



Effect of brine concentration on freezing time and energy consumption of an outdoor-AC-based ice-making system

M. Mirmanto^{*1}, I.M.A. Sayoga¹, Y. Alfarizi¹, M. Sultan², M.R. Bilad³

¹Mechanical Engineering Department, Engineering Faculty, the University of Mataram, Jl. Majapahit no. 62, Mataram, NTB, 83125, Indonesia. HP. 082111738971.

²Department of Agricultural Engineering Bahauddin Zakariya University (BZU) Multan, Pakistan.

³Department of Chemical and Process Engineering Faculty of Integrated Technologies Universiti Brunei Darussalam (UBD) Gadong, Brunei Darussalam.

*E-mail: mmirmanto@gmail.com

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ABSTRACT

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This study investigates the effect of brine concentration on the freezing performance of an ice-making machine based on a modified outdoor air-conditioning (AC) unit. The experimental system employed a parallel copper-tube evaporator immersed in a brine solution to extract heat from 10 kg of freshwater packaged in 500 g portions. Three brine concentrations—10%, 20%, and 30%—were evaluated under comparable initial conditions. The study's contribution is an integrated experimental assessment of freezing time and total heat-transfer rate across different brine concentrations in an outdoor-AC-based ice-making configuration. The results showed that freezing time decreased from approximately 6 h at 10% concentration to 3.5 h at 20% and 3 h at 30%, corresponding to a 50% reduction between the lowest and highest concentrations. In the representative first trial, the calculated total heat-transfer rate increased from 303.59 W at 10% to 503.63 W at 20% and 615.67 W at 30%. Recorded electricity consumption also decreased from 1.86 to 1.37 and 1.03 kWh per batch, respectively. These findings indicate that, within the tested operating conditions, the 30% brine solution provided the shortest freezing time, the highest calculated heat-transfer rate, and the lowest recorded electricity consumption. The results demonstrate the potential of brine concentration adjustment to improve the operational performance of outdoor-AC-based ice-making systems. Further validation using all experimental repetitions and statistical analysis is required to establish the reliability of the observed differences.

1. INTRODUCTION

Ice is widely used for food preservation, beverage cooling, and short-term cold-chain applications. Small-scale ice production is particularly relevant in areas where commercial ice-making equipment is expensive or unavailable. Vapour-compression refrigeration systems provide an opportunity to develop compact ice-making equipment by extracting heat from freshwater through a low-temperature evaporator. System performance depends on refrigeration-cycle characteristics, heat-exchanger configuration, thermal insulation, operating conditions, and material properties (Bergman et al., 2011; Çengel & Boles, 2006; Stoecker, 1989). Therefore, freezing time and electrical-energy consumption are important indicators for evaluating practical ice-making performance.

Brine is commonly used as a secondary coolant because dissolved salts depress the freezing point of water, allowing the solution to remain liquid below 0°C (ASHRAE, 2017; Melinder, 2010). In an indirect ice-making system, the evaporator extracts heat from the circulating brine, which subsequently absorbs heat from the freshwater load. The cooling process involves sensible heat removal followed by latent heat removal during solidification (Bergman et al., 2011; Çengel & Boles, 2006). Brine concentration affects the freezing point and thermophysical properties, including specific heat capacity, viscosity, and thermal conductivity, which may influence heat transfer and system response (ASHRAE, 2017; Melinder, 2010). Consequently, its effect on freezing time and energy consumption requires experimental evaluation rather than assumptions based on freezing-point depression alone.

Previous studies have established the importance of brine concentration and operating conditions in ice-generation processes. Yun et al. (2016) demonstrated that brine temperature, concentration, and fluid-flow conditions influence ice formation in a subcooled brine environment. Yun et al. (2020) examined phase transformation and heat and mass transfer in ice–water–brine systems. Similarly, Sidqy and Pamitran (2020) reported that sodium-chloride concentration and flow rate affect temperature reduction, supercooling, and ice fraction during ice-slurry production, while Wang et al. (2017) investigated the influence of salt concentration on crystallisation and latent-heat characteristics. Jayakody et al. (2018) investigated indirect freeze desalination using an ice-making machine, whereas Zhang et al. (2021) examined freezing desalination through heat- and mass-transfer modelling and experimental analyses. Although these studies provide important insights into ice formation, their configurations and objectives differ from batch freezing of packaged freshwater using brine as a secondary coolant.

