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Determination of Optimum Insulation Thickness in Building Insulation in Tokat Province and Its Effect on CO_2 Emission

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ABSTRACT

Agricultural structures are generally classified as rural structures, animal-plant production structures and protection-storage structures. As in all types of buildings, it is necessary to reduce energy costs by reducing thermal losses/gains in agricultural structures. Thus, the damage caused by the waste gases released to people and the environment is also reduced. For these reasons, it has become important to determine the type and thickness of the insulation material used to reduce thermal losses/gains in a way that will provide the most economic benefit. In this study, optimum insulation thicknesses, annual savings, payback period and reduction in CO_2 emissions on the outer walls of the building for heating and heating-cooling applications in Tokat province were calculated. Although the desired temperature values differ according to the building types, this study for residences is also an adaptive prediction for agricultural building types. XPS (extruded polystyrene) and RW (rock wool) insulation materials were used for two different wall types. Natural gas for heating and electricity for cooling were selected as energy sources. DD (degree day) and LCA (life cycle analysis) methods were used for thermal and economic analysis. According to the wall type, the optimum insulation thickness of XPS insulation material is 0.032m-0.029m for heating, 0.071m-0.068m for heating-cooling, payback period is 5.13years-6.92years for heating, 2.32years-2.94years for heating-cooling, and the reduction in CO_2 emission is calculated as 64.57%-57.77% for heating, 80.46%-76.28% for heating-cooling. According to the wall type, the optimum insulation thickness of RW insulation material was 0.023m-0.019m for heating, 0.055m-0.051m for heating-cooling, payback period 8.20years-11.93 years for heating, 3.33years-4.3years for heating-cooling, and the reduction in CO_2 emission was determined as 53.98%-44.65% for heating, 73.69%-68.49% for heating-cooling. In the insulation application of buildings, it has been determined that it is more appropriate to prefer XPS insulation material because it is more advantageous than RW insulation material in terms of both payback period and economy and environmental impact in reducing CO_2 emissions, at the calculated optimum insulation thicknesses.

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Introduction

Economic, political, and social factors are the most important factors influencing energy use (Coyle 2014). Total energy consumption in the world is 37.8% in industry, 30.1% in buildings, 26% in transportation and 6.1% in other sectors, respectively. Energy consumption in the building sector has increased by an average of 1% over the past decade. Natural gas meets 23% of the energy demand in buildings. It is estimated that the global total area in residential buildings will increase by 55% by 2050 and energy consumption in buildings will increase between 4.63%-5.26% by 2030 (International Energy Agency [IEA], 2023).

In 2020, 34.4% of Turkiye's total energy consumption was in industry, 25.5% in transportation, 24.5% in residential and 15.6% in services. It is estimated that in 2030, total energy consumption will increase by 2.9% for industry and decrease by 3.3% for residences (Turkey's National Energy Plan, 2022).

Energy consumption in buildings in the world and in Turkiye constitutes approximately 25% of total energy consumption. Monitoring and controlling CO_2 emissions caused by energy consumption in buildings, as in all sectors, is important in terms of its impact on climate change.

Total greenhouse gas emissions per capita in Turkiye were calculated as 4 tons of CO_2 equivalent in 1990 and 6.7 tons of CO_2 equivalent in 2021 (TUIK, 2023). As of 2021, the emissions of the EU-27 countries per capita in CO_2 equivalent are 7.9 tonnes/capita (EUROSTAT, 2020).

When compared in terms of construction costs, insulated buildings cost 15-40% more than non-insulated buildings, but when examined in terms of energy consumption costs, insulated buildings provide approximately 60% energy savings compared to non-insulated buildings (Paraschiv et al., 2020). For this reason, the importance of insulation applications is increasing to reduce energy use and negative environmental impacts of buildings. However, applications must be compatible with technology and public policies (Coyle&Simmons, 2014).

Tokat province is in the 3rd climate zone of the four climate zones listed from hot climate to cold climate according to Degree Day regions. Many studies based on economic analysis have been carried out using the DD method to determine the optimum insulation thickness in the heating and cooling of buildings in all climatic zones of Turkey. Some of the studies in the literature are given below.

