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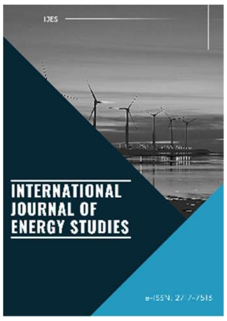

Research Article

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Investigation of using low GWP alternatives to replace R404A in the refrigeration system

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Highlights

- R407H, R448A, R454C, R468A synthetic mixtures and R290, R1270 natural refrigerants were proposed.
- R290 and R1270 were observed as good alternatives for R404A with 4.11 and 4.09 COP values.
- The CO_2 emission amount of R290 and R1270 refrigerants was achieved as 8.76% lower than R404A.
- The performance of R468A remained very low to others.

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ABSTRACT

In recent years, the use of refrigerants, which increase the global warming potential by creating a greenhouse effect, has begun to be restricted in refrigeration systems. More environmentally friendly and more efficient synthetic mixtures and natural refrigerants are replacing refrigerants with high global warming potential. In this study, R404A refrigerant, which is frequently preferred in refrigeration systems and has a high global warming potential, was discussed. Six different refrigerants (R407H, R448A, R454C, R468A, R290, R1270) that could be alternatives to R404A refrigerant were examined and compared with R404A. Energy, exergy, and environmental analyzes were performed under the same conditions according to -10 °C, -5 °C, and 0 °C evaporating temperatures. Among the refrigerants, R290 had the best value with a coefficient of performance of 4.11 and an exergy efficiency of 40.04%. The values of R1270 refrigerant were also almost the same as R290. Even if R468A shows the lowest performance, it can be preferred over R404A because its global warming potential is lower than R404A.

Keywords: Global warming potential, R404A, R290

1. INTRODUCTION

In recent years, technological developments, comfortable living preferences, and the use of fossil energy sources bring an increase in greenhouse gas emissions. Due to the rise in greenhouse gas emissions, various environmental problems such as global warming, climate change, and environmental pollution causes to occur. Energy consumption in buildings and industries constitutes a significant percentage of total energy consumption. According to the data of the International Energy Agency (IEA), energy consumption in buildings corresponds to more than 30% of the total energy consumption in the World. In the world, the energy consumption of buildings constitutes 40% of the total energy [1]. People widely use heating, ventilation, air conditioning and refrigeration systems to provide their needs and comfort in their daily lives. The energy consumed during the use of refrigeration systems is substantial. Although it varies from country to country, the energy consumption of refrigeration systems constitutes 16% to 50% of the total energy consumed in buildings [2] and corresponds to 33% of total greenhouse gas emissions [3].

Refrigeration systems use a vapor compression refrigeration cycle and the most commonly preferred refrigerant in this cycle is R404A. R404A refrigerant is highly used in the past decades because it is non-flammable, non-toxic, and has high energy efficiency and zero ozone depletion potential [4]. However, since the global warming potential (GWP) rate is high (approximately 3943), its use is phased out. Refrigerant mixtures are looked for as alternatives to R404A by researchers. Cabello et al. analyzed the effect of an internal heat exchanger in the vapor compression refrigeration cycle using alternative fluids of R404A. As an alternative to R404A, R454C, R455A, R468A, R290 and R1270 refrigerants were used. Experiments were carried out at three different condenser temperatures of 20 °C, 30 °C, and 40 °C in a freezing cabinet at -20 °C evaporator temperature. With the use of an internal heat exchanger, reductions in energy consumption have been achieved. R1270 showed the best performance among alternative refrigerants. The maximum energy saving was realized as 9.2% in the experiment carried out at 40 °C condenser temperature [5]. Makhnatch et al. suggested R449A refrigerant instead of R404A for medium temperature supermarket applications. R449A showed a 13% lower cooling potential. However, COP values between 1.9 and 2.2 had close results for both fluids [6]. R454A and R454C refrigerants instead of R404A were experimentally tested and compared by Oruc and Devecioglu at -5, 0, and +5 °C evaporator and 30, 40, and 50 °C condenser temperatures. It was observed that the energy consumption was reduced by approximately 6% and 15% for R454A and R454C for all temperatures. In addition, COP values increased by 14% and 10% for R454A and R454C [7]. Mota-Babiloni et al. performed an experimental study with R404A and R448A in a vapor compression system and compared their performance. Although the cooling capacity of both fluids was close to each other, the energy consumption of R448A was 13% lower. The COP value was 8% higher at 240 K and 9% higher at 265 K evaporator temperature [8].