Research has also investigated the use of outdoor air-conditioning units for ice production. Sunanto and Budhy Darmawan (2023) evaluated an ice maker using a split AC outdoor unit and a brine-based secondary cooling system. Tupamahu et al. (2025) examined the effect of capillary tube diameter on a 100-liter ice-making system using a 1 PK outdoor AC unit, reporting a maximum coefficient of performance (COP) of 3.41 for a 0.028-inch capillary tube. These studies demonstrate the potential of repurposed air-conditioning equipment and highlight the influence of refrigeration-system design on performance. However, component optimization and overall system evaluation do not directly establish the effect of brine concentration on the freezing of a constant freshwater load.

More directly, Mirmanto et al. (2024) investigated an ice-making system using a half-horsepower outdoor AC unit and R32 refrigerant. Their experiments maintained the brine concentration at 20% while varying the salt-solution mass between 10 and 14 kg. They reported freezing times of 3.5 hours for 10 kg and 6 hours for 14 kg, together with a maximum heat-transfer rate of 554 W under the tested conditions. These findings indicate that secondary-coolant mass can influence freezing performance. Setyawan et al. (2025) subsequently evaluated the thermal and energy performance of an outdoor-AC-based ice-making prototype and reported ice production during an eight-hour operating period. Nevertheless, Mirmanto et al. (2024) varied solution mass at a fixed concentration, whereas the present study maintains the freshwater load and varies brine concentration. This distinction provides a specific basis for comparing the two experimental approaches.

The research gap addressed here is the limited configuration-specific experimental evidence on how brine concentration affects the freezing time and electricity consumption of packaged freshwater in an outdoor-AC-based indirect batch-freezing system. Results from ice-slurry generation, freeze desalination, or experiments varying secondary-coolant mass cannot be directly assumed to represent this configuration (Jayakody et al., 2018; Mirmanto et al., 2024; Sidqy & Pamitran, 2020; Yun et al., 2016). The novelty of the present study is therefore limited to an experimental comparison of three brine mass concentrations—10%, 20%, and 30%—under a constant freshwater load of 10 kg. The study compares freezing time, calculated heat-transfer rate, and measured electricity consumption without claiming that brine concentration or outdoor-AC-based ice production has not previously been investigated.

Accordingly, this study evaluates the effects of brine concentrations of 10%, 20%, and 30% on the time required to freeze 10 kg of freshwater in an outdoor-AC-based ice-making system. Calculated heat-transfer rates and recorded electricity consumption are also compared to assess the response of the tested prototype under each

condition. By maintaining a constant freshwater load, the experiment focuses on brine concentration as the principal variable and provides practical evidence for selecting operating conditions in small-scale ice-making systems using repurposed air-conditioning equipment.

2. RESEARCH METHODS

2.1. Experimental setup

The experimental setup consists of a 0.5 HP outdoor air conditioning (AC) unit utilizing R-32 refrigerant, a capillary tube, an evaporator (constructed from serpentine-shaped copper tubing), an insulated cooling box, a brine circulation pump, temperature sensors, a data logger, and an electrical power meter (Figure 1). The evaporator is made of 1/4-inch copper tubing arranged along the inner walls and the bottom of the cooling box. The system operates on the vapor-compression refrigeration principle, with the evaporator absorbing heat from the brine solution.

Three brine concentrations (10%, 20%, and 30%) were tested in this study. Each solution was prepared by mixing salt and water according to the specified concentration: the 10% solution consisted of 1 kg of salt and 9 kg of water; the 20% solution consisted of 2 kg of salt and 8 kg of water; and the 30% solution consisted of 3 kg of salt dissolved in 7 kg of water. A 10 kg load of fresh water was used, divided into 20 sealed plastic packages, each containing 500 g. These packages were placed inside the cooling box and surrounded by the circulating brine solution. The initial temperature of both the fresh water and the cooling box was approximately 26 °C.

Each concentration was tested in three independent trials. The refrigeration unit and the circulation pump were operated until all 20 packages were completely frozen—indicated by them becoming solid and turning white—at which point the experiment was concluded. The brine temperature, ambient temperature, compressor power, power factor, and cumulative electrical energy consumption were recorded every 30 minutes.

