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Minimizing heat transmission loads and improving energy efficiency of building envelopes in sub-Saharan Africa using bio-based composite materials

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ABSTRACT

Increasing effect of climate change coupled with global warming has necessitated the need for mechanical cooling in buildings to provide indoor thermal comfort. Many countries in tropical climates, particularly in sub-Saharan Africa, use sandcrete blocks for constructing building envelopes which have relatively high thermal conductivity. This leads to increased heat transmission through the building walls resulting in increased building electricity consumption using air-conditioners. This study focused on opportunity of minimizing the thermal conductivity of sandcrete blocks by mixing it with available bio-based local materials, specifically treated sawdust and palm fibers. Experiments were conducted to determine the thermal conductivity, compressive strength and densities of sandcrete mixed with 10%, 20%, 30% and 40% of treated sawdust and palm fiber to form building block composites. The study results showed that incorporating the bio-based material into the sandcrete decreases its density and thermal conductivity, thereby decreasing the wall heat transmission load. Using a minimum standard limit of 3 MPa for compressive strength for building envelopes, the composite samples: S10, P10, P20 and P30 were found to be appropriate to be used to minimize wall heat transmission. The composite of 70% sandcrete with 30% treated palm fiber (P30) exhibited the best thermal performance with 38% reduction in thermal conductivity compared to the control sandcrete block. Maximum wall heat flux reduction of 52 W/m^2 was attained at peak load with the composite P30 compared to the control sample P0 (100% sandcrete). In addition, using the degree-days cooling for Ghana, the analysis indicated maximum electricity saving potential of 453.40 kWh per year for an office space cooling using the sandcrete-palm fiber composite P30 as the building envelope.

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Introduction

Electricity consumption of residential, commercial and public buildings in tropical climates is dominated by air-conditioning equipment to provide indoor thermal comfort [1–3]. The type of construction materials used in these buildings and the characteristics of the building envelopes have huge impact on the building energy consumption as far as air-conditioning is concerned [4,5]. In particular, air-conditioning equipment could consume as much as 60–80% of electricity used in commercial and public buildings in hot-humid climates [6].

Recent research and development in the building industry are therefore focused on sustainable energy efficient building materials that minimize wall heat transmission load in order to reduce the electricity consumption and the corresponding operational cost of buildings [7,8], and in addition reduce CO_2 emissions associated with electricity use in buildings [9,10].

Building codes in terms of thermal performance of building envelopes have therefore been established in different countries and research are being conducted all over the world to meet these green building codes [11–13]. For example, research on using phase change materials (PCM) to reduce cooling energy requirements of buildings have been investigated [14–17]. It has also been demonstrated that PCM can be used to reduce and control fluctuations in indoor temperature of buildings during the hot summer days [18]. In the work of Ramakrishnan et al., [19], they reported annual energy savings potential of 16–25% in commercial buildings in major Australian cities using thermal energy storage cementitious composites (TESC) to reduce peak indoor temperatures by approximately 5.6 °C during summer design days.

A number of studies have been conducted by different researchers to improve the thermal characteristics of building materials to minimize outdoor-to-indoor heat transmission via building envelopes in order to reduce energy consumption of buildings [20–22]. For instance, studies conducted by [23,24] have shown that conventional building materials can be modified to reduce building energy consumption as far as air-conditioning equipment energy consumption is concerned.

In the work of Boumhaout et al., [25], they conducted studies on the use of energy efficient composite material consisting of mortar reinforced with Date Palm Fiber (DPF) mesh. The bio-composite material used in their work was experimentally characterized in terms of thermal conductivity, diffusivity, thermal capacity, effusivity, compressibility and flexural strengths. They reported that the increase of DPF mesh content in mortar increases its insulating capacity by decreasing its thermal conductivity by up to 70%. Moreover, the heat damping properties of the composite material is enhanced as its thermal diffusivity is reduced by up to 52% and its thermal effusively is reduced by up to 56%. Furthermore, DPF mesh lightens the mortar by decreasing its density by up to 39%.

Using international building codes and standards, soil blocks used as building envelopes should have a minimum compressive strength of 3.0 MPa [26]. The work of Madrid et al., [27] also reports acceptable compressive strength of 3.0 MPa or more for non-load-bearing masonry units. In the experimental work of Danso et al., [28], compressive strength in the range of 1.6 3.0 MPa was obtained for soil building blocks mixed with different proportions of coconut, bagasse and oil palm fibers.

In the design of energy efficient building materials using composites, low thermal conductivity is desired. However, it is expected that the physical strength of the building material in terms of the compressive strength is not compromised. Compressive strength, density and thermal conductivity are therefore three decisive parameters to consider for light weight energy efficient insulating building materials [29].

Sandcrete block: the main building envelope in cities of sub-Saharan Africa

In the cities of Ghana and most sub-Saharan African countries, sand and cement are mixed in various proportions to form mortar sandcrete matrix which are then used to mould sandcrete blocks that are predominantly used as envelopes for buildings in the residential, commercial and public sector. The blocks are usually moulded with coarse sand and cement mixed in the proportions of 4:1 upto 6:1 by weight depending on the quality desired. Little water is added during the mixing process to facilitate bonding and subsequent curing of the sandcrete blocks. Fig. 1a shows solid sandcrete block for constructing buildings in Ghana. The individual blocks are layed to form the building envelope. After laying the blocks, the surface is then plastered with fine sand-cement mortar to give it a good finish (Fig. 1b).

In hot climates as we have in Ghana, much of the electricity consumption in buildings is for room air-conditioning during the daytime [6]. The high daytime air-conditioning load is largely attributed to the poor thermal resistance (that is, the high thermal conductivity) of the building envelope made of sandcrete blocks. Table 1 shows the thermal conductivity values of some building materials (building envelopes) used in different places [30–33].

As observed from Table 1, the thermal conductivity of sandcrete blocks which are predominantly used as the building material/envelope in Ghana and many countries in sub-Saharan Africa is very high compared to other building materials used in some developed countries (plaster board, clay bricks, etc.). The high thermal conductivity of the sandcrete blocks results in high heat transfer through the building envelope, thereby increasing the air-conditioning load. This effect subsequently increases the electricity consumption of the building because of the increased cooling load.