Zhang et al. proposed a non-flammable mixture called RTJU-Z with a GWP of 794 as an alternative to flammable and high GWP R404A. This mixture was tested for a cold storage system. Experimental results showed that this mixture had a higher COP of 5.71% and a lower optimum charge of 11.76% [9]. Altınkaynak thermodynamically investigated the use of R448A, R449A, and R452A refrigerants instead of R404A. Average COP values and exergy efficiencies for R448A, R449A and R452A were obtained as 2.419, 2.313 and 2.467 and 20.62%, 20.22% and 19.33%, respectively [10]. Deng et al. examined R404A and R448A refrigerants in a cold storage unit with and without an inverter. It was reported that the system with an inverter and R448A refrigerant had 13% better energy performance [11]. Yoon et al. researched mixtures of R32/R744/R1234yf (52/1/47 wt%) instead of R404A in a gas injection refrigeration system. This mixture showed a 9.56% increase in COP over R404A [12].

When the previous studies are viewed, it is seen that the R404A refrigerant has left its place for alternative refrigerants with lower GWP values because of its high GWP value. Many researchers have evaluated the performance of different refrigerants and compared them with R404A. In this study, six refrigerants that can be alternatives to R404A are thermodynamically tested and compared with R404A.

2. MATERIALS AND METHOD

2.1. System Description

While economical, safe, and easy to supply features are required from the refrigerants used in refrigeration systems, they should also not be harmful to the environment. For this reason, alternative refrigerants with very different properties and low GWP values have been produced and became to be used over time. In this study, a comprehensive thermodynamic analysis of R407H, R448A, R454C, R468A, R290, and R1270 refrigerants, which can be an alternative to R404A refrigerant, has been performed. The specifications of these refrigerants are given in Figure

1. among the alternatives, R290 and R1270 are natural refrigerants others consist of synthetic mixtures.

Figure 1. Chart of the characteristics of R404A and its alternative refrigerants

In this study, a vapor compression refrigeration cycle was used to determine the performances of alternative fluids of R404A. The schematic view of the vapor compression refrigeration cycle is illustrated in Figure 2. The basic components of this cycle are the evaporator, compressor, condenser, and expansion valve. The refrigerant leaving the evaporator as saturated vapor is compressed to the condenser pressure in the compressor. The refrigerant with increasing temperature enters the condenser as superheated steam and gives off heat at constant pressure. Meanwhile, the condensed refrigerant enters the expansion valve at constant enthalpy and is expanded to the evaporator pressure. The refrigerant entering the evaporator in gaseous form is separated as saturated vapor by absorbing heat here. Log P-h diagram of R404A refrigerant is given in Figure 3. Analyzes were performed using the Danfoss Coolselector software.