Kaynaklı (2013) determined the optimum insulation thicknesses, energy savings and payback periods of all cities in Turkiye according to their energy needs for heating, cooling and both. Effects of thermal and economic parameters on energy saving and optimum insulation thickness were determined.

Kürekci (2016) determined the optimum insulation thicknesses according to four different insulation materials and five different fuel types for heating, cooling and both heating and cooling applications for all provinces of Turkiye using DD and LCA methods. According to the 10-year lifetime and 9.83 PWF (present worth factor) the optimum insulation thickness in natural gas heating for Tokat province is calculated as 0.050 m for XPS insulation material, 0.071m for EPS (expanded polystyrene) insulation material, 0.096m for GW (glass wool) insulation material, 0.092m for RW insulation material and 0.036 m for Polystyrene insulation material, respectively.

Özel et al. (2015) claimed that the LCA method, which is widely used in determining the optimum insulation thickness due to the increasing effects of global warming, will not be sufficient to determine the optimum insulation thickness, and calculated the optimum insulation thickness for natural gas heating in Bilecik province for a lifetime of 10 years with a method called the Entasy method, which calculates the environmental impact using the life cycle analysis of materials, processes and systems. In the study, GW and RW were selected as insulation materials. According to environmental impact analysis, optimum insulation thicknesses were determined as 0.15 m and 0.064 m, and according to the LCA method, 0.012 m and 0.007 m.

Güven (2019) used DD method and exergetic environmental impact factor to examine the optimum insulation thicknesses and the change in CO_2 emissions for the provinces of Antalya, Bursa, Isparta and Erzurum in different climatic zones of Turkiye in heating with natural gas fuel. The study was carried out according to GW and RW insulation materials. The optimum insulation thickness was determined as the lowest 0.43 m and the highest 0.11 m, the reduction in CO_2 emissions between the minimum 64% and the highest 92%, and the net ecological environmental savings between the lowest 345 mPts/m^2.yr and 2249 mPts/m^2.yr according to the insulation material type.

Aşıkoğlu (2023) determined the heat losses and gains from the roofs and walls for four different insulation materials in the provinces of Turkiye located in the 1st degree day region with the Builder Simulation program according to the insulation thicknesses. When energy savings and investment costs were evaluated according to the net present value method, it was seen that the use of GW insulation materials for the roof and RW insulation materials for the wall were the most efficient options.

Ozkan&Onan (2011) calculated the optimum insulation thicknesses, energy savings, payback periods, reduction in CO_2 and SO_2 emissions of buildings according to two different insulation materials and two different fuel types, using the P_1-P_2 method for four different climate zones of Turkiye. In addition, it has shown that the increase in the percentage of glass area in buildings will cause a large increase in the optimum insulation thickness, revealing its disadvantage in terms of energy saving and emission of harmful gases.

Dombayci et al. (2017) calculated the energy requirement due to heat loss from the outer wall for four provinces located in different climate zones of Turkiye with DD method. Exergy analysis was used to calculate natural gas fuel consumption to cover heat losses. EPS and PU (polyurethane) made an economic analysis using LCA method for insulation materials and found optimum insulation thicknesses and energy savings. The optimum insulation thicknesses were calculated as between 2.3 cm and 10.7 cm depending on the type of insulation material, and energy savings were calculated as between 22% and 56% depending on the type of insulation material. The results showed that both the optimum insulation thickness and energy saving received the highest value in the province located in the colder climate zone.

Akan (2021) calculated the optimum insulation thicknesses, energy savings and payback periods for four different insulation materials for all provinces of Turkiye with DD and LCA methods for a life span of 10 years. Since the calculations contain many parameters and take time, it has developed 12 different models using regression analysis to make it easier to determine the optimum insulation thicknesses. Although the regression values of the models were found to be slightly lower than both heating and cooling only, they were over 96.8%, so they were successful in finding values close to the theoretical calculations. It has been suggested that the use of RW insulation material in all cities will be more appropriate.

Akan&Akan (2022) developed a model that predicts CO_2 emissions according to DD values and optimum insulation thicknesses according to four different insulation materials in all cities of Turkiye. It has been calculated that CO_2 emissions will be reduced by 66-76% and 46-69%, respectively, in heating-only and cooling-only application. It has been determined that the application of insulation will provide energy savings of 54.6-80.5% and 10.1-61.1%, respectively, in heating-only and cooling-only application.