This study focuses on opportunity of minimizing the thermal conductivity of sandcrete blocks by mixing it with available bio-based local materials, specifically treated sawdust and palm fibers, without compromising on the strength. The study objectives are to: determine the thermal conductivity and the compressive strength of the composite blocks by varying the proportions of the sawdust and palm-fiber in the sandcrete material; measure and analyze the effect of density on the

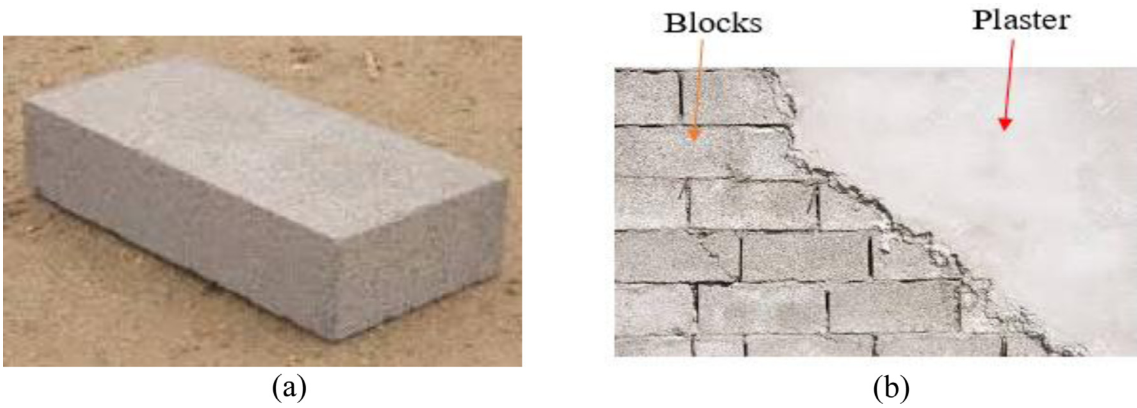

Fig. 1. (a) Sample sandcrete block and (b) cement plaster on wall.

Table 1
Thermal conductivity of different building materials/envelopes.

Building Material	*Thermal conductivity (W/m K)*
Clay	0.151.81
Sandcrete block (mixture of cement and sand)	1.131.41
Straw	0.090.20
Wood	0.100.14
Clay bricks	0.701.32
Plaster board	0.170.19
Glass	0.930.96
Rigid polyurethane	0.0220.028
Autoclaved aerated concrete	0.160.20
Timber	0.120.19

Table 2
Composition for preparing the composite sandcrete blocks.

Sample	Composite of sandcrete and treated sawdust	Sample	Composite of sandcrete and treated palm fiber
S0	100% sandcrete, 0% sawdust	P0	100% sandcrete, 0% palm fiber
S10	90% sandcrete, 10% sawdust	P10	90% sandcrete, 10% palm fiber
S20	80% sandcrete, 20% sawdust	P20	80% sandcrete, 20% palm fiber
S30	70% sandcrete, 30% sawdust	P30	70% sandcrete, 30% palm fiber
S40	60% sandcrete, 40% sawdust	P40	60% sandcrete, 40% palm fiber

thermal conductivity and compressive strength of the composite blocks; and determine the potential reduction in wall heat flux and electricity consumption of the composite blocks relative to the pure sandcrete blocks.

Materials and methods

Preparation of composite sandcrete blocks

In this study, new composite materials comprising of sandcrete mixed with treated palm fiber and sawdust were prepared in different proportions (by weight) as presented in Table 2. The raw sawdust and the palm fiber materials (shown in Fig. 2, a b) were initially treated with Chlorpyrifos (CPS) solution to kill any potential hidden insects/pests. CPS is an organophosphate pesticide [34] and has no effect on the chemical composition or mechanical properties of plant based materials [35]. It also has no chemical bonding property when used in treatment of wood, building materials and structures [36]. In this study, the treatment process using CPS (50% liquid concentrate) was undertaken over a 24 h period by missing it with water in the proportion of 1% CPS with 99% water, by volume [36]. Thereafter, the treated sawdust and palm-fiber materials were dried in the open sun for 3 days before mixing with the sandcrete mortar to obtain the bio-based composite materials. For the sawdust, grain diameters between 0.5 and 1.4 mm were measured using a standard mechanical sieve whilst for the palm-fibers, diameters of 0.4 0.8 mm were measured with digital Vernier caliper.

Using a standard mould from the Civil Engineering Laboratory at KNUST, the sandcrete-bio-based composite materials were moulded to form different samples of blocks (Fig. 2d) based on standard block dimensions used in Ghana of 450 mm x 125 mm x 225 mm. The blocks were then cured for 28 days before determining their thermo-mechanical properties (thermal conductivity, compressive strength and density).

