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RESEARCH ARTICLE

Physicochemical and Performance Assessment of Clay Based Refractory Bricks for Incinerator Application

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ABSTRACT

Refractories bricks' excellent thermomechanical and chemical resistant features makes it invaluable materials in modular incinerator > 1000 °C applications. In this research, suitable physicochemical and performance evaluation were employed using X-Ray Fluorescence (XRF), dimensional property assessment, linear shrinkage and water absorption analysis. The samples were sourced from Auchi (ARB1), Afowa (ARB2), Ayogwiri (ARB3), Aviele (ARB4) and Agbede (ARB5) clay minerals deposit in Edo North, Edo State, Nigeria. Then green compact samples were fired into dense phase. The result from the XRF study revealed a generally established composition of ARB1 clay mineral of SiO_2: 44.34%, Al_2O_3: 36.36% and others. ARB2 clay mineral of SiO_2: 41.78%, Al_2O_3: 39.62% and others. ARB3 clay mineral of SiO_2: 45.04%, Al_2O_3: 34.01% and others. ARB4 clay mineral of SiO_2: 40.12%, Al_2O_3: 38.96% and others. ARB5 clay mineral of SiO_2: 47.03%, Al_2O_3: 34.52% and others. The elemental composition of ARB1-5 revealed a similar trend of alumina and silica content to high-Al_2O_3 bricks (SiO_2: 45.0 – 56.0%, Al_2O_3: 39.0 – 48.0% and others) and commercial clay bricks (SiO_2: 48.0%, Al_2O_3: 36.96% and others) respectively. An average lower percentage error ERL, ERW, and ERH of ARB1 samples 0.148, 0.248 and 0.28% were recorded respectively. The average linear shrinkage and water absorption analysis of 9.91 and 4.71% demonstrated a potential for high elasticity of modulus. The overall data from this research shows that ARB1-5 bricks can find use in incinerator and high temperature applications.

Keywords: Physicochemical, refractories, incinerator

1 Introduction

There is a rising trend in the use of ceramic refractory bricks in high combustion applications due to its excellent pyrolytic, chemical, and thermomechanical properties [1]. Refractories are a category of ceramics with elevated fusion points. The term refractories connotes materials that are hard to fuse. Virtually all ceramics melt above a temperature of 2000 °C. Most refractories are ceramics. They have the ability to retain their physical shape and chemical identity when subjected to high temperatures. This property makes them useful at high temperatures [2]. The classification of refractory materials is broadly based on attributes like, size, production process, shaped products, degree of porosity and type thermal treatment. In addition, refractory materials can be categorised on the of basis chemical features such as acid, basic and neutral products. The increase in silica in a batch formulation the increase the acidity properties [3].

The amount of global of refractories consumption in the steel industry was approximately 27 million tons/year. The projection for other industries utilizing 35% of the remaining refractories produced and that of steel industry is presumed to be roughly 42 million tons/year. The Asia/Pacific region with an overwhelmingly 33 million tons/year refractory production consumed more than Europe (6 million tons/year); North America (3 million tons/year); Africa/the Middle East (2 million tons/year); South America (2 million tons/year). The overall refractory production in 2016 was placed at approximately 46 million tons/year [4]. The recent researches in refractory include impact of catalysts on microstructure and thermo-mechanical properties of Al_2O_3-C refractories novel mullite based Refractory optimization [5].

The vast majority of refractory are produced from geological high melting point oxides or compounds such as, alumina, carbon, magnesia, zirconia, aluminosilicate, silica, dolomite, chrome-magnesite. Among the favoured refractory material due to availability is the fireclay, which is category of aluminosilicate refractory materials [3]. Clays are hydrated silico-aluminous minerals whose structure is made up of a stacking of two types of layers containing, respectively, aluminium in an octahedral environment and silicon in tetrahedral coordination. Their large specific surface (10 to 100 m^2g^{-1}), their plate-like structure and the physicochemical nature of their surface enable clays to form, with water, colloidal suspensions, and plastic pastes [6].