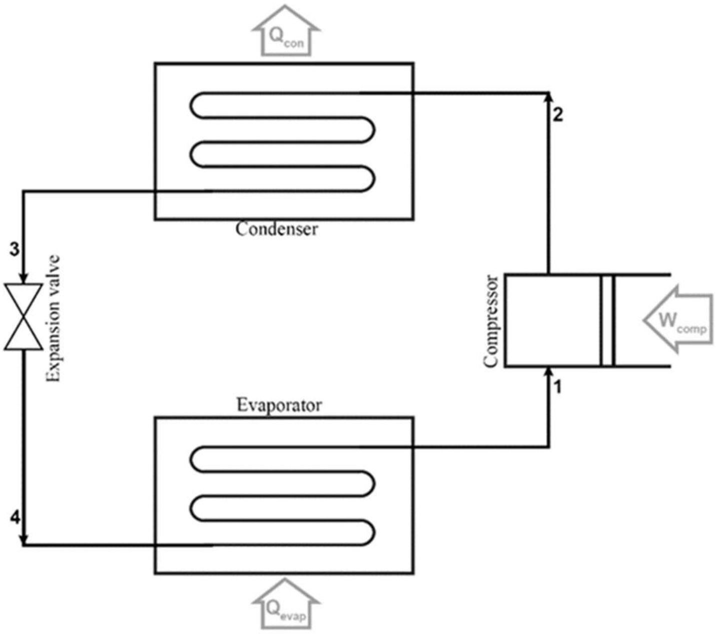

Figure 2. Schematic illustration of the vapor-compression refrigeration cycle

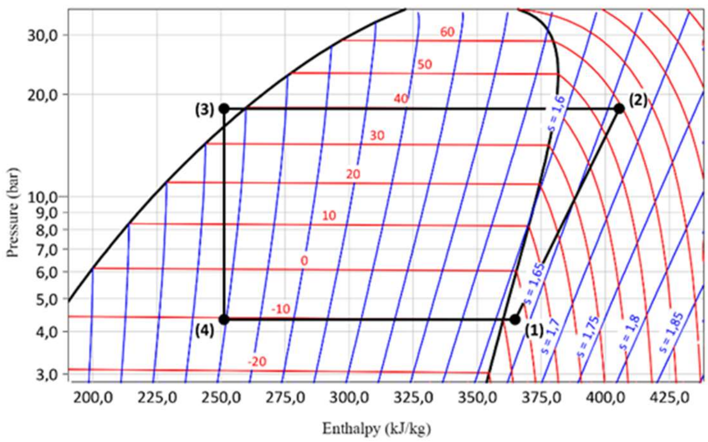

Figure 3. Log P - h diagram of R404A refrigerant

Theoretical analyses of R404A and its alternatives were performed under the same conditions given in Table 1. For these analyses, some assumptions stated below were taken into account:

- Pressure and heat losses and gains in the system components and pipes were neglected.
- It was assumed that all components in the system were in a steady state.
- It is assumed that there are no kinetic and potential energy changes.
- Evaporation and condensation processes were isobaric.

Table 1. Assumptions required for analyses

Parameters	Value
Cooling Capacity	10 kW
Evaporator Temperature, T_{evap}	-10℃, -5℃, and 0 ℃
Condenser Temperature, T_{con}	40 ℃
Ambient Temperature, T_o	25 ℃
Mechanical efficiency of compressors, η_{mec}	90%
Electrical efficiency of compressors, η_{el}	93%
Superheating	5 ℃
Subcooling	5 ℃

2.2. Thermodynamic Analysis

The energy equations condenser capacity ($\dot{Q}_{con}$, kW), evaporator capacity ($\dot{Q}_{evap}$, kW), and the power of compressor ($\dot{W}_{comp}$, kW) of the vapor compression refrigeration cycle are given below, respectively [13]:

$$\dot{Q}_{con} = \dot{m}_r\left(h_{con,i} - h_{con,o}\right) \tag{1}$$

$$\dot{Q}_{evap} = \dot{m}_r\left(h_{evap,o} - h_{evap,i}\right) \tag{2}$$

$$\dot{W}_{comp} = \dot{m}_r(h_{comp,o} - h_{comp,i})/\eta_{is}\eta_{mec}\eta_{el} \tag{3}$$

$$\eta_{is} = 1 - (0.04xPR) \tag{4}$$

where $\dot{m}_r$ (kg) represents the mass flow rate of the refrigerant and h (kJ/kg) represents its enthalpy. Also, in Eq. (4), η_{is} indicates the isentropic efficiency of the compressor and PR is the pressure ratio. The COP value of the refrigeration system is obtained as the ratio of the evaporator capacity to the compressor power.

$$COP_{system} = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \tag{5}$$

The exergy equations and second law efficiency of the refrigeration system can be expressed with the following equations [14]:

$$\dot{E}x_{d,evap} = \left(\dot{E}x_{evap,o} - \dot{E}x_{evap,i}\right) + \dot{Q}_{evap}\left(1 - \frac{T_o}{T_{evap}}\right) \tag{6}$$

$$\dot{E}x_{d,con} = \left(\dot{E}x_{con,i} - \dot{E}x_{con,o}\right) + \dot{Q}_{con}\left(1 - \frac{T_o}{T_{con}}\right) \tag{7}$$

$$\dot{E}x_{d,comp} = \dot{E}x_{comp,o} - \dot{E}x_{comp,i} \tag{8}$$

$$\dot{E}x_{d,ex} = \dot{E}x_{ex,i} - \dot{E}x_{ex,o} \tag{9}$$

$$\eta_{II} = \frac{\dot{E}x_{evap,o} - \dot{E}x_{evap,i}}{\dot{W}_{comp}} \tag{10}$$