The freezing duration was determined from the start of the operation until complete freezing was achieved. The heat transfer rate is calculated as the amount of heat transferred per unit of time, expressed in watts (W), while electrical energy consumption is reported in kilowatt-hours (kWh). Energy measurements include the energy used by compressors and circulation pumps.

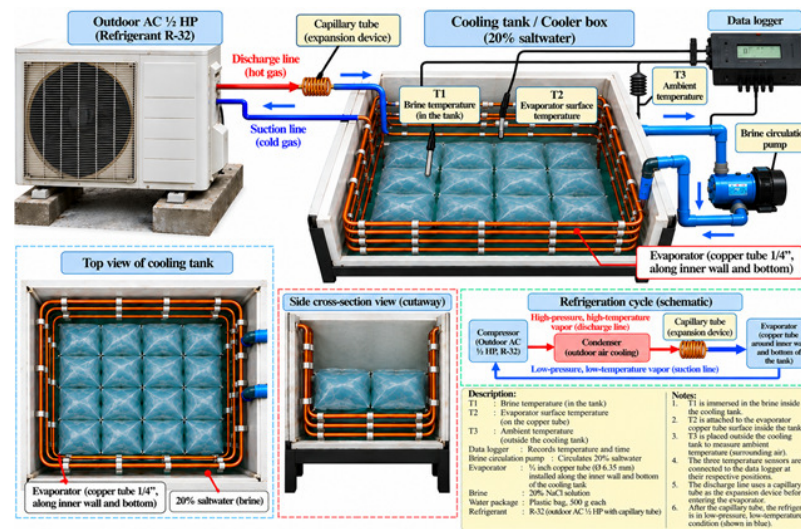


Figure 1. Experimental setup of the outdoor air-conditioning-based ice-making system, showing the refrigeration unit, brine circulation loop, evaporator, instrumentation, and refrigerant flow direction.

2.2. Refrigeration and brine circulation systems

The refrigeration system operated according to the vapour-compression refrigeration cycle. The compressor increased the pressure of the refrigerant vapour before it entered the condenser of the outdoor air-conditioning unit, where heat was rejected to the surrounding air. The refrigerant subsequently passed through a capillary tube, which reduced its pressure before it entered the evaporator. Inside the evaporator, the refrigerant absorbed heat from the brine solution and evaporated at a low temperature. The refrigerant vapour then returned to the compressor to complete the refrigeration cycle. Meanwhile, the brine solution served as an intermediate heat-transfer medium between the evaporator and the freshwater packages. A circulation pump was installed to promote brine movement within the cooling arrangement and improve temperature distribution around the

packages. This arrangement enabled the refrigeration system to cool the brine, which subsequently extracted heat from the freshwater during both sensible cooling and the freezing process.

2.3. Temperature measurement and data acquisition

Temperature measurements were conducted using thermocouples positioned at selected locations in the experimental apparatus. The first thermocouple (T1) measured the brine temperature inside the cooling tank, while the second thermocouple (T2) measured the evaporator surface temperature. The third thermocouple (T3) measured the ambient temperature surrounding the apparatus. The temperature sensors were connected to a data logger to record temperature variations during system operation. These measurements were used to evaluate the cooling behaviour of the brine, the temperature of the evaporator surface, and the influence of ambient conditions on the freezing process. A power meter was also used to monitor electrical power consumption, as indicated in the experimental setup. The recorded temperature and electrical measurements provided the basis for analysing the thermal response and energy use of the ice-making system.

2.4. Experimental procedure

Before each experiment, the cooling tank, evaporator, brine circulation system, and measurement instruments were checked to ensure that the apparatus was properly assembled and operational. The cooling tank was filled with a 20% brine solution, and the freshwater packages were arranged inside the tank according to the experimental configuration. The temperature sensors were positioned at their designated measurement locations and connected to the data logger. The refrigeration unit and brine circulation pump were then switched on to initiate the cooling process. During operation, the evaporator extracted heat from the brine, while the circulating brine absorbed heat from the freshwater packages. Temperature measurements were recorded throughout the experiment to monitor the progression of cooling and freezing. The experiment continued until the specified freezing endpoint was reached, after which the recorded data were used to evaluate the freezing process.