The largest group of fireclay refractories is based on mixtures of plastic fireclay, flint clay, and fireclay grog. All these materials tend to form mullite on heating. In addition, quartz is often present as an impurity in plastic fireclay and is sometimes added to reduce firing and drying shrinkage. The fine structure in the grog (pre-fired clay) or flint clay particles is difficult to resolve with an optical microscope but consists of fine mullite crystals in a siliceous matrix. Alkali, alkaline earth, iron, and similar impurities that are present largely combine with the siliceous material to form a low-melting-point glass and decrease the refractoriness of the brick [2]. Production of refractory bricks of all sort largely depends on the diminutive preparation from its powder state prior to densification. Variety of powder production methods are employed for high temperatures refractories such astronautics, crucibles applications etc., this methods include sol gel, ultra-fine ball milling [7]. Moreover, comprehensive physicochemical and mechanical properties evaluation is key to ascertaining an excellent brick [8].

The chief lagging material for incinerator construction is refractory. Clay-based refractory materials are abundant locally with alumina-silicates as the major constituent. The low purchasing cost of clay-based refractory is it major advantage [9]. Therefore, the goal of this work is to produce clay-based refractory bricks and evaluate the performance of such bricks for incinerator applications.

2 Research Methodology

2.1 Materials

The clay ceramics raw materials employ in this research were excavated from Auchi (7.0669° N, 6.2748° E), Afowa (6.98763° N, 6.30595° E), Ayogwiri (7.0907° N, 6.2934° E), Aviele (7.0143° N, 6.2785° E) and Agbede (6.8619° N, 6.2648° E) in Edo-North, Edo State Nigeria. The acronyms based on location parameter shall be ascribed to each sample as Auchi: ARB1, Afowa: ARB2, Ayogwori: ARB3, Aviele: ARB4 and Agbede: ARB5. Furthermore, the properties of samples ARB1, ARB2, ARB3, ARB4 and ARB5 (ARB1-5) would be compared with commercial refractory bricks (CB). After exaction of samples from various locations, they were beneficiated, prepared for physicochemical analysis, and ultimately featured in the construction of a modular incinerator. The samples ARB1-5 were prepared for chemical analysis, physical testing and firing.

The ARB1-5 granular were mixed with proportionately with eight percent of water for optimal plasticity clay. The consistent malleable paste was achieved by thorough milling. The wet paste were cast into wooden moulds (L × W × H: 3000 mm x 2000 mm x 1500 mm) of mould and rammed hand pressure. The emerged ARB bricks were dried at ambient temperature for 7 days.

2.2 Characterization

2.2.1 XRF Chemical Analysis of ARB1-5

One of the leading non-destructive qualitative and analysis of element chemical constituent is the X-Ray Fluorescence (XRF). It probes into wide array of quantitative and qualitative chemical nature of most materials [10]. XRF investigation employ emission spectroscopic technique for its operation. The detection and analysis of specific element rely on the unique characteristics of its emission or XRF spectra. The ARB

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powder sample was prepared by the addition of flux and vitrify into glass-bead for chemical spectra inferences.

2.2.2 Physical Testing

Physical tests were shape and size test, Linear shrinkage, and water absorption [11], [12] and cold crushing strength (ASTM D412) were used for performance assessment.

2.2.3 Shape and Size Test

Refractory bricks frequently finds application in high-temperature processing and allied industry. In this test, arbitrarily twenty (10) ARB1 bricks were collectively stacked along length, width, and height. The discrepancy in sizes of the ARB1 samples were then measured in reference to the standard. Dimension properties such as the sample's edge are carefully observed for sharpness, straightness, and uniformity in shape.

Error calculation involves length Ml, width Mw and height Mh calculation.

Permissible value for length, width and height are PVl (3120 mm), PVw (2120 mm) and PVh (15120 mm) respectively.

