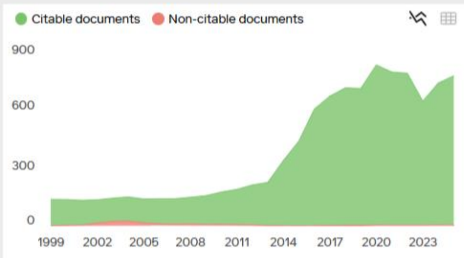

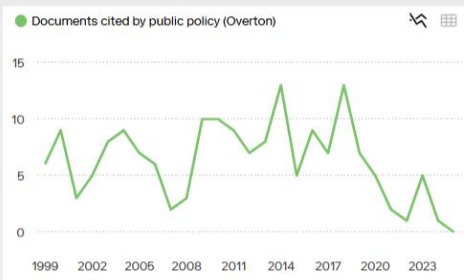

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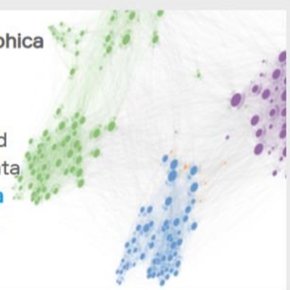

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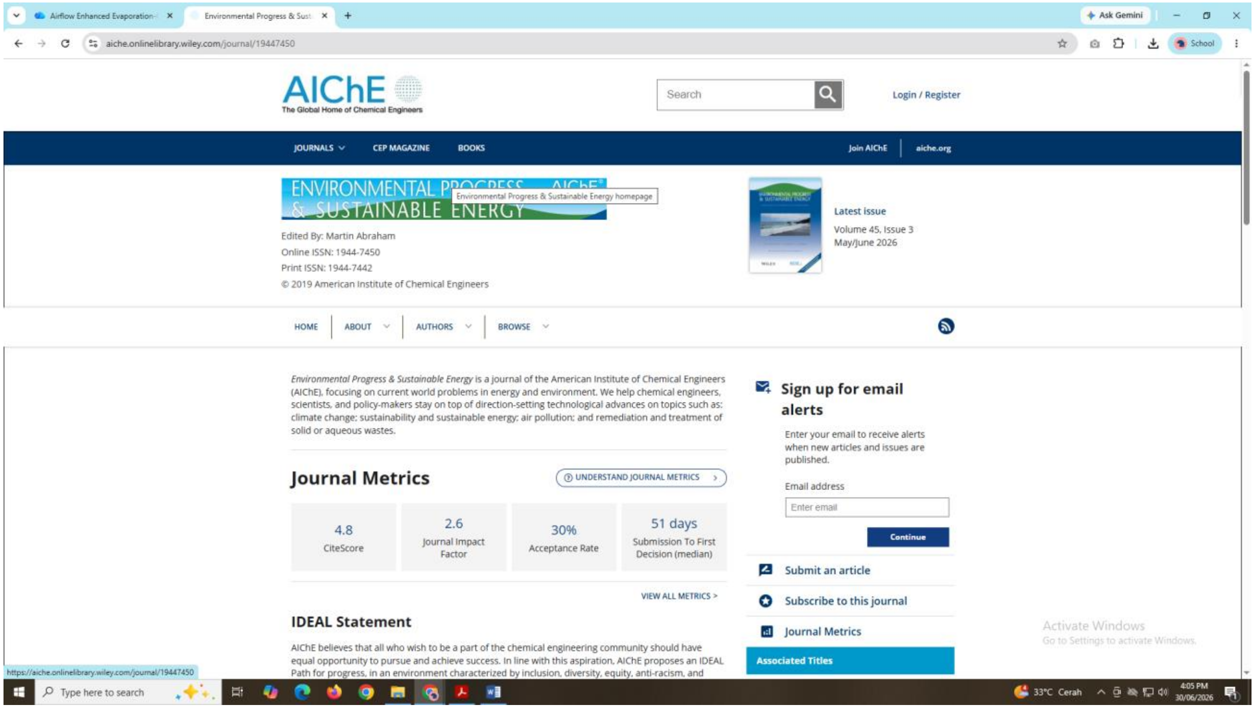