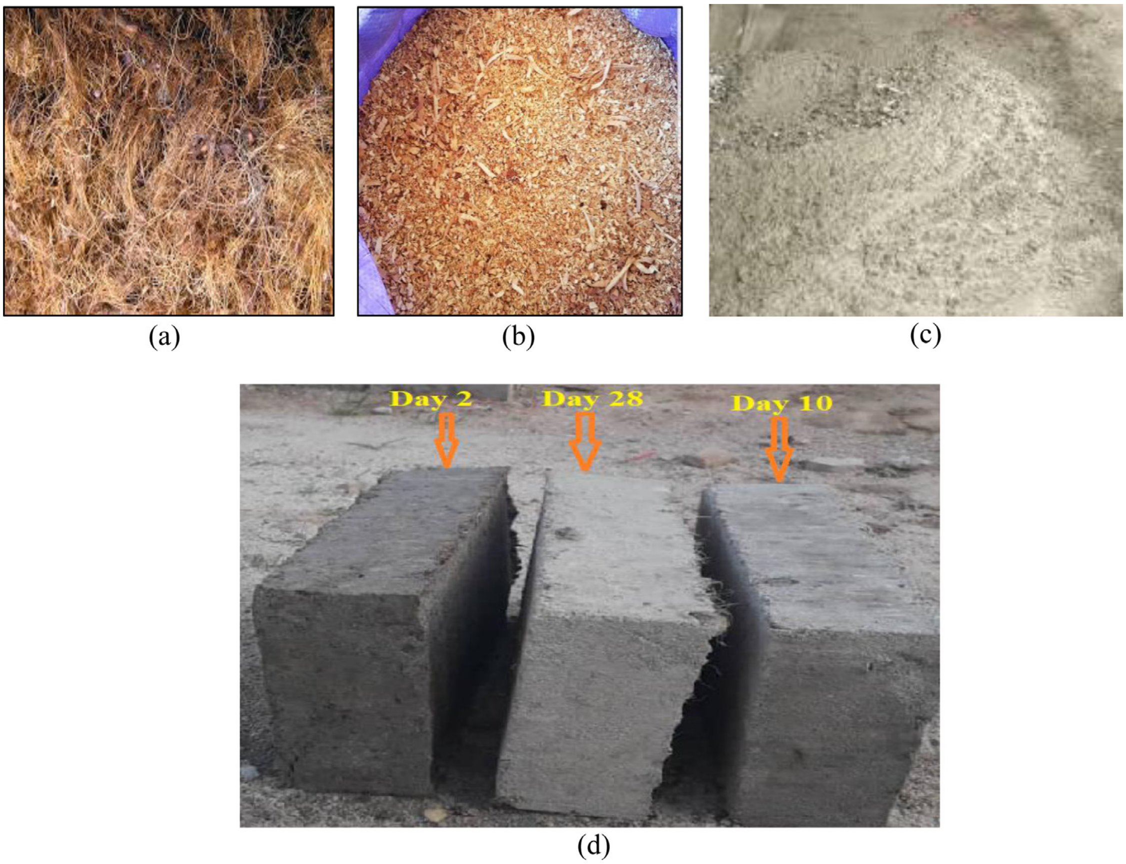

Fig. 2. Composite Preparation: (a) Treated palm-fiber, (b) Sawdust, (c) Sandcrete (sand-cement mixture) and (d) Sandcrete-bio-based composite blocks at different curing days.

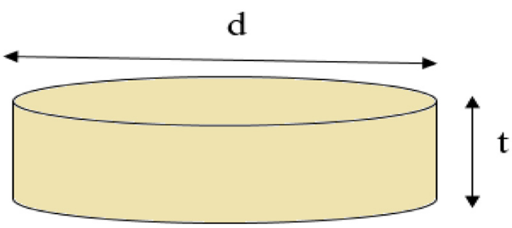

Fig. 3. disk-shaped block element to determine '*k*' value.

Determination of thermo-mechanical properties

Thermal conductivity

The thermal conductivity (k) of the various block samples of sandcrete with treated palm fiber and sawdust were determined using the Slab method with a TPS 2500S Hot Disk Thermal Constant Analyzer (HDTCA). The accuracy of the temperature sensors of the HDTCA was ±0.01 °C and thermal conductivity reproducibility of ±2.0%. disk-shaped block samples/elements were made as shown in Fig. 3 and tested in the hot disk thermal constant analyzer (Fig. 4) to determine the thermal conductivities. Prior to the measurement of the thermal conductivity values, the measuring instrument was calibrated based upon ANSI/NCSL Z540.1 (R2002).

In the determination of the thermal conductivity values of the samples with the HDTCA, the requirement for the ratio of sample thickness (t) to the sensor radius (r) was ensured such that: $0.03125 < \frac{t}{r} < 0.79836$. The disk-shaped block samples were subjected to heat flow (Q) by the hot-disk apparatus and the temperature difference (ΔT) across the surfaces were measured at steady state conditions. The thermal conductivity values were then determined using the Fourier 1-D heat

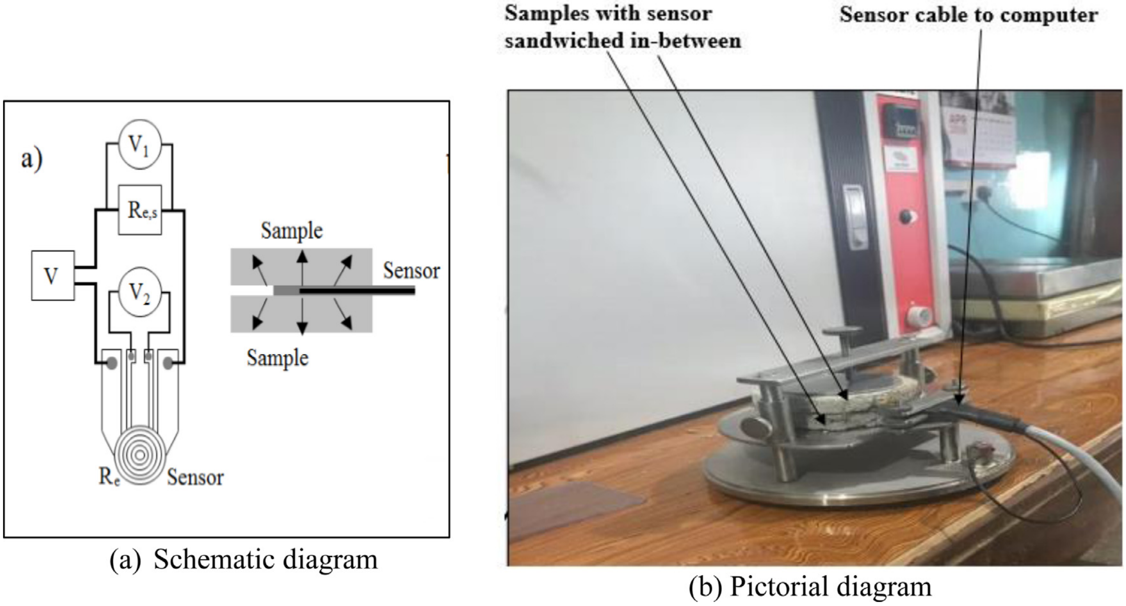

Fig. 4. Setup for thermal conductivity measurement using the HDTCA.