Aktemur et al. (2021) calculated energy savings, payback periods and CO_2 emissions according to the optimum insulation thicknesses in natural gas heating application in all cities of Turkiye using XPS, EPS, GW and RW insulation materials. Researchers determined RW as the most advantageous insulation material and GW insulation material as the most disadvantageous insulation material. The optimum insulation thicknesses were found to be between 0.07 m and 0.23 m, the total annual energy savings were 4.4-53.5 (\$/m^2.year), the payback period was 0.11-0.38 years, and the CO_2 emissions were between 53.2%-94%.

Küçüktopçu&Cemek (2019) determined the optimum insulation thickness, energy savings, payback periods and CO_2 emissions for heating and heating-cooling application in laying hen houses. The study was conducted for ten provinces by selecting two different insulation materials and five different energy types.

In this study, optimum insulation thicknesses, payback periods, annual fuel savings and reduction in CO_2 emissions for XPS and RW insulation materials according to two different wall types in the heating and heating-cooling applications of Tokat province were calculated using DD and LCA methods. Although there are similar studies in the literature, most studies do not have CO2 emission values. There is only one study on CO_2 emissions for Tokat province. The fact that the heating and cooling day values that change with the effect of global warming and the inflation, interest, unit price of insulation material and fuel prices that change according to the years using up-to-date data makes the study different from previous studies.

Materials and Methods

The Properties of the Buildings Wall

The wall design for the insulation application to be made on the outer wall of the building is shown in Figure 1. Two different thickness wall types were selected to study the optimum change of insulation thicknesses in the exterior wall with different thermal resistances. The thicknesses and thermal properties of the construction materials in the exterior wall design are given in Table 1.

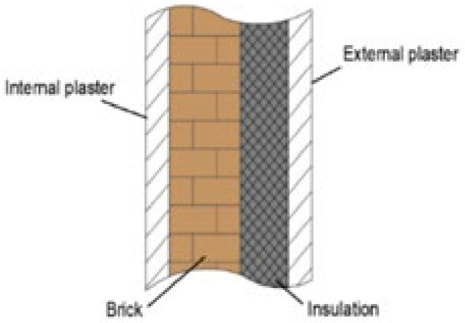

Figure 1. External wall structure (anonymous)

Table 1. Physical parameters of wall structure

WS	Thickness(m)		k (W m^{-1} K^{-1})		R (m^2 K W^{-1})	
	Type I	Type II	Type I	Type II	Type I	Type II
IP	0.02	0.02	0.87	0.87	0.023	0.029
B	0.13	0.19	0.45	0.50	0.289	0.380
EP	0.03	0.03	1.40	1.40	0.021	0.025
R_i	-	-	-	-	0.130	0.130
R_o	-	-	-	-	0.040	0.040
R_{wt}*	-	-	-	-	0.503	0.604

WS Wall structure; IP: Internal plaster; B Bricks; EP: External plaster; *(uninsulated)

Where, k is thermal conductivity, R is thermal resistance, R_o is outside thermal resistance, R_i is inside thermal resistance and R_{wt} is thermal resistance of wall layers in Table 1. In the literature, thermal resistances of the exterior wall were selected between 0.503-0,627 for Tokat province. (Kaynaklı, 2012; Kürekçi, 2016; Akan, 2021; Aktemur et al., 2021). In this study, the thermal resistance of two different wall structures was selected at 0.503 and 0.604 for Tokat province.

The Properties of the Insulation Materials

The thermal and economic values of XPS and RW insulation materials used in wall insulation are shown in Table 2.

Table 2. Features of insulation material

Insulation Material	k (W m^{-1} K^{-1})	Price (\$/m^3)
XPS	0.035	198
RW	0.039	309

* İzocam Company

Degree day's method

The Degree Day (DD) method, which is used to determine energy losses and gains in heating and cooling applications in building, is the sum of the difference between the preferred comfort temperatures and the outside temperatures over a certain period, usually between 14-18 °C for heating and 22-26 °C for cooling (Bulut at al., 2007; Bayram&Yeşilata, 2009).