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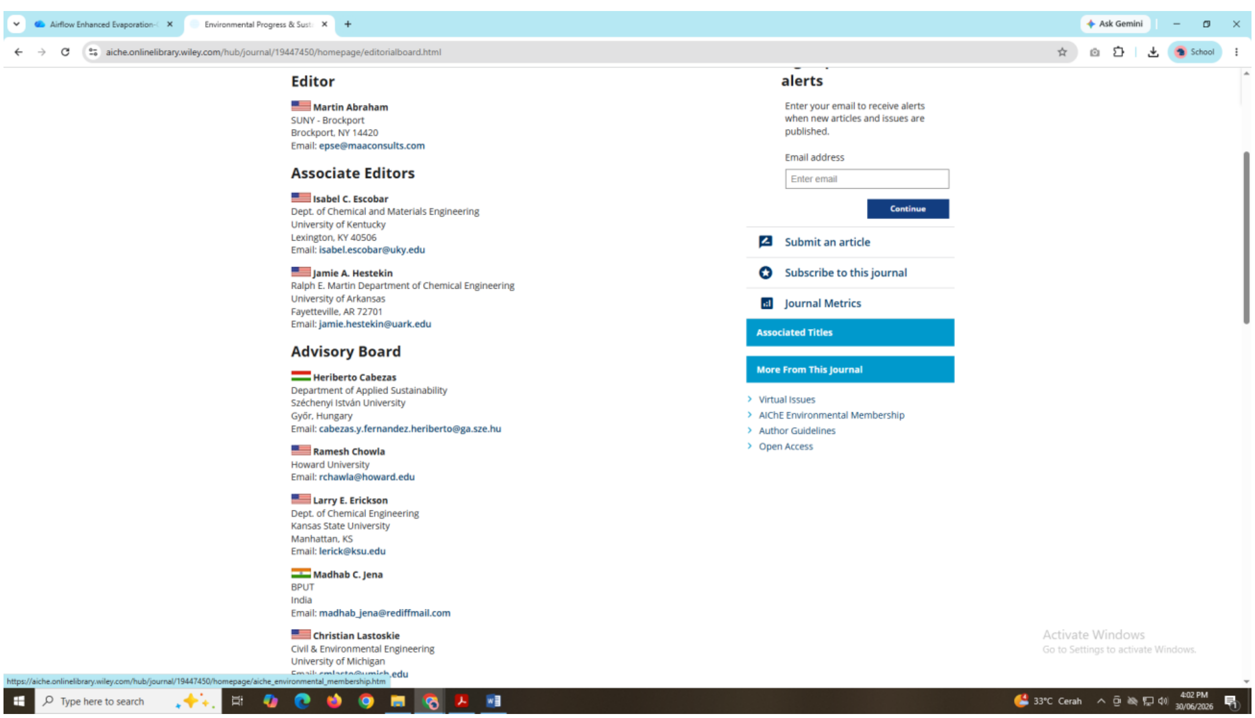

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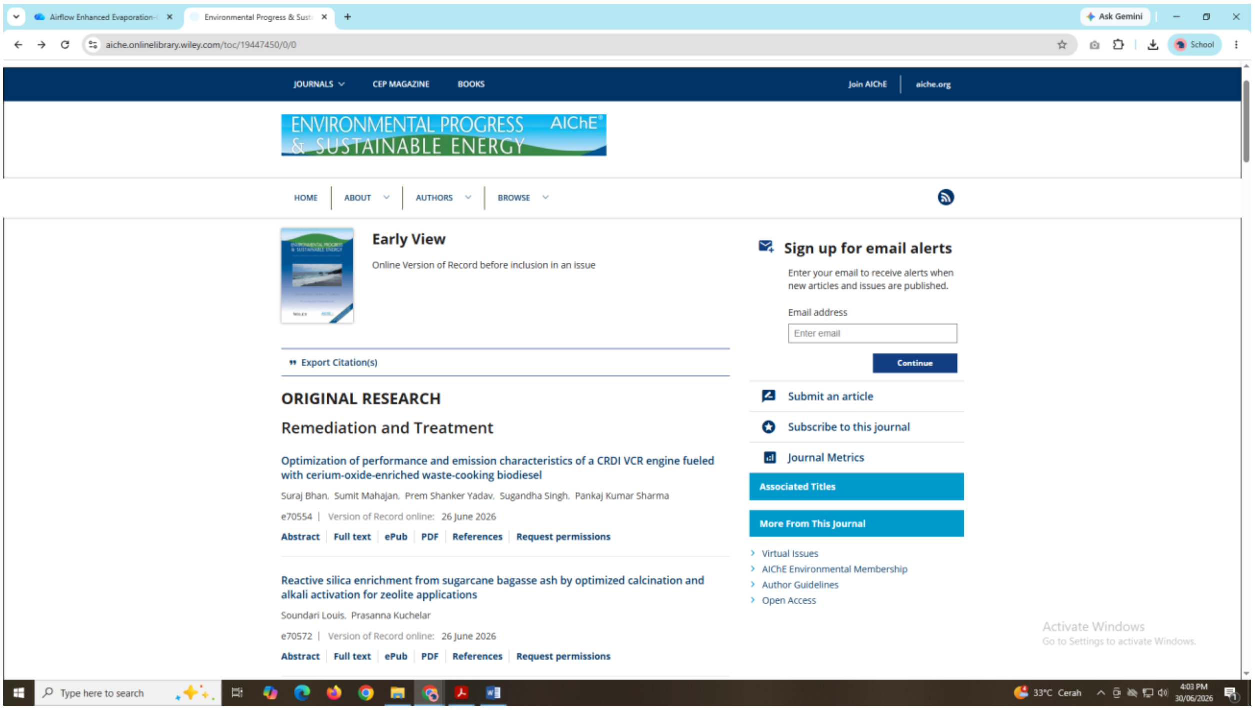

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ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

ORIGINAL RESEARCH

Sustainable Energy

Airflow-enhanced evaporation–condensation seawater desalination using residential air conditioner waste heat