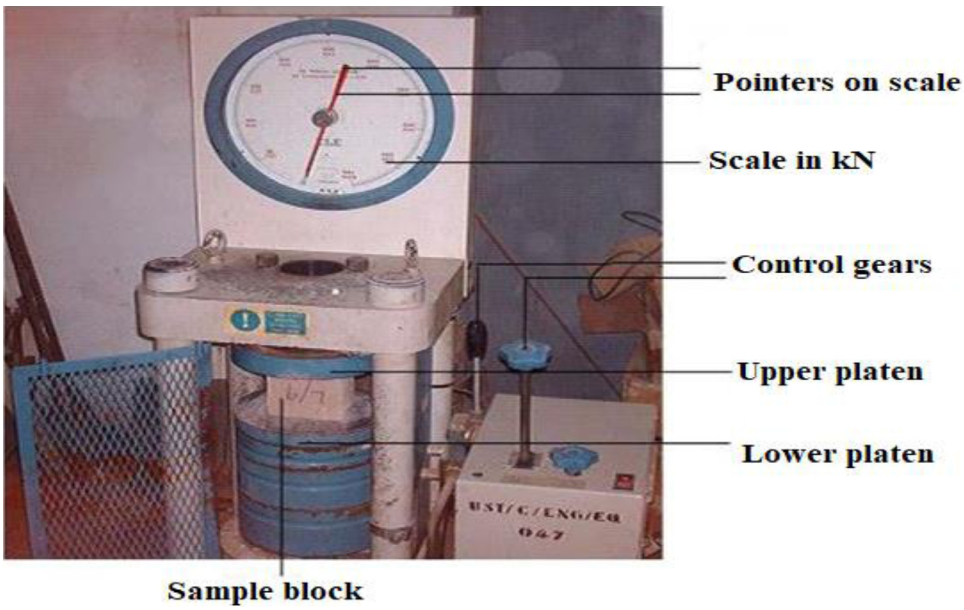

Fig. 5. Setup for compressive strength test.

equation as:

$$k = \frac{Q \times t}{A \times \Delta T} \tag{1}$$

where; A is the surface area of the disk-shaped block element, t is the thickness, and ΔT is the difference in the surface temperatures of the block element being tested. Five experimental trials were conducted for each element and the mean thermal conductivity value was computed.

Compressive strength

The compressive strength of each of the samples of the sandcrete-bio-based composite blocks was also determined with an Avery Testing Machine (ATM). Fig. 5 shows a sample of the solid block mounted in the ATM. The accuracy of the ATM is ±1.5%.

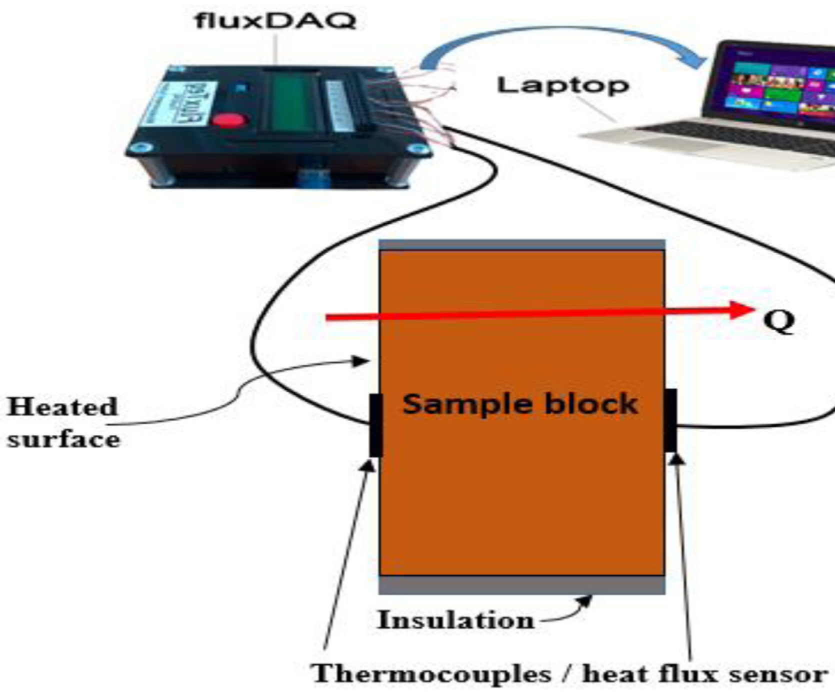

Fig. 6. Experimental setup for wall heat transfer analysis.

The compressive strengths (Cs) of the composite blocks were computed using Eq. (2).

$$C_s = \frac{F_c}{A} \tag{2}$$

where Fc is the ultimate load applied to cause crushing of the blocks and A is the cross-sectional area perpendicular to the load.

Block heat transmission experiment

For the purpose of determining the heat transmission through the control block sample (100% sandcrete) as well as the composite blocks of sandcrete with treated sawdust and palm-fiber, experiments were conducted to measure the rate of heat transfer per unit area through them. Fig. 6 shows the experimental setup. FluxDAQ instrument which measures and records both temperature and heat flux (the rate of heat transfer per unit surface area, in W/m^2) was used. In the experimental simulations, heat was applied on one side of the block surface (outer surface) using a resistive surface heater. The surface temperatures across the block samples were then measured at steady state conditions for each heat flux applied. In the experiment, it was ensured that the block outer surface temperature did not exceed 50 °C to mimic practical scenarios of building surface temperatures as reported in the work of Zempare et al.[37].

The heat flux and surface temperatures data were recorded onto a computer via the FluxDAQ instrument. The accuracies of the temperature and the heat flux sensors were ±0.75% and 0.02 W/m^2, respectively.

Thermal modeling of a composite wall system

For the purpose of estimating the wall heat transmission load for space cooling of an office constructed with the different block samples with cement plaster (k = 0.72 kW/m °C) on both sides of the block, the overall heat transmission coefficient (U) was computed using a thermal resistance circuit (Fig. 7). Each layer of the composite wall (comprising outside cement plaster, middle block, and inside cement plaster) was represented with a thermal resistance.

The total thermal resistance was computed for the three thermal resistances in series as:

$$\begin{aligned} R_{total} &= \sum R = R_{po} + R_b + R_{pi} = 2 \times R_p + R_b \\ &= 2 \times \tfrac{\Delta x_p}{k_p} + \tfrac{\Delta x_b}{k_b} \end{aligned} \tag{3}$$

where R_{po}, R_b andR_{pi} are the thermal resistances for the outer plaster, the block and the inner plaster, respectively. The inner cement plaster and the outer cement plaster are usually of the same material and thickness such that $R_{po} + R_{pi} = 2 \times$

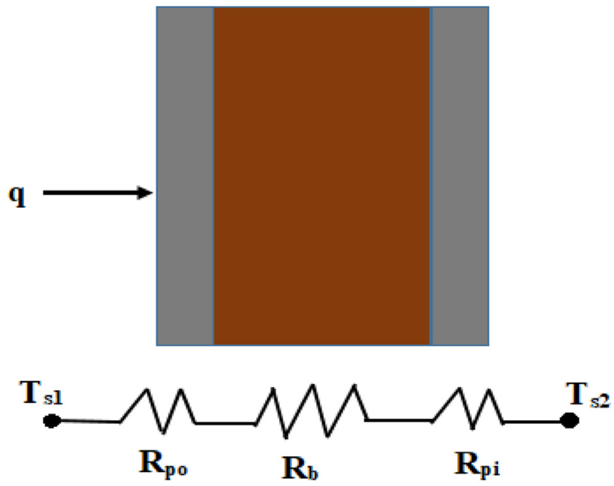

Fig. 7. Thermal resistance circuit for the wall.