2.5 Data acquisition and heat transfer calculation

Temperature measurements were collected during each freezing experiment to evaluate the thermal behavior of the system under different water-mass conditions. The temperatures of the water inside the packages, the brine solution, and the evaporator-related measurement point were monitored using temperature sensors connected to a data logger. The temperature data were recorded throughout the freezing process, while the freezing time was determined for each water-mass variation. The total heat removed from the water was estimated by considering both sensible and latent heat transfer. The sensible heat associated with cooling the water was calculated using:

$$Q_s = m_w c_{pw} (T_i - T_f) \quad (1)$$

Where Q_s is the sensible heat energy (J), m_w is the water mass (kg), c_p is the specific heat of water (J/kg°C), T_i and T_f is the initial and final temperatures of the water (°C). The latent heat associated with the phase change from water to ice was calculated as:

$$Q_L = m_w L_f \quad (2)$$

Where (Q_L) is the latent heat (J) and (L_f) is the latent heat of fusion of water (J/kg). The total heat removal (Q_t) was estimated by adding the sensible and latent heat components:

$$Q_t = Q_s + Q_L \quad (3)$$

The average heat transfer rate was then determined by dividing the total heat removed (Q_t) by the measured freezing time (t):

$$\dot{Q}_{avg} = Q_t / t \quad (4)$$

where ($\dot{Q}_{average}$) is the average heat transfer rate (W) and (t) is the freezing time (s). These calculations can be obtained in Bergman et al. (2011), Mirmanto et al. (2024) and the above equations were used to compare the estimated thermal load associated with freezing different water masses. The recorded temperature profiles and calculated heat transfer parameters were subsequently analyzed to assess how the water mass affected the freezing time and thermal performance of the experimental system.

3. RESULTS AND DISCUSSION

Figure 2 shows the variation in brine temperature at salt-solution concentrations of 10%, 20%, and 30%. All solutions cooled rapidly during the initial period. At 5,400 s, the temperatures were −1.6, −6.0, and −7.3 °C,

respectively, while at 10,800 s they were -9.1 , -6.6 , and -10.4 °C. The temporary temperature increase in the 20% solution, from -8.8 °C at 9,000 s to -6.6 °C at 10,800 s, should be verified against the original records.

As shown in Table 1, the reported freezing times for 10 kg of freshwater were 6 h, 3.5 h, and 3 h for the 10%, 20%, and 30% brine solutions, respectively. Compared with the 10% solution, the 20% and 30% solutions reduced freezing time by approximately 41.7% and 50%, respectively. The 30% solution also exhibited the highest reported heat-transfer rate (615.67 W), compared with 503.63 W for 20% and 303.59 W for 10%. These results indicate that higher brine concentrations were associated with faster freezing in this prototype.

This trend may be related to the lower freezing point of concentrated brine and the resulting temperature difference driving heat transfer. However, concentration also affects brine thermophysical properties, so its influence is system-dependent. Yun and Quarini (2017) found that lower brine concentrations and lower bath temperatures favoured ice formation in a direct-contact system, demonstrating that performance depends on the heat- and mass-transfer configuration. Mirmanto et al. (2024) likewise showed that brine-solution mass affected freezing time in an outdoor-AC-based system. Therefore, the present results support the 30% solution as the best-performing condition among those tested, but further replicated experiments and uncertainty analysis are needed to confirm the differences and explain the underlying mechanisms.