Error = $Mx - PVx$ where x denote length, width, or height

$$\% \text{ of Error, ER}l \;=\; \left[\frac{Ml - PVl}{PVl}\right] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots. Eq. 1$$

$$\% \text{ of Error, ER}w \;=\; \left[\frac{Mw - PVw}{PVw}\right] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots. Eq. 2$$

$$\% \text{ of Error, ER}h \;=\; \left[\frac{Mh - PVh}{PVh}\right] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots. Eq. 3$$

2.2.4 Linear Shrinkage

The measurement of linear shrinkage of ARB1-5 bricks was done by examining differential dimension properties of green compact and fired samples. The important dimension features for linear shrinkage measurement are dimension and thickness. The process involves taking the linear measurement of the brick surface of green compact and the fired brick. Each measurement for both green compact and fired bricks were measured three times to ensure accepted value range. Then, the percentage of linear shrinkage was calculated in accordance with the equation [13]:

$$\% \text{ of linear shrinkage}, \% SL \;=\; \left[\frac{SLo - SLf}{SLo}\right] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots. Eq. 4$$

where $\%SL$; percentage shrinkage in surface area of ARB, SLo; surface area of green compact ARB1-5 in mm, SLf; surface area of fired ARB1-5 in mm.

2.2.5 Water Absorption

The water absorption of the ARB1-5 samples were evaluated in accordance with Standard Archimedes technique established by ASTM C830-00. Archimedes' principle states that a force equal to the weight of the fluid that it displaces buoys up an object immersed in a fluid. Two basic hypotheses supporting this principle are first, the total fluid force on an arbitrarily shaped sample retains equal volume of the fluid, which was in equilibrium prior to the object displacement. Thus, the buoyant force is equal to the displaced. Secondly, the net change of hydrostatic pressure of basic geometric like rectangle or cylindrical specimen is dependent on the fluids' depth provided the specimen is totally immersed into the fluid.

In this work, three ARB bricks and dry these in the oven at a temperature of 110-115 °C for at least 48 hours. These are then allowed to cool in the oven with the oven switched off until they reach ambient room temperature and then each weighed on the weighing balance and the dry weight of sample is taken as W_1 Each specimen was then placed in turn in the water bath allowing water freely to circulate on all sides for 24 hours. The samples were removed and allow to dry to saturated surface dried condition and weighed on the balance. The weighing was completed within 120 seconds from their removal from the bath and the weight of the sample was taken as W_2.

$$\text{\% of Water absorption} = \left[\frac{W2 - W1}{W1}\right] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots. Eq. 5$$

2.2.6 Firing

The ARB1-5 green compact were arranged in a checkered geometry in order to allow for optimal heat flow. They were then fired with dry wood for 10 hours. The foundation bricks where laid horizontally adjacent to each other. Approximately 10 mm space was created between the horizontally adjacent bricks at the foundation structure. Three more bricks were laid to form the entire superstructure with a vent for charging wood during firing. All exterior vent where sealed with clay paste prior to firing to conserve heat.

2.2.7 Cold Crushing Strength (CCS)

The failure of ceramics brick sample is assessed by method such as cold crushing strength that operate based on compression strength analysis. The ASTM D412 method was selected for the CCS preparation and testing of five (5) ARB1-5 samples. Thereafter the samples were placed in a furnace at a temperature of 110 °C with a soaking time of 6 hours. The samples were cooled to ambient temperature. Appropriate pressure was applied to all samples respectively using hydraulic press machine and crushing strength for each sample were recorded. The ARB1-5 samples were positioned on a compressive machine and load was axially applied by revolving the land wheel at an even rate until failure takes place. Consequently, the manometer analyses were taken. The average cold crushing strength (CCS) of each sample was estimated using Eq. 6.

$$\text{CCS} = \frac{\text{Load (NM)}}{\text{Area (mm}^2\text{)}} \ldots\ldots\ldots\ldots\ldots\ldots. \text{Eq. 6}$$

3 Results and Discussion

3.1 XRF Chemical analysis of ARB1-5

XRF analysis is reported to be consistently accurate in measuring ceramics samples as it quantify the bulk rather than mare surface point [14]. The XRF analysis of the ARB1-5 samples in Tab. 1 indicate oxide compositions in percentile component consistent with geological clay samples in Nigeria. It showed a close compositional oxide and value across all ARB1-5 due to location proximity as well as geological belt of all clay mineral deposit in Edo North of Edo State Nigeria. The coordinate for all five deposits include Auchi, Afowa, Ayogwori, Aviele and Agbede. It is also worth stating that all ARB1-5 samples have compositional oxides and content approximately matching that of high Al_2O_3 bricks (HAB) and commercial bricks (CB). Studies of clay with 37.93 wt.% alumina content and 0.67 alumina: silica ratio was shown to possess kaolinite ($Al_2Si_2O_5(OH)_4$), illite ($K_{0.65}Al_2(AlSi_3O_{10})(OH)_2$), anatase ($TiO_2$), quartz ($SiO_2$) and feldspar