Table 3
Wall characteristics of a standard office and climatic data for Kumasi city.

Wall characteristics		Month	RH (%)	T_{db} (°C)
Total wall surface area	66 m^2	Jan	70.2	27.8
Wall surface made of blocks	49.5 m^2	Feb	66.0	29.5
Cement plaster on blocks	12 mm thickness	Mar	70.3	29.0
	k = 0.72 W/m K	Apr	75.0	28.9
		May	78.0	28.0
Control sandcrete block	125 mm thickness	Jun	80.1	26.5
	k = 1.34 W/m K	Jul	82.1	25.9
		Aug	84.0	25.0
Composite sandcrete blocks	125 mm thickness	Sep	81.2	26.1
	Varying "k" value	Oct	78.5	27.0
Air-conditioner installed in the office	EER = 3.15 and electricity consumption of	Nov	76.1	28.1
for space cooling	2600 kWh/yr	Dec	70.3	27.5
		Annual	***76.0***	***27.4***

$R_p$where k_p and k_b are the thermal conductivities of the cement plaster and the block, and Δx_p and Δx_b are the thicknesses of the cement plaster and the block, respectively.

The wall heat flux can be written in terms of the overall heat transmission coefficient (U) as:

$$q = U \cdot \Delta T = \frac{\Delta T}{R_{total}} \tag{4}$$

where $\Delta T = T_{s1} - T_{s2}$ and $U = {}^{1}/_{R_{total}}$

Using the information on the overall heat transmission through the block walls, analysis was conducted on the potential electricity savings for space cooling for a standard office located in Kumasi city, Ghana. The characteristics of the office wall and the energy efficiency rating (EER) of the air-conditioner installed in the office are presented in Table 3. The monthly mean relative humidity (RH) and dry bulb temperatures ($\mathbf{T_{db}}$) of Kumasi are also presented [6].

Statistical analysis

Three main thermo-mechanical properties including thermal conductivity (k), compressive strengths (Cs) and the density ($\boldsymbol{\rho}$) of the different samples were measured. In the measurement of the thermo-mechanical properties, the experiments were repeated 5 times for each material sample. The mean values and the standard deviations associated with the measurement were then computed using Eqs. (5) and 6 [38], at 95% confidence level.

$$\overline{X} = \frac{1}{N} \cdot \sum_{i=1}^{N} X_i \tag{5}$$

$$\sigma_s = \frac{t}{\sqrt{N}} \times \sqrt{\frac{\sum_{1}^{N} \left(X_i - \overline{X}\right)^2}{N-1}} \tag{6}$$

Table 4
Thermo-mechanical properties of the composite materials.

Sample	Composition	k (W/m K)	C_S (MPa)	ρ_m (kg/m^3)
S0	100% sandcrete, 0% sawdust	1.34 ± 0.014	4.196 ± 0.016	2053.71
S10	90% sandcrete, 10% sawdust	0.98 ± 0.016	4.160 ± 0.018	2002.74
S20	80% sandcrete, 20% sawdust	0.95 ± 0.016	2.489 ± 0.019	1840.44
S30	70% sandcrete, 30% sawdust	0.56 ± 0.018	1.244 ± 0.019	1753.55
S40	60% sandcrete, 40% sawdust	0.37 ± 0.021	1.156 ± 0.020	1721.96
P0	100% sandcrete, 0% palm fiber	1.34 ± 0.014	4.196 ± 0.016	2053.71
P10	90% sandcrete, 10% palm fiber	1.03 ± 0.015	4.569 ± 0.017	1990.52
P20	80% sandcrete, 20% palm fiber	0.97 ± 0.016	4.089 ± 0.017	1943.13
P30	70% sandcrete, 30% palm fiber	0.83 ± 0.017	3.911 ± 0.019	1887.84
P40	60% sandcrete, 40% palm fiber	0.45 ± 0.019	2.382 ± 0.019	1824.64

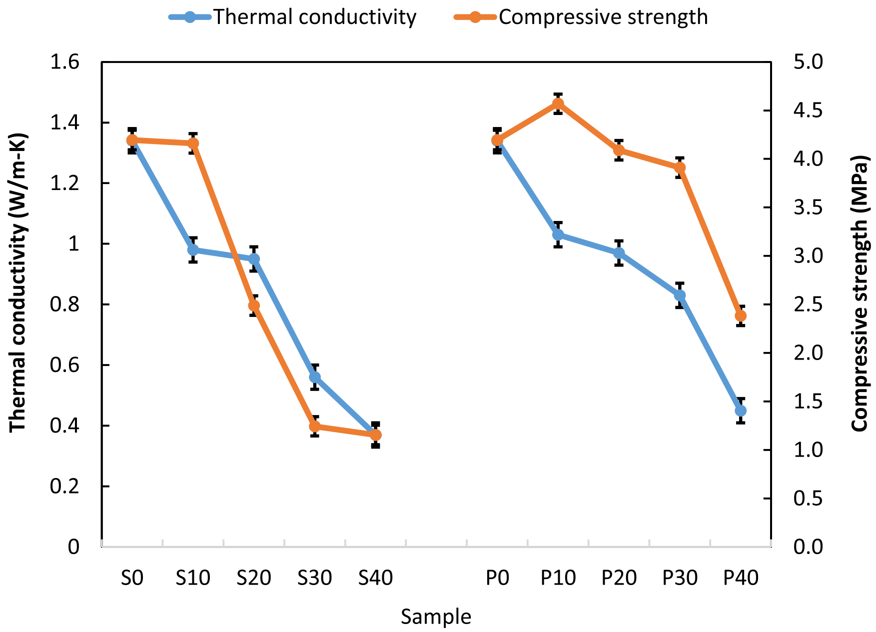

Fig. 8. Thermal conductivity and compressive strength of the composite blocks.