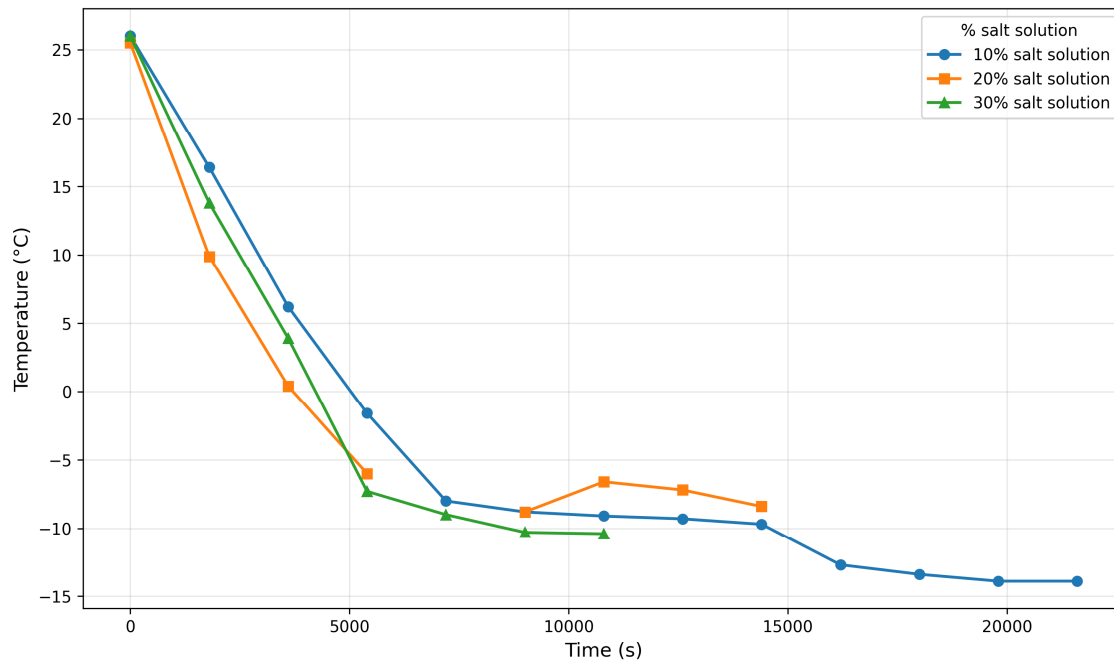


Figure 2. Variation in brine temperature over time at different salt-solution concentrations (10%, 20%, and 30%).

Table 1. Freezing time and calculated total heat-transfer rate for the representative first trial, transcribed from the source thesis.

Brine concentration (%)	Salt / water (kg)	Freezing time (h)	Reported first-trial $\dot{Q}_{total}$ (W)
10	1 / 9	6.0	303.59
20	2 / 8	3.5	503.63
30	3 / 7	3.0	615.67

Figure 3 illustrates the relationship between brine concentration and the total heat-transfer rate absorbed by the evaporator. The reported heat-transfer rates increased from 303.59 W at 10% concentration to 503.63 W at 20% and 615.67 W at 30%. This corresponds to increases of approximately 66% and 103%, respectively, relative to the 10% solution. If the error bars do not overlap, the results may indicate differences between the tested conditions; however, statistical significance should be confirmed using an appropriate statistical test.

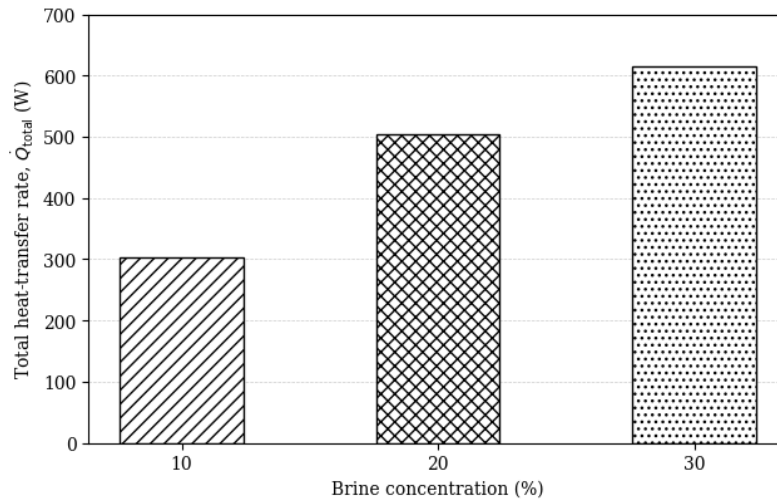


Figure 3. Effect of brine concentration on the total heat-transfer rate absorbed by the evaporator.

The observed increase may be associated with differences in brine temperature, the temperature difference between the brine and the evaporator surface, and the thermophysical properties of the solution. Salt concentration affects the freezing point, density, specific heat capacity, viscosity, and thermal conductivity of brine (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2025). Nevertheless, higher density alone does not necessarily produce a higher heat-transfer rate. For a circulating fluid, the heat-transfer rate depends on factors including mass flow rate, specific heat capacity, temperature change, and convective heat transfer at the evaporator surface.