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Abstract

Water scarcity remains a major global challenge, particularly in developing countries with limited freshwater access. At the same time, the increasing use of residential air-conditioning (AC) systems generates substantial low-grade waste heat that is typically rejected into the environment. This study investigates a household-scale evaporation–condensation desalination system driven by waste heat recovered from a residential split-type AC unit. The proposed system integrates vortex-generator-assisted airflow enhancement within a compact evaporation channel to intensify heat using channels with different cross-sectional areas under vortex-generator (VG) and non-vortex-generator (NVG) configurations. Air temperature, relative humidity, evaporation rate, seawater salinity, and AC coefficient of performance (COP) were measured, while computational fluid dynamics (CFD) simulations were performed to analyze airflow and evaporation behavior. The results showed that vortex generators enhanced airflow mixing and evaporation performance. Maximum freshwater production of approximately 950–980 mL/h was achieved at channel cross-sectional areas of 0.015–0.025 m^2. Although COP decreased from 3.92 to approximately 3.02 under the most restrictive channel configuration, the values remained within the typical residential AC operating range. The CFD predictions showed strong agreement with experiments, with $R^2 > 0.95$ and average deviations below 10%. A preliminary economic analysis estimated the operational cost at approximately USD 0.017/L of freshwater produced. The proposed system demonstrates promising potential for decentralized and energy-efficient household freshwater production using readily available AC waste heat.

KEYWORDS

air conditioning, CFD simulation, desalination, vortex generator, waste heat

1 | INTRODUCTION

Although water is a basic need for human life, freshwater resources, which represent only about 2.8% of total global water resources, are limited.[1] Moreover, a 15% increase in population may result in a water shortage of up to 40% of total water demand.[2,3] Water scarcity can trigger humanitarian, political, and social conflicts.[4] This challenge is particularly pronounced in many coastal and tropical developing regions, where limited freshwater resources and growing populations increase vulnerability to water shortages and present challenges in accessing clean water.[5–7]

Global warming, another critical issue, has intensified the use of air conditioning (AC) units in tropical regions.[8,9] During operation, AC units reject low-grade heat (50–80°C) into the environment without recovery,[10] thus constituting a widely available but underutilized thermal resource. In dense urban areas, the accumulation of waste heat from AC units can increase local ambient temperatures by up to 1°C,[11,12] thereby exacerbating the urban heat island effect. Recovering this waste heat therefore offers a dual benefit: improving energy utilization and mitigating localized thermal accumulation.

One potential approach to utilizing this waste heat is evaporation–condensation desalination, whereby hot air is directed over seawater to generate vapor that is subsequently condensed into freshwater. The use of waste heat from AC units as a thermal source can drive the desalination process while simultaneously reducing environmental thermal discharge and producing freshwater as a valuable by-product. Airflow over water surfaces has been shown to significantly enhance evaporation by increasing convective heat and mass transfer at the air–water interface[13] and influence distillation productivity in evaporation–condensation desalination systems.[14]

1.1 | Literature review of desalination using AC

Previous studies have investigated heat pumps, solar thermal systems, photovoltaic thermal (PV/T) systems, and AC-assisted desalination technologies, including multistage flash distillation (MSF), membrane distillation (MD), adsorption desalination (ADS), and humidification–dehumidification (HDH), to improve thermal efficiency and reduce energy consumption.[15–20] Although hybrid desalination systems driven by low-grade thermal energy have shown promising capability for improving freshwater productivity and energy,[21–23] many existing systems are designed for relatively large-scale applications and commonly require solar collectors, auxiliary heating systems, or complex thermal integration.

Recent studies have also explored the recovery of waste heat from residential AC systems for simultaneous cooling and freshwater production. Condenser waste heat from vapor–compression refrigeration systems has been reported to provide sufficient low-grade thermal energy for seawater heating and evaporation in HDH and membrane-based desalination systems.[24–27] Nevertheless, many proposed systems still depend on solar-assisted heating, evaporative condensers, multistage humidification arrangements, or additional thermal components, all of which increase complexity and installation cost.

Evaporation enhancement remains a key factor governing freshwater productivity because thermal desalination strongly depends on heat and mass transfer at the air–water interface. Previous studies have shown that improving airflow characteristics, turbulence intensity, and boundary-layer disruption significantly enhances evaporation and vapor transport.[28,29] Other enhancement techniques, including thin-film evaporation, wick structures, porous materials, and photothermal evaporation, have also demonstrated improved freshwater productivity.[30,31] Previous investigations further reported that lowering pressure above the water surface increases the driving force of evaporation due to higher vapor pressure at the liquid surface.[32]

Based on these considerations, the present study investigates a residential split-type AC waste-heat-driven desalination system combined with vortex-generator-assisted airflow enhancement. In contrast to many previous solar-driven or multi-component HDH desalination systems, the proposed configuration focuses on a compact household-scale arrangement utilizing existing residential AC infrastructure. Hot air rejected from the condenser is directed through an evaporation channel above the brine surface, while vortex generators intensify airflow mixing and turbulence near the air–water interface. Combined experimental investigation and CFD analysis were performed to evaluate evaporation behavior, freshwater production, and AC operational performance, thereby contributing to decentralized and energy-efficient desalination technology development.