Where X_i is the ith data point, $\overline{X}$ is the mean value, N is the number of data points and t depends on N and the confidence level (in this case 95%). A value of $t = 2.57$ was used from statistical tables [39]. The results obtained from the experimental measurement and the analysis of the energy savings potential with the different bio-based composite blocks are presented in the following sections.

Results and discussions

Thermo-mechanical properties

The computed mean values and standard deviations from the experimental measurement for the different composite materials are presented in Table 4.

From Table 4, it is observed that all the blocks produced are categorized under dense aggregate masonry blocks [27] since their densities are between 1700 2400 kg/m^3. For the purpose of comparing the thermal conductivity and the compressive strength of the different composite blocks with their densities, the values are plotted and presented in Fig. 8.

It is observed from Fig. 8 that for both composite blocks of sandcrete with sawdust and palm-fiber, the thermal conductivity and the compressive strength generally decreases with increasing percentage of the plant-based material. The thermal conductivity values of the sandcrete-sawdust composites were found to be lower than that of the sandcrete-palm fiber composites. The thermal conductivity values for the composite blocks obtained in this work compare well with the values ($k = 0.44$ –1.02 W/m K) reported in the works of [29,40,41].

For the compressive strength, the sandcrete-palm fiber composites exhibited relatively higher values compared to that of the sandcrete-sawdust composites. From literature and building codes, materials used as building envelopes should have

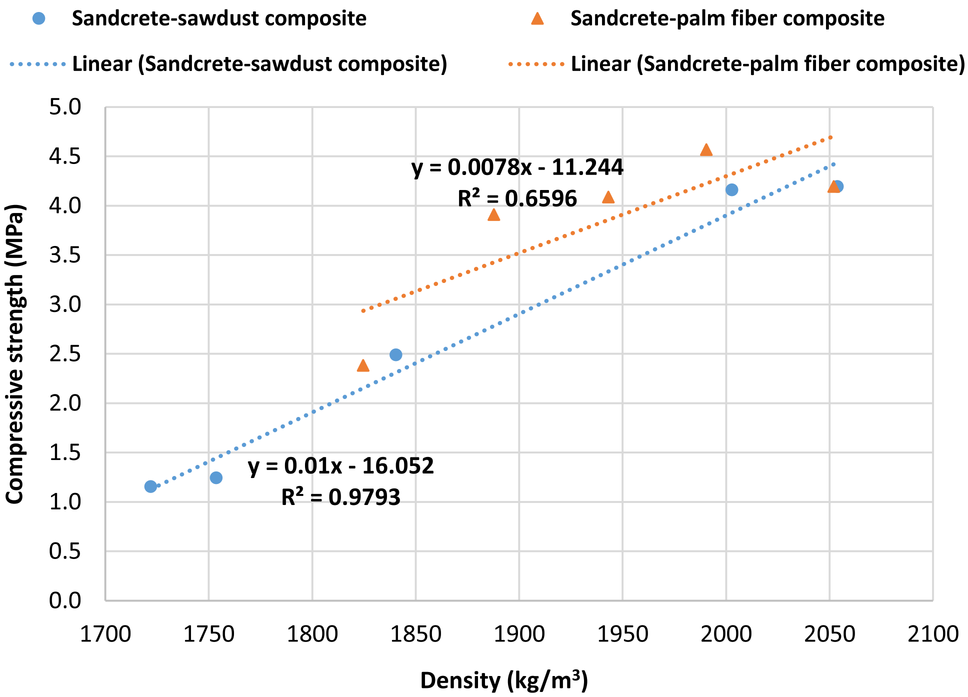

Fig. 9. Compressive strength versus density.

minimum compressive strength of 3.0 MPa [26]. Using this minimum compressive strength (Cs ≥ 3.0 MPa) as yardstick and comparing with the results of Fig. 8, the following cases (with conditions) emerged:

1 Compressive strength (Cs) ≥ 3.0 MPa $\{90\%\,\text{Sandcrete},\ 10\%\,\text{Sawdust}\,(\text{S10})$
$90\%\ Sandcrete,\ 10\%\ Palm\ fiber\ (\text{P10})$
2 Compressive strength (Cs) ≥ 3.0 MPa $\{80\%\ Sandcrete,\ 20\%\ Palm\ fiber(\text{P20})$
$70\%\ Sandcrete,\ 30\%\ Palm\ fiber\ (\text{P30})$

The results indicate that for the sandcrete-sawdust composite materials, only sample (S10) meets the compressive strength requirement of (Cs) ≥ 3.0 MPa, with thermal conductivity of 0.98 W/m K. In the case of the sandcrete-palm fiber composites, the composite samples (P10), (P20) and (P30) meet the compressive strength requirement of (Cs) ≥ 3.0 MPa, with corresponding thermal conductivity values of 1.03 W/m K, 0.97 W/m K and 0.83 W/m K, respectively. Comparing these thermal conductivity values of the composite blocks that meet the compressive strength standard (Cs ≥ 3.0 MPa) with the control sandcrete block (100% sandcrete with $k = 1.34$ W/m K), it is determined that there is maximum reduction in thermal conductivity value of 38.1% with the composite block sample P30.

Variation of compressive strength with density

The compressive strengths of the composite blocks are plotted with their densities as shown in Fig. 9.

From the results of Fig. 9, it is observed that the compressive strengths of the sandcrete palm fiber composites are generally higher than that of the sandcrete sawdust composites. The higher compressive strength of the sawdust-palm fiber composites could be attributed to the morphological arrangement of the palm fiber which are cylindrical in shape and irregular with many filaments and cells allowing good adhesion between the fibers and the sandcrete matrix Braiek et al., [42].

Variation of thermal conductivity with density

The thermal conductivity values were also plotted against the densities for the different samples as shown in Fig. 10.