The following equations were used to calculate Heating Degree Days (HDD) and Cooling Degree Days (CDD).

$$T_o < T_b$$
$$HDD = \sum_{i=1}^{n}(T_b - T_o) \quad (1)$$

$$T_o > T_b$$
$$CDD = \sum_{i=1}^{n}(T_o - T_b) \quad (2)$$

Where, T_b is inside temperature, T_o is outside temperature.

The average HDD and CDD values of the city of Tokat used in the study were accepted as 2068 and 171, respectively. These values were determined based on the base temperature of $T_b \leq 15$°C and $T_0 > 22$ °C recommended by Turkish State Meteorological Services (MGM,2024) between 2014 and 2023.

Economic Analysis

The heat loss per unit from the external building wall is given by,

$$q = U.(T_b - T_o) \quad (3)$$

Where, U is the overall heat transfer coefficient. The annual heat loss per unit area can be calculated from,

$$q_a = 86400.DD.U \quad (4)$$

Annual heating requirement per unit area of building wall,

$$E_{Ah} = \frac{86400.DD.U}{\eta} \quad (5)$$

Annual cooling requirement per unit area of building wall,

$$E_{Ac} = \frac{86400.DD.U}{COP} \tag{6}$$

Overall heat transfer coefficient for a typical building wall is given by,

$$U = \frac{1}{R_i + R_w + R_{ins} + R_o} \tag{7}$$

Where, R_i and R_o are convection resistances for inside and outside of the wall. R_w is the total thermal resistance of wall substances and R_{ins} is the thermal resistance of insulation material,

$$R_{ins} = {}^{x}\!/_{k} \tag{8}$$

Where, x and k are the thickness and thermal resistance of insulation material.

The cost of energy used in heating and cooling applications per unit area is calculated by the following equations.

Annual heating cost per unit area,

$$C_h = \frac{86400.HDD.C_f}{\left[\left(R_{wt} + \frac{x}{k}\right).H.\eta\right]} \tag{9}$$

Annual cooling cost per unit area,

$$C_c = \frac{86400.CDD.C_e}{\left[\left(R_{wt} + \frac{x}{k}\right).COP.\eta\right]} \tag{10}$$

In the study, the fuel price (C_f), the lowest calorific value (H_u), the fuel efficiency (η) and the price (C_e) of the electricity used in the cooling application and the cooling efficiency coefficient (COP) of the natural gas used as fuel in building heating are given in Table 3.

Table 3. Characteristics of fuels

Fuel	C_f (\$/m^3)	H_u (J.m^{-3})	COP	η (%)
N. Gas	0.26*	345.18 105	-	90
Electricity	1.98**	-	2.5	-

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In calculating the annual energy cost, it is necessary to determine the present worth factor;

If $i > g$ then

$$r = \frac{i-g}{1+g} \tag{11}$$

If $i < g$ then

$$r = \frac{g-i}{1+i} \tag{12}$$

$$PWF = \frac{(1+r)^N - 1}{r.(1+r)^N} \tag{13}$$

Where, i is interest rate, g is inflation and N is lifetime.

The inflation rate, interest rate and present value factor (PWF) calculated for the 10-year lifetime of the insulation material are given in Table 4.

Table 4. Financial Parameters

% Inflation (g)	% Interest (i)	PWF
61.78*	60*	9.4

*TCMB

The cost of insulation per unit area

$$C_i = C_l.x \tag{14}$$

Where, C_l is the cost of the insulation material and x is the insulation thickness

The total heating cost of an insulated wall as per the life cycle analysis

$$C_{t,h} = C_h.PWF + C_l.x \tag{15}$$

Both heating and cooling cost of an insulated wall as per the life cycle analysis

$$C_{t,h,c} = C_h.PWF + C_c.PWF + C_l.x \tag{16}$$

Total energy savings and payback period for buildings both heated and cooled are calculated with the following equations.

Optimum insulation thickness minimizing the total both heating and cooling;

$$x_{opt-h} = 293{,}94.\sqrt{\frac{HDD.PWF.k.C_f}{C_l.H.\eta}} - k.R_{wt} \tag{17}$$

$$x_{opt-hc} = 293{,}94.\sqrt{\frac{HDD.PWF.k.C_f}{C_l.H.\eta} + \frac{CDD.PWF.k.C_e}{C_l.COP}} - k.R_{wt} \tag{18}$$

$$A_{years} = C_{tpre-ins} - C_t \tag{19}$$

$$PP = \frac{C_i}{C_{tpre-ins} - C_t} \tag{20}$$

Emission Analysis

CO_2, CH_4, N_2O and fluorinated gases are directly called greenhouse gases. Million-ton CO_2 equivalent of direct greenhouse gases in Turkiye increased by 157.1% in 2021 compared to 1990. 85.2 % of total CO_2 emissions originated from the energy sector in 2021. CO_2 emissions due to electricity and heat generation in the energy sector are 32.7% (TUIK, 2021).