1.2 | Statement of industrial relevance and novelty

This study is relevant to applications in which energy efficiency and resource recovery are increasingly important, such as heating, ventilation, and air conditioning (HVAC), desalination, and sustainable residential building. Residential AC units continuously discharge low-grade waste heat that is generally released without productive utilization. The proposed system demonstrates how this waste heat can drive a compact evaporation–condensation desalination process capable of producing freshwater at the household scale, particularly for coastal housing, tourism facilities, and small-island infrastructure.

Our previous study demonstrated that vortex generators significantly enhanced evaporation in AC-assisted desalination systems,[33] but the work was limited to numerical analysis without experimental validation or evaluation of system-level performance.

The novelty of the present study lies in its integration of vortex-generator-assisted airflow enhancement with a compact household-scale desalination system driven by residential split-type AC waste heat. In contrast to previous AC-assisted desalination studies that focused mainly on thermodynamic cycle integration or HDH configuration, this work emphasizes airflow-driven evaporation intensification through channel geometry modification and turbulence enhancement. The study further evaluates the trade-off between evaporation enhancement and AC operational performance under different channel cross-sectional areas using combined CFD simulations and experimental validation.

This study therefore aims to design, analyze, and validate a household-scale desalination unit utilizing waste heat from a residential split-type AC system. The effects of channel geometry and vortex generators on airflow behavior, evaporation enhancement, air temperature reduction, and AC coefficient of performance (COP) were systematically evaluated using experimental measurements and CFD simulations.

2 | MATERIALS AND METHODS

2.1 | Description of the desalination unit

The desalination unit (DU) was integrated with a residential AC system to recover condenser waste heat for freshwater production through evaporation–condensation processes. In this system, saline

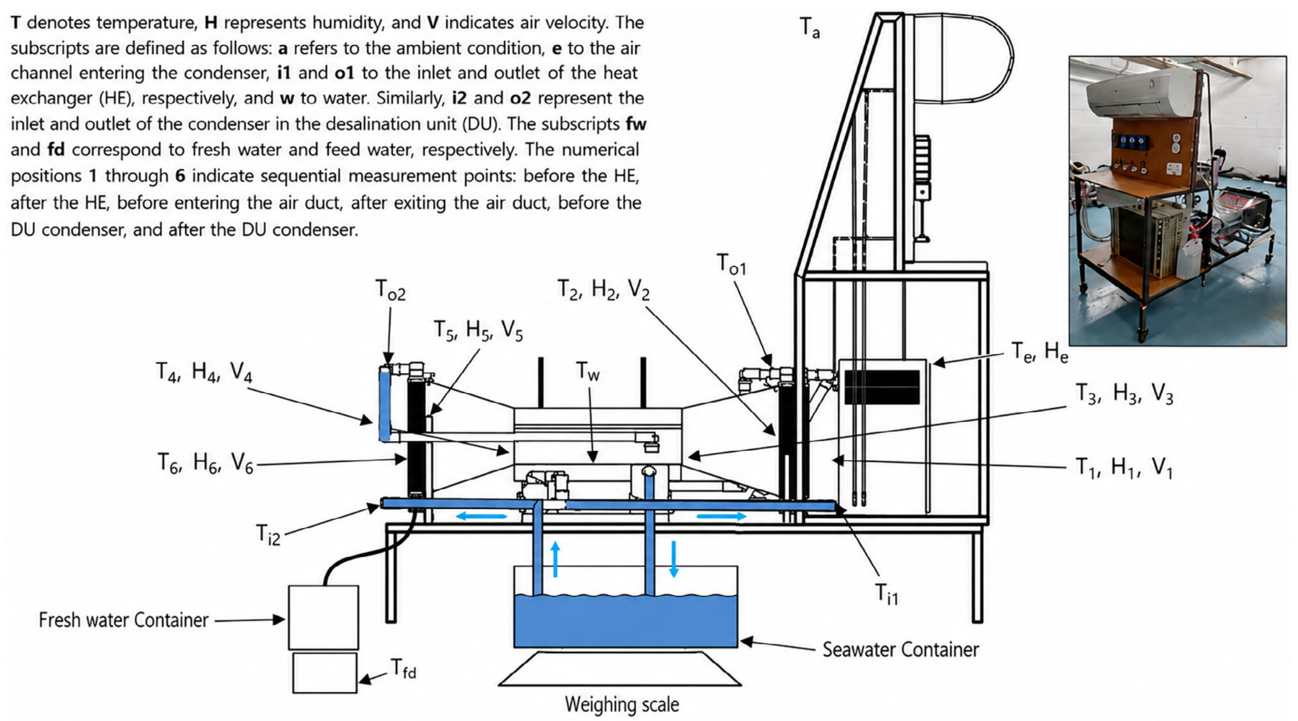

FIGURE 1 Experimental rig.

feedwater is heated using AC waste heat to generate water vapor, which is then condensed on a cooler surface to produce distilled water.