The sustainable index value (SI) is proportional to the exergy efficiency and is expressed below:

$$SI = \frac{1}{1 - \eta_{II}} \tag{11}$$

The calculation of CO_2 emissions for the cooling system based on the power consumption of the compressor is given in the equation below [15]:

$$\Phi_{CO_2} = \Psi_{CO_2}\ x\ \dot{W}_{comp,total} \tag{12}$$

where Φ_{CO_2} represents the amount of CO_2 (kg CO_2/h) reduced per hour and and Ψ_{CO_2} denotes the average amount of CO_2 emissions (2.08 kg CO_2/kWh) generated during power generation from coal.

3. RESULTS AND DISCUSSION

In this study, the performances of six different refrigerants that can be used as an alternative to R404A refrigerant with a high GWP value were investigated and compared thermodynamically. These alternative refrigerants were R407H, R448A, R454C, R468A, R290 and R1270. Theoretical analyzes were carried out with evaporator temperatures of -10 °C, -5 °C, 0 °C and condenser temperatures of 40 °C. According to the cooling capacity of 10 kW, the energy consumption graph of these refrigerants is illustrated in Figure 4. When the graph is examined, it is seen that the power consumption of the system is the highest for all refrigerants at -10 °C evaporator temperature. Since when the desired evaporator temperature is increased, the compressor draws more current and does more runs. The power consumption of R404A was calculated as 3.61, 3.1 and 2.64 kW for -10 °C, -5°C and 0 °C. The highest power consumption was obtained in the R468A refrigerant as 5.12, 4.49, and 3.92 kW for -10 °C, -5°C, and 0 °C. On the other hand, the lowest power consumptions were found in the R290 refrigerant as 3.3, 2.85, and 2.43 for -10 °C, -5°C, and 0 °C, respectively. The power consumption of R1270, which is a natural refrigerant like R290, was very close to that of R290.

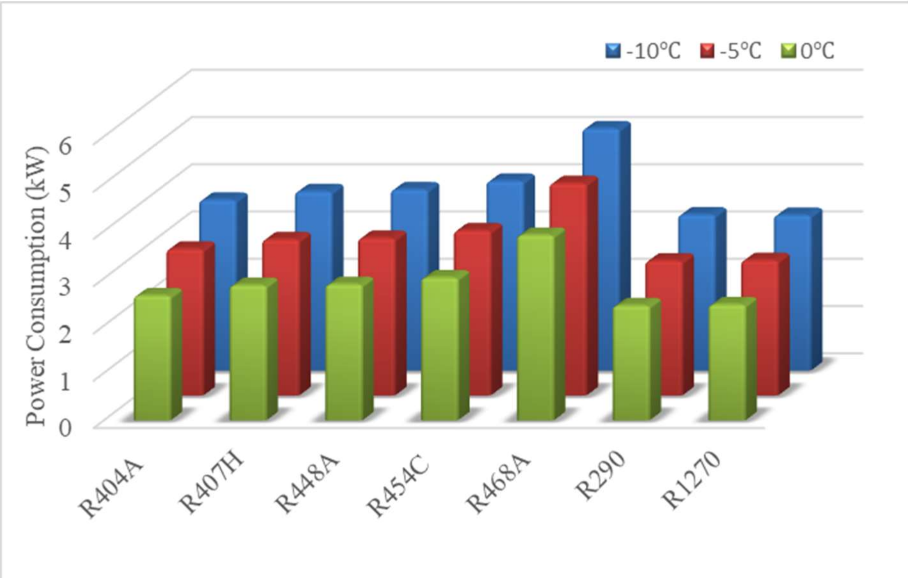

Figure 4. Power consumption of R404A and its alternatives

Since the COP value is the ratio of the cooling capacity to the power of the compressor, it is inversely proportional to the energy consumption. Therefore, it gives an aspect about which refrigerant is more efficient. The graph of the COP values of R404A and alternatives is given in Figure 5. With COP values of 4.11 and 4.09, the highest value was obtained at 0 °C evaporator temperature with R290 and R1270 natural refrigerants. Conversely, the COP value was calculated for the R468A and R454C refrigerants at 1.95 and 2.5 at -10 °C evaporator temperature. The closest refrigerant to the COP of R404A was R407H. COPs of other alternatives were seen to be close to each other with small decreases.