($K_xNa_yCa_{1-(x+y)}Al_{2-(x+y)}Si_{2+(x+y)}O_8$) phase [5]. In this research, the average alumina content ARB1-5 was recorded as 36.69 wt.% and alumina:silica ratio at 0.84. The XRF result of ARB1-5 displays the presence of derivative phases such as kaolinite ($Al_2Si_2O_5$ $(OH)_4$), illite ($K_{0.65}Al_2$ $(AlSi_3O_{10})(OH)_2$), quartz (SiO_2) and feldspar ($K_xNa_yCa_{1-(x+y)}Al_{2-(x+y)}Si_{2+(x+y)}O_8$). The absence of anatase phase in ARB1-5 samples was due to the apparent lacking TiO_2 in all samples.

Table 1: *Elemental composition of ARB1-5 in comparison with high Al_2O_3 bricks (HAB) and commercial bricks (CB)*

Oxides	**Refractory Compositions (wt. %)**						
	ARB1	**ARB2**	**ARB3**	**ARB4**	**ARB5**	**HAB**	**CB**
SiO_2	44.34	41.78	45.04	40.12	47.03	45 – 56	48.90
Al_2O_3	36.36	39.62	34.01	38.96	34.52	39 – 48	36.96
Fe_2O_3	2.85	2.15	2.45	2.92	2.08	< 2	2.24
MgO	0.92	0.89	0.66	0.82	0.72	0.5	0.70
CaO	1.34	1.38	1.41	1.40	1.56	0.5	3.34
MnO	0.42	0.47	0.42	0.44	0.38	0.5	0.21
Na_2O	1.32	1.31	1.38	1.30	1.01	<1.5	2.00
K_2O	1.29	1.32	1.28	1.34	1.24	<1.5	4.0
Cr_2O_3	0.07	0.03	0.06	0.05	0.01	-	0.03
ZnO	0.38	0.29	0.32	0.35	0.27	-	0.30
TiO_2	-	-	-	-	-	~2	-

3.2 Shape and Size Test

Randomly selected 10 number of bricks of standard sizes were selected from ARB1 stock and stacked along lengthwise, width wise, height wise, and the measurement noted. Shape and size test measurement were employed on ARB1 samples because dimensional properties is largely a function of the mould, provided the material composition, rheology and viscosity are the same. In the case of this measurement, ARB1-5 have the same composition, rheology and viscosity, hence, the information from ARB1 will suffice. A standard range of permissible value of 120 mm was established along each parameters. The ideal size and shape of interest for most ideal quality bricks application are Length: 3800 mm to 3920 mm; Width: 1740 mm to 1860 mm and Height: 1740 mm to 1860 mm. In this research, bricks dimensions selected are length: 3000 mm with a PV_l of 3120 mm; width: 2000 mm with a PV_w of 2120 mm and height: 1500 mm with a PV_h of 1620 mm. The results showed uniformly close values for ER_l (0.148%), ER_w (0.248%) and ER_h (0.28%) confirming lower dimensional discrepancy.

Table 2: *Percentage error test of shape and size of ARB1 samples*

S/N	ER_l (%)	ER_w (%)	ER_h (%)
	PV_l = 3120	PV_w = 2120	PV_h = 1620
1	0.140	0.21	0.29
2	0.149	0.13	0.32
3	0.212	0.12	0.27
4	0.145	0.24	0.31
5	0.137	0.20	0.29
6	0.142	0.41	0.23
7	0.145	0.33	0.21
8	0.141	0.22	0.36
9	0.121	0.29	0.25
10	0.148	0.33	0.27