Natural seawater with an initial salinity of approximately 35 ppt was placed inside an evaporator chamber and heated indirectly by a heat exchanger containing freshwater circulated from the AC condenser waste heat loop. The increased seawater temperature promoted evaporation, and the generated vapor subsequently condensed on a cooler surface to produce freshwater. In addition, airflow from the AC condenser was directed through a channel above the water surface to enhance evaporation through forced convection by increasing airflow velocity, turbulence intensity, and vapor transport near the air–water interface. The airflow channel was configured with cross-sectional areas of 0.006, 0.012, 0.018, 0.024, 0.030, 0.036, and 0.042 m^2, each tested with and without vortex generators (VG and NVG). The vortex generators enhanced airflow mixing and boundary-layer disruption, thereby improving heat and mass transfer during evaporation. The experimental setup is shown in Figure 1.

2.2 | Experimental setup and procedures

The data in this study were obtained experimentally and compared using CFD simulation. The instruments used are presented in Table 1.

To enhance airflow mixing and evaporation performance inside the channel, a delta-wing vortex generator (Figure 2a) was selected because it efficiently directs airflow and generates strong vortices

TABLE 1 Experimental instruments.

Device	Range	Accuracy
Thermocouples PT100	−50–110°C	±0.1°C
Weighing scales	0–20 kg	±0.05%
Humidity meter	10%–99%	±1%
Anemometer GM-816	0–30 m/s	±5%
Pressure gauge class 1,6	0–550 psi	±1.6%
Pressure meter PCE-PDA 1L	±2 kPa	±0.5%
Salinity refractometer ATC	0–100 ppt	±1 ppt

with relatively low flow resistance.[34] The ratio of channel height to vortex generator height was set at 0.47 to balance vortex formation and flow obstruction, thereby enhancing mixing while limiting aerodynamic losses.[35,36] In addition, a spacing-to-channel-length ratio of 0.18 was applied to sustain vortex interaction and turbulence,[37] while a 45° attack angle was selected to optimize vortex strength, flow attachment, and thermo-hydraulic performance.[38] The simulated evaporation region is indicated by the red arrows in Figure 2b, while areas outside this region were excluded from the model scope.

The results were validated using CFD simulations performed with Cradle CFD based on its continuity, momentum, and energy equations. Detailed governing equations and numerical settings are provided in Appendix S1.

An octagonal mesh was employed because it provides better grid quality and smoother element transition in complex geometries

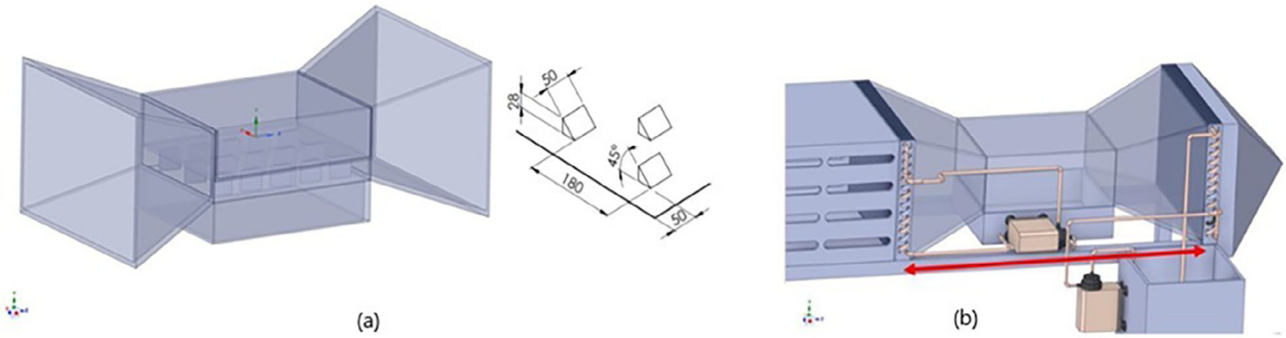

FIGURE 2 Vortex generator (a) and evaporation zone (b).

TABLE 2 Mesh independence study.

No.	No. of elements	Evaporation rate (kg/s m^3)	Difference (%)
1	141,567	0.003998	–
2	221,325	0.004489	0.12
3	532,624	0.004623	0.03
4	821,653	0.004623	0.00
5	1,036,877	0.004623	0.00

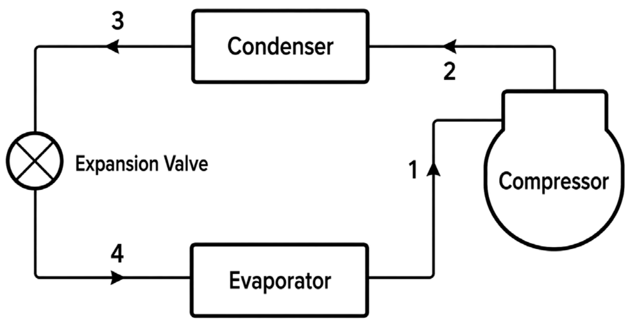

FIGURE 3 Schematic of the refrigeration loop.

compared with conventional triangular or quadrilateral meshes, thereby improving numerical stability and simulation accuracy. A mesh size of 0.05 with a refined region of 0.02 was used, resulting in 532,624 elements based on the mesh independence study (see Table 2).