From the result of thermal conductivity versus density, it is observed that generally, a change in density causes a change in the same direction in thermal conductivity. The implication is that as density of the composite materials decreases thermal conductivity also decreases. There is a strong relationship between the thermal conductivity and density of the composites (with $R^2 = 0.95$ and $R^2 = 0.86$ for composites of palm-fiber and sawdust, respectively). This result is consistent with the findings of Riaz et al., [29] which emphasized strong dependence of thermal conductivity on density. Inferring from the best fit line, it is observed that the thermal conductivity has a relation with the density (ρ) with the following empirical

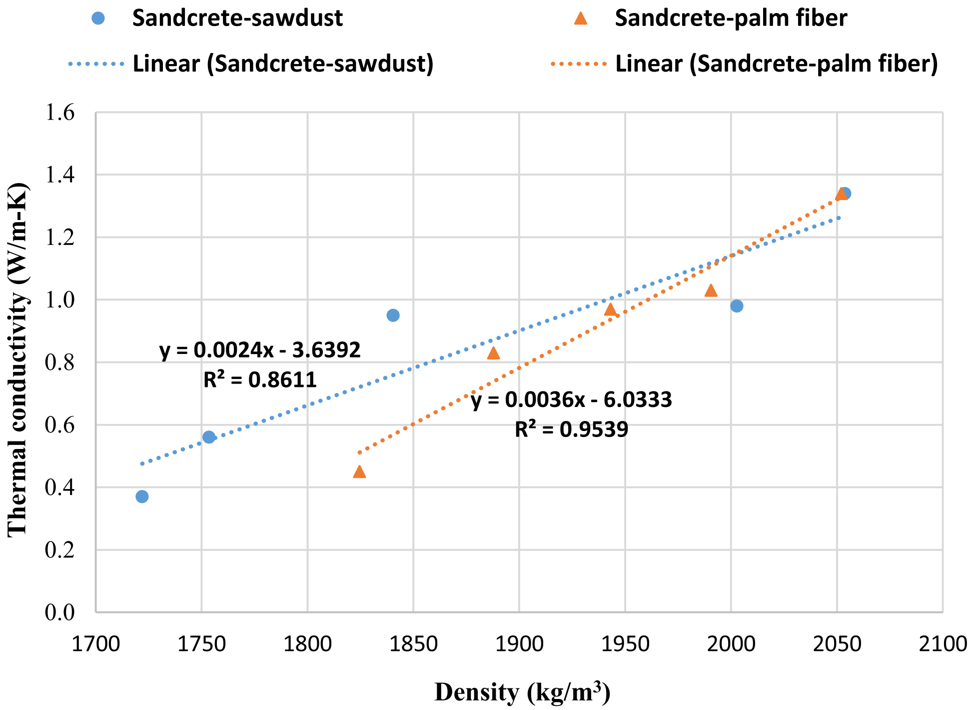

Fig. 10. Thermal conductivity versus density.

expression:

$$k(\rho) = \begin{Bmatrix} k_s = 0.0024\rho - 3.6392 \\ k_p = 0.0036\rho - 6.0333 \end{Bmatrix} \tag{7}$$

where: k_s and k_p represent the thermal conductivity of the sawdust and palm fiber composites, respectively. Testing the empirical correlations with other thermal conductivity values for plant-based composite building materials reported in literature [33, 43–45], it is found out that the developed empirical correlation (Eq. (7)) is able to estimate their values within 18% margin. This implies that Eq. (7) can be used to estimate the thermal conductivity of plant-based composite building materials within uncertainty band of 18%.

Heat transmission analyses

Heat transfer analyses were conducted on the bio-based sandcrete composite blocks as well as the control sample (100% sandcrete). The thermal conductivity values (k) obtained for each sample was used to evaluate the rate of heat transfer per unit surface area of the blocks using the experimental setup of Fig. 6 above. The rate of heat transmission per unit surface area (heat flux) is defined as:

$$q = -k_m \frac{T_{S2} - T_{S1}}{L} = k_m \frac{T_{S1} - T_{S2}}{L} = k_m \frac{\Delta T}{L} \tag{8}$$

where L is the thickness of the block in the direction of the heat flux and ΔT is the difference in surface temperatures of the block. Fig. 11 shows the results of the heat flux through the blocks at different simulating times (from sunrise to sunset: 7:00 GMT to 18:00 GMT) for the composites blocks of sandcrete–sawdust and sandcrete palm fiber. The results are shown for only the blocks that meet the minimum 3.0 MPa compressive strength standard.

From the results of Fig. 11, it is observed that for both composites of sandcrete-sawdust and sandcrete-palm fiber, the wall heat flux initially increases at sunrise, peaks at around 2 pm (14 GMT) and then decreases till sunset. It is also observed that there is no appreciable difference in the heat flux for S10, P10, and P20. Sample P30 had the lowest heat flux values at all times compared to the other composite samples. Comparing P30 to the control sample, there is a maximum heat flux reduction of about 52 W/m^2 around 2 pm (14:00 h GMT). This result gives an insight of using sample P30 as an efficient building material to reduce wall transmission load of buildings in order to minimize their air-conditioning load thereby reducing the electricity demand for air-conditioning equipment.

The result also shows that at any given time, the heat flux decreases with increasing composition of the bio-based material in the composite block. The decrease in the heat flux is as a result of decrease in the thermal conductivity of the composite block due to increasing percentage of the sawdust and palm fiber in the sandcrete material. This results compares

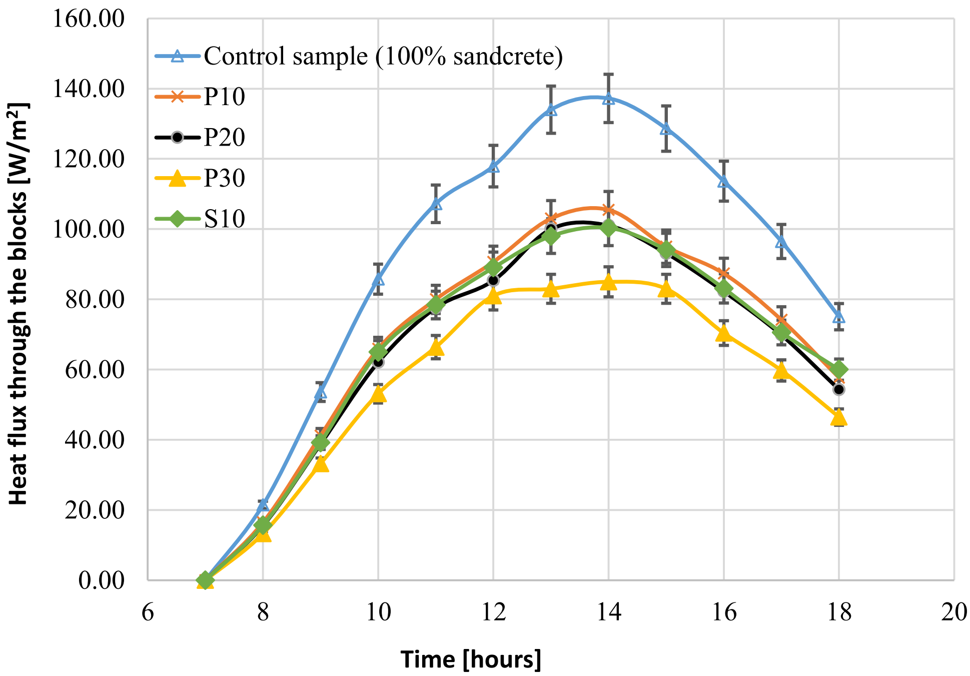

Fig. 11. Heat flux for sandcrete-bio-based composite blocks.