The general combustion equation of fuels used to obtain heat energy is given in the equation below.

$$C_aH_bO_dS_eN_f + \varepsilon\, X\,(O_2 + 3{,}76\, N_2) \rightarrow aCO_2 + \left(\frac{b}{2}\right) H_2O + (\varepsilon - 1)XO_2 + eSO_2 + YN_2 \tag{21}$$

The X and Y coefficients given in the general combustion equation are found by equations (22) and (23) below.

$$X = \left(a + \frac{b}{4} + e - \frac{d}{2}\right) \tag{22}$$

$$Y = \left(3{,}76\, \varepsilon\, X + \frac{f}{2}\right) \tag{23}$$

The molecular weight of the fuel,

$$M = 12a + b + 16d + 32e + 14f \tag{24}$$

Annual fuel consumption,

$$M_f = \frac{86400\, HDD}{(R_{wt} + R_{ins})\, \eta\, H} \tag{25}$$

Total annual CO_2 emissions due to fuel consumption,

$$M_{CO_2} = \frac{44a}{M}\, M_f \tag{26}$$

Result and Discussion

Optimum insulation thicknesses, energy savings, payback periods and reduction in CO_2 emissions calculated only in heating and heating and cooling application according to the type of insulation material in Tokat province are given in Table 5.

Table 5. Optimum insulation thickness, payback period, energy saving and reduction in CO_2 emissions compared to the insulation material of Tokat province.

Insulation material	Wall Type	X_{opt-h} (m)	X_{opt-hc} (m)	A_{year-h} (%)	$A_{year-hc}$ (%)	PP_h (years)	PP_{hc} (years)	$CO_{2(h)}$ (%)	$CO_{2(hc)}$ (%)
XPS	Type I	0.032	0.071	41.838	64.28	5.133	2.32	64.57	80.46
	Type II	0.029	0.068	33.166	58.06	6.922	2.94	57.77	76.28
RW	Type I	0.023	0.055	28.544	54.55	8.194	3.33	53.98	73.69
	Type II	0.019	0.051	19.426	47.07	11.928	4.30	44.65	68.49

Table 6. Comparison with other studies in the literature for Tokat province

Parameters	Present study Type I/ Type II	Kaynaklı (2012)	Kürekci (2016)	Akan (2021)	Aktemur et al. (2021)
R_{wt}	0.503/0.604	0.617	0.503	0.604	0.627
HDD	2068	2399	2399	2060	2150
CDD	171	5	97	106	-
η (N.Gas)	0.90	0.93	0.90	0.90	0.90
Cf ($ m^{-3})	0.26	0.386	0.385	0.232	0.367
Ce ($ kWh^{-1})	1.98	0.132	-	0.0912	-
C_l XPS ($ m^{-3})	198	-	180	150	93.921
C_l RW ($ m^{-3})	309	-	80	70	131.193
C_l PS ($ m^{-3})	-	80	-	-	-
COP	2.5	2.5	2.5	2.5	-
N	10	20	10	10	10
PWF	9.400	15.100	9.830	9.640	8.759
k					
XPS	0.035	-	0.031	0.030	0.031
RW	0.039	-	0.040	0.040	0.040
PS	-	0.035	-	-	-
X_{opth} (m)					
XPS	0.032/0.029	-	0.050	0.032	0.06
RW	0.023/0.019	-	0.092	0.061	0.05
PS	-	0.107	-	-	-
$X_{opt/hc}$ (m)					
XPS	0.071/0.068	-	0.052	0.034	-
RW	0.055/0.051	-	0.094	0.064	-
PS	-	0.107	-	-	-
A_{year-h}					
XPS	1.244/0.821	-	-	1.399	18
RW	0.849/0.481	-	-	1.570	14
$A_{year-hc}$					
XPS	6.064/4.561	-	-	1.530	-
RW	5.146/3.698	-	-	1.828	-
A_{year-h} (%)					
XPS	41.837/33.166	-	-	-	-
RW	28.543/19,425	-	-	-	-
$A_{year-hc}$ (%)					
XPS	64.28/58.06	-	-	-	-
RW	54.55/47.07	-	-	-	-
PS		83.2	-	-	-
PP_h (year)					
XPS	5.133/6.922	-	-	3.431	0.30
RW	8.184/11.928	-	-	2.720	0.45
PP_{hc} (year)					
XPS	2.32/2.94	-	-	3.333	-
RW	3.33/4.30	-	-	2.451	-
PS	-	6.89	-	-	-
Heating CO_2 (%)					
XPS	64.57/57.77	-	-	-	-
RW	53.98/44.65	-	-	-	-
Heating/Cooling CO_2(%)					
XPS	80.46/76.28	-	-	-	74
RW	73.69-68.49	-	-	-	66