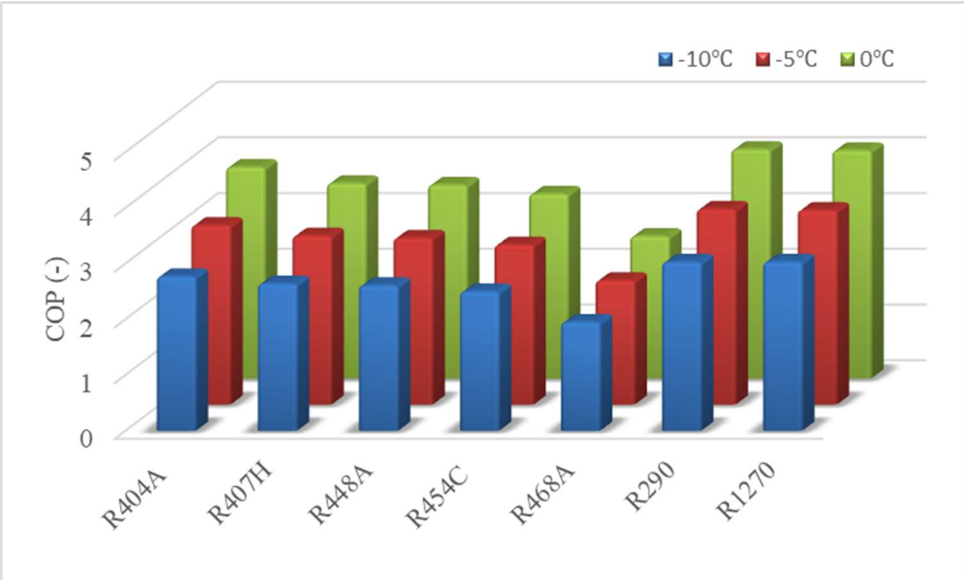

Figure 5. COP values of R404A and its alternatives

Figure 6 depicts the evaluated second law efficiencies for R404A and its alternatives. The exergy efficiencies of R404A varied between 36.62% and 35.04% depending on the evaporator temperatures. The highest exergy efficiency of 40.04% was gotten in both R290 and R1270 refrigerants. The lowest exergy efficiency was found among 27.33% and 29.38% in R468A. The sustainability index given in Eq. (11), depending on the exergy efficiency, was calculated for all refrigerants, and a similar trend was observed. The SI values at -10 °C evaporator temperature were calculated as 1.57, 1.59, 1.59, 1.55, 1.42, 1.66, and 1.66 for R404A, R407H, R448A, R454C, R468A, R290, and R1270, respectively.