The mesh independence study was conducted using five mesh densities. The evaporation rate became constant beyond 532,624 elements, indicating that further refinement would have a negligible influence on the simulation results. A relative deviation below 10% was considered acceptable for establishing mesh independence.[39–41]

The simulations focused on evaporation dynamics inside the airflow channel downstream of the AC condenser, where inlet air temperatures reached approximately 55°C. The channel cross-sectional area was varied from 0.042 to 0.006 m^2 to systematically evaluate the effect of airflow confinement on evaporation performance and AC operation. The maximum area of 0.042 m^2 was selected to represent a relatively low-confinement condition, corresponding to approximately two-thirds of the estimated effective condenser fan flow area. The area was then gradually reduced to 0.006 m^2 to increase airflow velocity over the seawater surface and intensify convective heat and mass transfer. However, reducing the channel area also increased pressure drop and airflow resistance, allowing the study to identify the trade-off between evaporation enhancement and AC COP reduction.

Because the desalination unit was directly integrated with the AC system, the operational parameters were selected to represent practical residential operating conditions while evaluating the trade-off between evaporation enhancement and AC performance. Smaller channel areas increased airflow velocity and evaporation intensity, but also increased pressure losses and reduced condenser heat rejection effectiveness, thereby lowering AC COP. Conversely, larger channel areas reduced pressure losses but weakened evaporation enhancement. The vortex generator geometry was adopted from previous thermo-fluid studies[33] to enhance airflow mixing and boundary-layer disruption with minimal aerodynamic penalty.

AC performance was evaluated by measuring refrigerant pressure and temperature at several points in the refrigeration loop, as illustrated in Figure 3. Since the residential split-type AC operated as a factory-integrated commercial unit, condenser fan current and standalone fan power were not measured separately. Therefore, the performance evaluation was based on overall system COP variation before and after integration with the desalination unit. The experiments employed a residential split-type AC unit (SHARP AH-A9BEY2, 1 PK), representing a typical household cooling system in tropical regions. The operating temperature range of 50–60°C corresponded to practical condenser waste heat conditions during normal AC operation while remaining sufficiently low to minimize severe scaling formation.

The following expressions were used to calculate the performance of the vapor compression refrigeration system,[42] the process refers to Figure 3:

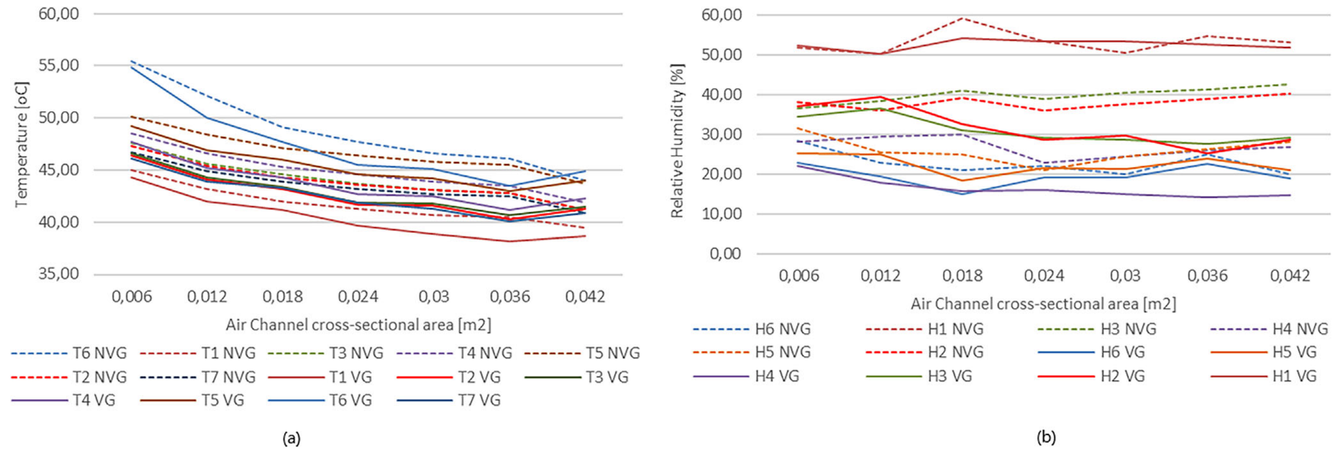

FIGURE 4 Desalination unit temperature (a) and relative humidity (b).