Optimum insulation thicknesses, energy savings, and reduction in CO_2 emissions were found to be higher in Type I wall type of both insulation materials compared to Type II wall type, while payback periods were calculated to be lower. In the heating-cooling application of the same insulation material and wall type, optimum insulation thicknesses, energy savings, reduction in CO_2 emissions are quite high and the payback period is very low compared to the heating application alone. For this reason, it will be advantageous to prefer the Type I wall type with XPS insulation material, which has a low payback period and a high reduction in CO_2 emissions, in buildings where cooling is expected to be used effectively in terms of comfort as well as in heating applications.

The comparison between this study and four similar studies in the literature for Tokat province is shown in Table 6.

Optimum insulation thicknesses vary due to the differences in thermal and economic parameters. In addition, since the equations used to calculate the payback period and energy savings are similar in some studies and differ in others, a wide variety of results have been obtained. In terms of some of the thermal parameters (*HDD* and R_{wt}), the most similar study to the Type II wall type of this study is the study of Akan (2021). In the heating application alone, the optimum insulation thickness of the XPS insulation material was calculated as 0.029 m in this study and the Akan (2021) was calculated as 0.32 m. The optimum insulation thickness of the RW insulation material was found to be 0.019 m in this study and 0.061 m in Akan (2021)'s study. The fact that there is a large difference in the unit price of RW insulation material between the two studies shows that economic parameters cause large differences in the optimum insulation thickness.

As the price of insulation material increases, the optimum insulation thickness decreases, and according to Kaynaklı (2013)'s study, our study has shown similar results.

Conclusion

According to the two different wall thermal properties of XPS insulation material, the optimum insulation thicknesses are calculated as 0.032 -0.029 m, annual savings are 41.83%-33.17% and payback periods are 5.13-6.92 years, respectively, in heating application.

The optimum insulation thickness for heating-cooling application was found to be 0.071-0.068 m, annual savings were 64.28%-58.06% and payback periods were 2.32-2.94 years.

According to the two different wall thermal properties of the RW insulation material, the optimum insulation thicknesses for heating application were determined as 0.023-0.019 m, annual savings as 28.54%-19.42%, payback periods as 8.19-11.93 years.

The optimum insulation thicknesses for the heating-cooling application of RW insulation material were 0.055-0.051m, annual savings were 54.55%-47.07%, payback periods were 3.33-4.30 years.

The reduction in CO_2 emission in the heating-only application of XPS insulation material was 64.57%-57.77%, and the reduction in CO_2 emission in heating-only application of RW insulation material was 53.98%-44.65%.

The reduction in CO_2 emission for both heating and cooling application was 80.46%-76.28% for XPS and 73.69%-68.49% for RW.

Since the payback period and CO_2 emission were calculated with a lower value in the use of XPS insulation material than in RW insulation material, it has been determined that it is more appropriate to prefer XPS insulation material in terms of economy and environment only in heating and heating-cooling application in the province of Tokat.

Declarations

Author Contribution Statement

Yunus Kültürel: Conducted the study, data collection, review, formal analysis, and writing the original draft.

Lütfullah Dağkurs: Management, supervision, review, editing, and calculations of the study.

Conflict of Interest

"We declare that the authors have no conflict of interest."

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