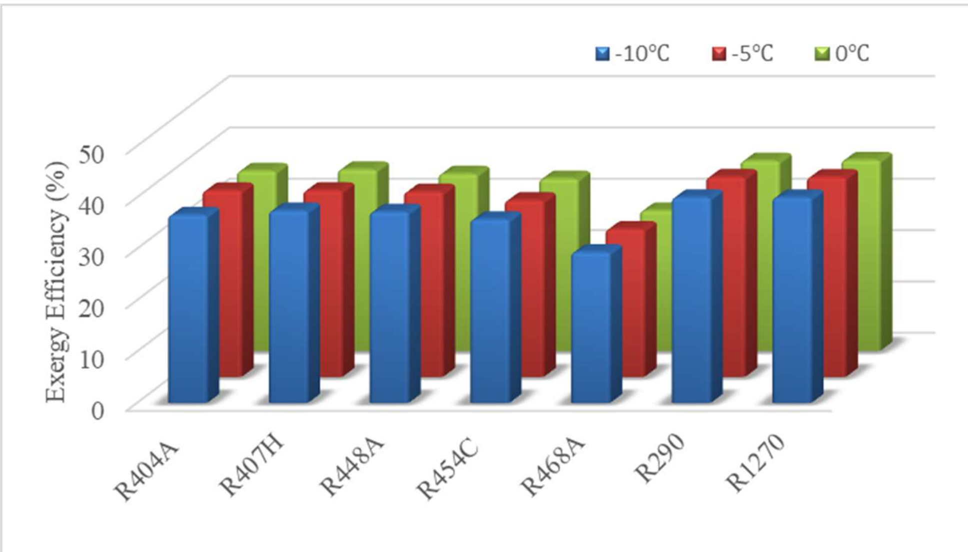

Figure 6. Exergy efficiency of R404A and its alternatives

Figure 7 shows the annual total CO_2 emissions for R404A and its alternatives according to -10 °C, -5°C and 0 °C evaporator temperatures. It was taken into account that coal fuel was used in the electricity generation required for the vapor compression refrigeration system. The lowest emission values were achieved for -10 °C, -5 °C, and 0 °C, as 2.51, 2.16, and 1.85 in R290 and R1270. The highest CO_2 emissions value was found as 3.88 in R468A at -10 °C evaporator temperature. Even if the highest values have been obtained in this refrigerant, R468A can be used as an alternative to R404A since the GWP value is 146.

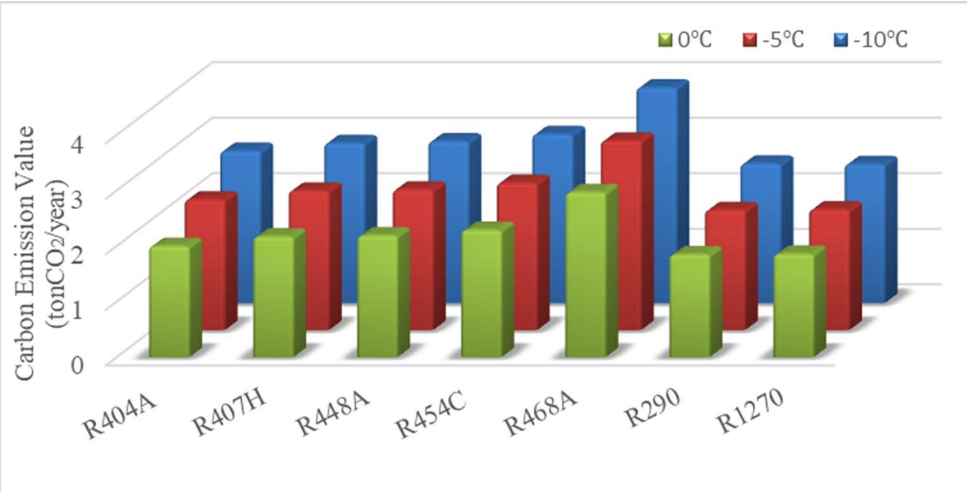

Figure 7. Annual total CO_2 emissions for R404A and its alternatives

4. CONCLUSION

In this study, the performance of the refrigerants that can replace the R404A refrigerant has been researched. Hence, R407H, R448A, R454C, R468A, R290, and R1270 refrigerants were chosen and energy, exergy, and environment analyses were conducted. Maximum energy consumption was obtained in R468A as 5.12 kW at -10 °C evaporator temperature. At the same temperature, the energy consumption of R404A was 29.5% less. Accordingly, the COP value was observed the lowest at R468A. COP values of R404A, R407H, R448A, R454C, R468A, R290, and R1270 refrigerants at 0 °C evaporator temperature were calculated as 3.79, 3.49, 3.47, 3.31, 2.55, 4.11, and 4.09 respectively. R290 with the highest COP value was 7.70% higher than R404A. Similarly, the exergy efficiencies of R290 and R1270 refrigerants were the highest at 40.04%. The carbon emission amount of R290 and R1270 alternatives was approximately 8.76% lower than R404A. It was observed that R468A was 29.38% higher than R404A. As a result, it was seen that the best alternative refrigerants to R404A are natural refrigerants R290 and R1270. The performance of R468A remained very low. Although the R407H, R448A, and R454C performances were slightly lower than R404A, they could be preferred because their GWP values are very low compared to R404A.

DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Meltem Koşan: Conceptualization, methodology, performed the analyses, evaluation and interpretation of the results, writing, review and editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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