Compression process (processes 1–2):

$$W_c = (h_2 - h_1) \tag{1}$$

Heat rejection process (processes 2–3):

$$Q_c = (h_2 - h_3) \tag{2}$$

Throttling (processes 3–4):

$$h_3 = h_4 \tag{3}$$

Heat absorption (processes 1–4):

$$R_e = (h_1 - h_4) \tag{4}$$

Coefficient of performance (COP):

$$COP = \frac{R_e}{W_c} \tag{5}$$

3 | RESULTS AND DISCUSSION

The experiment evaluated evaporation and condensation behavior using temperature and relative humidity measurements. As shown in Figure 4a, the air temperature decreased for both NVG and VG configurations due to evaporative cooling, while Figure 4b shows that smaller channel cross-sectional areas produced larger humidity fluctuations because of stronger airflow interaction. The relative humidity distribution supports the temperature and evaporation trends. As hot air from the AC condenser passed over the seawater surface, additional water vapor was generated, increasing the local relative humidity. However, RH did not increase uniformly because it depends not only on the amount of vapor added but also on the local air temperature. Warmer air can hold more moisture,[43] therefore, some positions near the condenser fan showed lower RH despite active evaporation. Smaller channel areas produced stronger airflow interaction and larger RH fluctuations, indicating more intensive vapor transport and mixing. In contrast, larger channel areas showed more uniform RH values because of lower airflow velocity and weaker local disturbance. The VG configuration further promoted local mixing, although the RH variation remained strongly governed by channel geometry and temperature distribution. The desalination unit reduced incoming hot-air temperature by approximately 6–11°C.

Although the experiments were conducted under controlled laboratory conditions, ambient temperature and humidity are expected to influence evaporation driving force and condenser heat rejection in practical tropical environments. Higher ambient temperatures may enhance evaporation but simultaneously reduce condenser cooling effectiveness and AC COP, particularly in smaller channel areas with higher airflow resistance. Conversely, high ambient humidity may reduce the vapor pressure gradient and shift the optimal operating condition towards slightly larger channel cross-sectional areas with lower pressure losses.

Consistent with the observed temperature and humidity distributions, Figure 5a shows that increasing the channel cross-sectional area consistently reduced evaporation for both NVG and VG configurations because larger areas decreased airflow velocity and convective heat and mass transfer.[28] Smaller areas generated higher airflow velocity and shear stress, thinning the boundary layer above the water surface and enhancing vapor diffusion. The VG configuration further increased evaporation by inducing longitudinal vortices that enhanced turbulence, airflow mixing, and boundary-layer disruption,[44,45] although channel geometry remained the dominant factor.

A comparison between the experimental and CFD results demonstrated strong agreement, with coefficients of determination of $R^2 = 0.9643$ and $R^2 = 0.958$ for NVG and VG configurations (Figure 5b), respectively.[46,47] Average deviations remained within the accepted validation threshold, reaching 10% for NVG and 6% for VG,[48,49] confirming that the CFD model reliably predicts evaporation behavior across different channel geometries. The produced

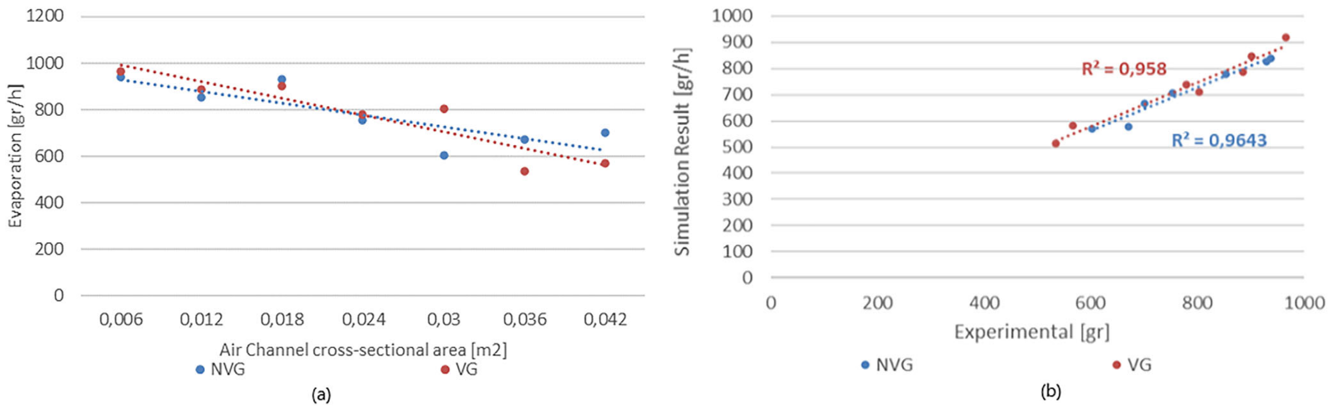

FIGURE 5 Evaporation results for each channel cross-sectional area (a) and comparison of the experimental and simulation results (b).

freshwater had a TDS of approximately 71 ppm and a pH of 6.5, which remain within the acceptable ranges specified by WHO[50] and the Indonesian Ministry of Health regulations for clean water quality.[51] These results also indicate that seawater was not significantly carried over into the condensation section, since the seawater used in this study had a TDS of 31,710 ppm and a pH of 7.7, which are within the typical ranges for seawater, namely a TDS of approximately 29,000–39,000 ppm[52] and a pH ranging from 7.5 to 8.4.[53]

At the smallest channel cross-sectional area (0.006 m^2), the increased flow confinement produced higher pressure losses and reduced condenser airflow effectiveness. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions. Although the fan power and electrical current were not monitored separately from the AC system, the reduction in the overall AC COP indirectly reflects the increased aerodynamic resistance experienced by the condenser airflow under smaller channel geometries.