3.3 Linear Shrinkage

Linear Shrinkage test procedure for sample preparation and measurement of the change in length or diameter over time has been stated to show consistent in shrinkage analysis. In comparison to the direct measurement of the limit of shrinkage using a shrinkage curve, the linear shrinkage is repeatable and predictable [15]. The dimensional linear shrinkage of five random ARB1-5 samples revealed a fairly lower shrinkage rate of (Table 3 and Figure 1) in the range of commercial bricks (CB) with 7.74% previously reported by [16]. The relatively lower shrinkage in clayed-based bricks has been shown to increase the modulus of elasticity of ceramics bricks. The lower the drying shrinkage the higher the young modulus or elastic modulus [17]. Moreover, works by [13] shows that highly refractory material possessed a range of linear shrinkage of 4 – 10%. The linear shrinkage value for all five arbitrarily selected samples ARB1: 9.94, ARB2: 8.32, ARB3: 11.01, ARB4: 10.61 and ARB5: 9.65 averages an acceptable value of 9.91%. It was documented that such lower linear shrinkage values were more necessary as this connote the clay is less predisposed to volume alteration [18]. Furthermore, the linear shrinkage from this research indicate that all ARB1-5 sample can withstand high temperature with deformation (high dimensional stability). Consequently, the samples can be considered as fully having the feature refractory clay with potential structural applications such as incinerator [18].

Table 3: *Linear shrinkage and water absorption test of ARB sample*

	Content (%)					
	ARB1	**ARB2**	**ARB3**	**ARB4**	**ARB5**	**CB**
Linear Shrinkage	9.94	8.32	11.01	10.61	9.65	7.0-9.0
Water absorption	4.87	4.59	4.32	5.02	4.75	4.09-4.5
CCS (NM/m^2)	21.23	20.42	19.8	20.05	20.82	-

3.4 Water Absorption

The water absorption study in this research demonstrated consistent values among five randomly selected ARB1-5 samples. The samples marked ARB1, ARB2, ARB3, ARB4 and ARB5. Absorption are shown in Table 3 and Figure 1. It is worth noting that the entire sample agrees with BS 3921 standard for clay bricks. The standard gives A low water absorption of <4.5% (class A brick) and <7.0% (class B bricks) for high water absorption are categorize as structural bricks [19]. Furthermore, recent report placed the average water absorption of clay based bricks in the range of 4.01-4.5 [19], [20]. The average water absorption of the five ARB1-5 samples is 4.71. In another study, the water absorption of a refractory brick of 4.6-6.2 was found to have a compressive strength range of 81-84 Nmm^{-2} [19], which is a major structural requirement in kilns or incinerator applications. A relatively fair compressive strength like that recorded in our research (4.71) can be employed for incinerator construction.

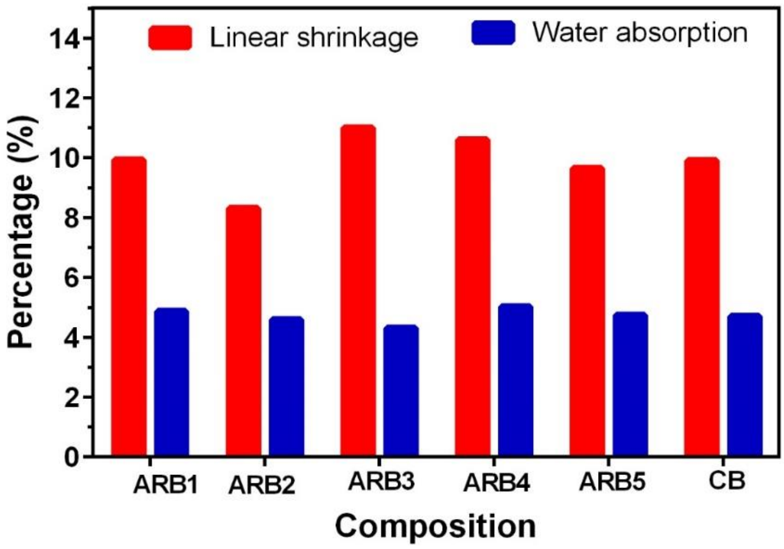

Figure 1: *Linear shrinkage and water absorption of randomly selected ARB samples.*