The trend is consistent with the results of Mirmanto et al. (2024), who demonstrated that brine-solution mass affected heat-transfer rate and freezing time in an outdoor-AC-based ice-making system. Their findings also highlight the importance of the coolant thermal load and system configuration. Therefore, the 30% solution exhibited the highest measured heat-transfer rate under the present experimental conditions, but this result should not be interpreted as evidence that increasing brine concentration will always improve heat-transfer performance. Replicated experiments and statistical analysis are required to establish the reliability of the observed differences.

Electricity consumption decreased with increasing brine concentration, from 1.86 kWh at 10% to 1.37 kWh at 20% and 1.03 kWh at 30% (Figure 4). For a 10 kg freshwater batch, the corresponding specific electricity consumptions were 0.186, 0.137, and 0.103 kWh kg⁻¹, respectively. The 30% brine condition reduced electricity consumption by 44.6% compared with the 10% condition. These values represent the first experimental trial rather than averages across the three repetitions.

The lower electricity consumption coincided with shorter freezing times at higher brine concentrations, suggesting improved operational performance under the tested conditions. This relationship may reflect differences in freezing duration and heat transfer; however, concentration also influences brine properties, including viscosity, specific heat capacity, and freezing point, which can affect circulation and thermal performance (ASHRAE, 2025). Mirmanto et al. (2024) similarly demonstrated that brine-solution mass influences freezing time and heat-transfer rate in an outdoor-AC-based ice-making system, highlighting the importance of operating conditions when evaluating refrigeration performance.

Although the 30% solution exhibited the lowest recorded energy consumption and shortest freezing time, these results do not establish a universal optimum. A reliable comparison requires energy measurements from all repetitions, including the electricity consumed by both the compressor and circulation pump. Long-term considerations, such as corrosion and material compatibility, should also be assessed. Therefore, the 30% solution appears to be the most promising concentration among those tested, pending statistical validation and further evaluation of overall system performance.

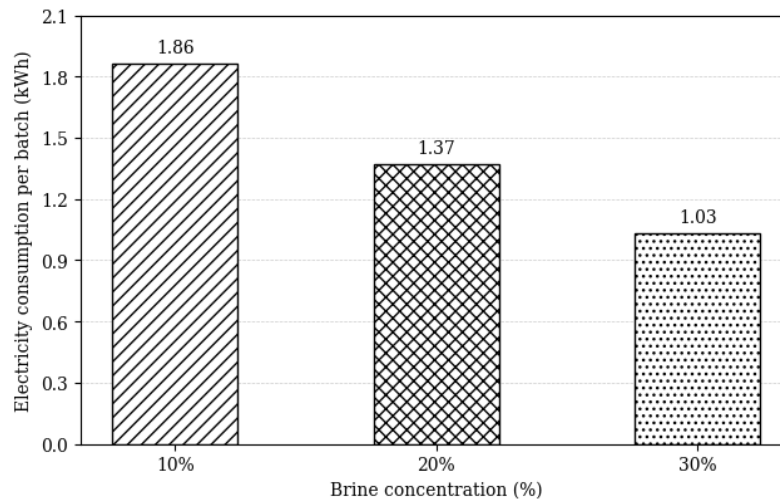


Figure 4. Electricity consumption per batch at different brine concentrations.

4. CONCLUSION

This study experimentally demonstrated that brine concentration influenced the freezing performance of an outdoor-AC-based ice-making machine processing 10 kg of freshwater. Increasing the concentration from 10% to 30% reduced the reported freezing time from approximately 6 h to 3 h, representing a 50% reduction. In the representative first trial, the calculated total heat-transfer rate increased from 303.59 to 615.67 W, while electricity consumption decreased from 1.86 to 1.03 kWh per batch, a reduction of approximately 44.6%. The principal contribution of this study is the combined evaluation of freezing time, calculated heat-transfer rate, and electricity consumption under three brine-concentration conditions in the tested system. Among these conditions, 30% brine showed the most promising overall performance. However, this finding is limited to the tested prototype and operating conditions and should not be interpreted as a universal optimum. Analysis of all experimental repetitions, verification of the heat-transfer calculations, and appropriate statistical testing are needed to confirm the robustness of the results and support recommendations for practical application.

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