During operation, continuous evaporation and the addition of make-up seawater gradually increased salinity from approximately 35 ppt to nearly 55 ppt after 8 h. The higher salinity reduced water activity and saturation vapor pressure, slightly decreasing the evaporation driving force. Nevertheless, severe scaling was not observed on the heat exchanger because evaporation mainly occurred in the evaporator basin rather than on the heating surface. Small salt deposits gradually accumulated at the bottom of the basin, while moderate operating temperatures (50–60°C), continuous circulation, and forced airflow helped suppress local supersaturation and scaling formation. However, long-term operation may still require periodic brine discharge or seawater replacement.

Since the residential split-type AC operated as a factory-integrated commercial system, the condenser fan current and standalone fan power were not monitored separately. AC operational performance was evaluated using the COP calculated from Equations (1)–(5). Conventional residential AC systems generally exhibit COP values between 3.02 and 4.04,[54,55] while the baseline COP of the AC unit used in this study was 3.92. After integration with the desalination unit, smaller channel areas produced higher pressure losses, restricting condenser airflow and reducing heat rejection effectiveness, thereby lowering

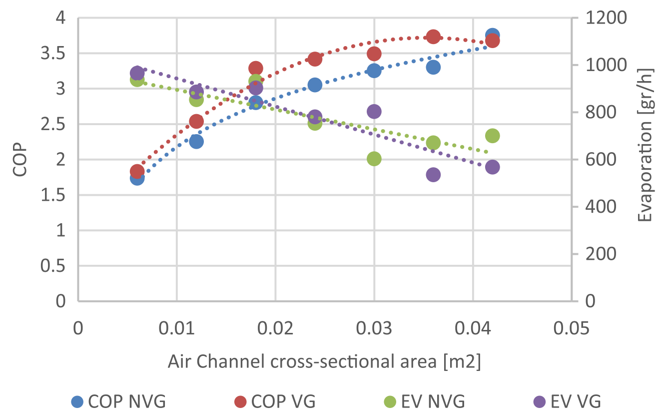

FIGURE 6 COP of split-type AC compared with evaporation for each cross-sectional area.

COP. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions.

As shown in Figure 6, COP increased progressively with increasing channel cross-sectional area because larger channels reduced airflow resistance and pressure drop. However, evaporation and COP did not exhibit a direct cause–effect relationship; both responded independently to airflow characteristics induced by channel geometry. Smaller channel areas increased airflow velocity and evaporation, while the associated pressure losses simultaneously reduced condenser performance and COP. Thus, the observed changes in evaporation and COP were primarily governed by airflow velocity and pressure-drop effects rather than by direct interaction between the two parameters.

A preliminary economic analysis showed that the system produced approximately 950–980 mL/h of freshwater (7.6–7.8 L during 8 h of operation). Based on the observed COP reduction from 3.92 to 3.02 and a cooling capacity of 2.64 kW, the additional electricity consumption was estimated at approximately 1.61 kWh per 8 h cycle, corresponding to an operational cost of about USD 0.13 or USD 0.017/L of freshwater produced. Although capital and maintenance costs were not included, the results indicate promising potential for low-cost household-scale freshwater production using readily available AC waste heat.

4 | CONCLUSION

This study demonstrates that waste heat from residential split-type AC units can drive an evaporation–condensation desalination process. Increasing the channel cross-sectional area reduced air temperature by approximately 6–11°C and improved AC performance by lowering pressure drop and enhancing heat rejection, although freshwater production decreased accordingly. The system produced approximately 950–980 mL/h of freshwater, indicating the potential to satisfy basic household drinking water requirements. A preliminary economic analysis estimated the additional operational cost at approximately USD 0.017/L of freshwater produced. Experimental–CFD validation showed strong agreement ($R^2 > 0.95$), with deviations of 6%–10%, confirming the reliability of the numerical model. Smaller channel areas enhanced evaporation but reduced AC COP because of higher airflow resistance and pressure losses, whereas a channel area of 0.015–0.025 m^2 provided the best balance between freshwater production and AC efficiency.

Although the study was conducted under controlled conditions using a single AC configuration, the results demonstrate the feasibility of household-scale desalination using AC waste heat. Future work should investigate long-term operation, varying environmental conditions, and system scalability. While severe scaling was not observed on the heat exchanger surface, gradual salt accumulation occurred at the bottom of the evaporator basin during prolonged operation, indicating that periodic brine discharge, seawater replacement, or routine cleaning may be required for stable long-term performance.

AUTHOR CONTRIBUTIONS

Dan Mugisidi: Conceptualization; writing – review and editing; investigation; methodology; writing – original draft; formal analysis; funding acquisition; supervision. **Oktarina Heriyani:** Conceptualization; investigation; software; data curation; project administration; supervision. Conceptualization; investigation; data curation; formal analysis; supervision. **Amir Khalid:** Writing – review and editing; visualization; conceptualization. Conceptualization; visualization; validation; software; writing – review and editing. **Ahmed Rahmani:** Writing – review and editing; validation; conceptualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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