3.5 Result from Firing

The firing of chequered arranged ARB1-5 is shown in figure 2. Upon heating pure raw clay mineral, identical closely to the formula $A1_2O_3.2SiO_2.2H_2O$, under conditions of constant heat supply, as, for instance, in a furnace, to gradually elevated temperatures, it undergoes certain physical and chemical variations. Two distinct lags are often observed in clay firing between 200-300 °C and another completed between 570-620 °C. The beginning of the second lag takes place just after 500 °C is attained, which is termed as the dissociation temperature proper. The first lag evidently is due to the mechanical water held so persistently, the second due to the decomposition of the kaolinite molecule [21]. Both lags are part of the dehydration and calcination processes of clay. The ARB1-5 bricks were uniformly fired, and every stacked brick were thermally toughened. The colour, linear shrinkage and water absorption studies are in good agreement with effective firing of ARB1-5 samples. The extrapolated phases kaolinite ($Al_2Si_2O_5$ $(OH)_4$), illite ($K_{0.65}Al_2(AlSi_3O_{10})(OH)_2$), quartz ($SiO_2$) and feldspar ($K_xNa_yCa_{1-(x+y)}Al_{2-(x+y)}Si_{2+(x+y)}O_8$) emanate directly from firing of ARB1-5 samples at 1050 °C. The correlation between the firing result and phases of ARB1-5 is in agreement with other firing studies. For instance, [5] indicated that the clear present of higher polymorphic transformations such as mullite, and amorphous phase clay minerals occurs in firing temperature above 1250 °C. The absent of such elevated temperature phases in ARB1-5 samples confirm the efficacy of the chequered brick arrangement and firing method adopted.

Figure 2: *Typical chequered geometry structure of fired ARB1-5 samples.*

3.6 Cold Crushing Strength (CCS)

Cold crushing strength as a refractory feature of ceramics material demonstrates how resilient the bricks can endure compressive loading at low temperature. CCS is the assurance property that indicate if refractory bricks can survive high handling situation within storage or during transportation. The cold crushing strength values for ARB1-5 samples in table 1 and figure 3 are respectively 21.23, 20.42, 19.8, 19.93, 20.05 and 20.82 MN/m². The average CCS result of 20.38 MN/m² indicate consistent values across the selected sample. The overall CCS data indicate that ARB1-5 samples can be able to endure heavy load at low temperature. [5]. The cold crushing strength (mechanical strength) of the ARB1-5 are within the standard values of for refractories [22].

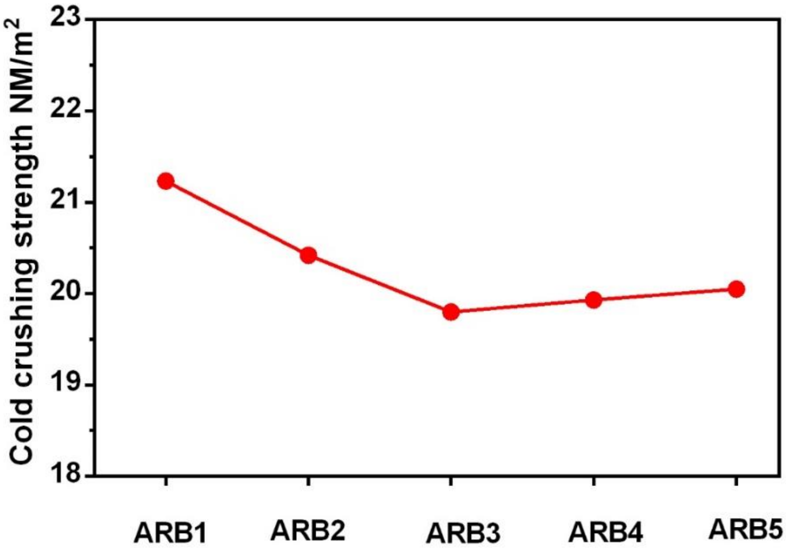

Figure 3: *Cold crushing strength of random five samples ARB1-5.*

4 Conclusion

This research describes the production and assessment of clay-based refractory (ARB1-5) sourced from five different locations of Edo North in Edo state, Nigeria. The bases for assessment are chemical nature, dimensional properties, linear shrinkage and water absorption analysis. The data from this study indicate that ARB1-5 samples have comparative value with the commercial bricks (CB) across the selected parameters of interest. In general, this study indicates that ARB1-5 bricks are suitable in incinerator and high temperature refractory applications.

5 Declaration

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5.3 Competing Interests

The authors declare no conflict of interest in this research.

5.4 Publisher's Note

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