Table 5
Difference in overall heat transmission coefficient.

Block type	Difference in overall heat transmission coefficient ($U - U_{com}$) (W/m^2 °C)
Control	–
S10	1.68 ± 0.09
P10	1.43 ± 0.07
P20	1.73 ± 0.09
P30	2.46 ± 0.11

favorably well with the findings of [42,46,27,47] when plant based materials were used to reduce the thermal conductivity of building materials.

Electricity savings potential with bio-based sandcrete building blocks

Using the data presented in Table 3 above and the overall heat transmission coefficient for the office wall, the potential savings in the office electricity consumption for space cooling considering the office walls being constructed of the different composite blocks compared to the control sample was computed using Eq. (9) [48].

$$E_{savings} = \frac{H \cdot A_{wall} \cdot (U - U_{com}) \cdot DDC}{EER} \tag{9}$$

where H is the number of hours of space cooling per day. For the cooling of the office space, 8 h of cooling per day was used. The degrees days cooling (DDC) values were obtained from the database of [49]. The overall heat transmission coefficients of the multi-layered wall were computed (Eq. (4)) in the case of the wall with the control sample (U) and the composite samples (U_{com}) for S10, P10, P20 and P30 which satisfied the compressive strength standards. Table 5 presents the difference in overall heat transmission coefficient ($U - U_{com}$) for the building wall envelope using the different composite blocks with the cement plaster on the inner and outer surfaces.

The results of the annual electricity savings potential obtained with the office wall constructed with the different composite blocks are presented in Fig. 12.

The result of Fig. 12 shows that there is substantial potential electricity savings in the office space cooling using the different composite blocks for the office wall compared to the control sample. From the result, it is found out that the composite materials S10, P10, P20 and P30 have potential electricity savings of 309.9 kWh/yr, 264.1 kWh/yr, 319.2 kWh/yr and 453.4 kWh/yr, respectively, compared to the control sample. This study has revealed that there is maximum electricity savings potential of 453.40 kWh per year for the office using the sandcrete-palm fiber composite P30. The results obtained in this study give insights to huge potential reduction in building electricity consumption using bio-based materials to improve

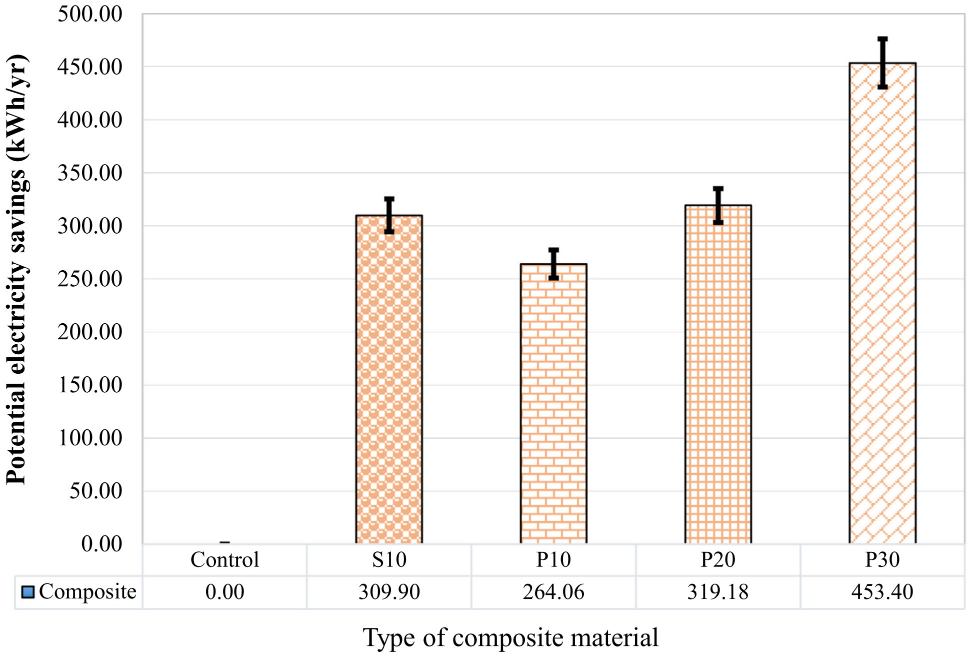

Fig. 12. Potential annual electricity savings with bio-based composite blocks.

the thermal performance of building envelopes made of sandcrete blocks which are predominantly used in sub-Saharan Africa.

Conclusion and recommendations

From the results obtained in this study, the following key conclusions are made:

i The density and the thermal conductivity of the composite sandcrete blocks decreased with increasing proportion of the bio-based materials. To achieve the minimum possible thermal conductivity that fulfills the requirement for efficient energy use, a minimum limit was set for the compressive strength of the composite sandcrete blocks.
ii Using a minimum limit or constraint of 3 MPa for compressive strength for building envelopes, the composite samples: S10, P10, P20 and P30 were found to be appropriate to be used to minimize wall heat transmission.
iii A maximum heat flux reduction of 52 W/m^2 was attained at peak wall heat transmission load with the composite P30 compared to the control sample of 100% sandcrete (PO). The results from this study also show that there is maximum electricity savings potential of 453.40 kWh per year for an office space cooling using the sandcrete-palm fiber composite P30 as the building envelope.

Declaration of Competing Interest

We write to confirm that there is no conflict of interest with this submitted article with our institutions or our funding agency. The sponsor of this research has been duly acknowledged in the work and we believe that the review and publication of this article does not pose any threat to your Journal.

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