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Research Article

Comparative Study on Hygrothermal Behavior of Sustainable Building Materials

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Abstract

Hygrothermal transfers have a decisive influence on the thermo-hydraulic behavior and durability of building materials. They directly influence energy performance of buildings, thermal comfort of occupants, and longevity of structures. This study presents a comparative analysis of heat and mass transfer mechanisms in various commonly used building materials, such as concrete, cement blocks, compressed earth bricks (CEB), and cut laterite blocks (CLB). The analysis is based on the thermo-hydraulic properties of these materials, as well as on the coupled phenomena of thermal conduction and water vapor diffusion. The materials are assumed to be placed in air. We used a numerical method to solve the equations. This numerical method involved formulating the transport equations according to the Luikov model. These equations are solved using an implicit finite-difference scheme. A Fortran code combined with the Thomas algorithm for solving the equations was developed and validated using the literature. The results are presented as the spatiotemporal evolution of temperature and moisture content at the center of the materials. The results show that hygrothermal transfers depend on the temperature of the air in contact with the materials. When this air temperature increases, the temperature within the materials increases by 5%. However, this increase is more rapid in cementitious materials, where it can reach 10%. The moisture content decreases by 0.3% for most materials, except for cementitious materials, which decrease by 0.5%. Materials with low thermal conductivity conduct less heat and retain more moisture.

Keywords

Heat Transfer, Mass Transfer, Building Materials, Thermo-hydraulic Behavior, Energy Performance

1. Introduction

In the context of the current energy transition and sustainable development, improving the energy performance of buildings is a major challenge. Construction materials play a significant role in heat and moisture exchange between the outdoor environment and the interior of buildings. Heat and mass transfer, which are often closely coupled, determine the regulation of temperature, relative humidity, and, consequently, hygrothermal comfort. Porous materials, widely used in the building sector, have a complex internal structure that facilitates heat and mass transfer. Understanding and comparing these transfers across different materials is essential for guiding material selection and optimizing the design of building envelopes [1, 2]. Most of the research in this field focuses on laboratory studies under controlled conditions and some field work [3]. This does not accurately reflect the actual conditions in a tropical climate. In light of these challenges, numerical

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modeling has emerged-indispensable tool for accurately predicting heat and hygrothermal transfer phenomena in building materials. Numerous numerical studies have been conducted to analyze the influence of ambient air temperature and relative humidity on hygrothermal transfers in porous media. The main transfer models for these porous media include the model by Crausse et al. [4], which calculates the spatial distributions of temperature and humidity within a building wall, the Philip and De Vries model [5], which characterizes heat and mass transfer in unsaturated porous media, and the Luikov model [6], which describes coupled transport in hygroscopic porous media by highlighting the phenomenon of thermo-diffusion. All of these numerical simulation models have been applied to various types of construction materials, such as wood [7], cement mortar, sandstone [8], cork concrete [9], and cement cinder block [10]. This work is essential not only for characterizing materials but also for accurately evaluating a building's performance. This study concerns the development and application of numerical models designed to investigate coupled heat and mass transfer in different building materials. Indeed, concrete blocks are among the most widely used materials in construction [11], but their thermal and hygrothermal performance depends heavily on various factors, such as their composition, porosity, and the environment in which they are stored and used. Thus, the main objective of this research is to provide an in-depth understanding of the transfer mechanisms in building materials commonly used in dry and humid tropical climates, using numerical models based on Luikov's equations. This approach will enable the evaluation of the impact of different parameters on the thermal and hygrothermal performance of these materials, thereby paving the way for optimization strategies aimed at improving the energy efficiency and sustainability of building structures.

2. Method and Theory

2.1. Description of the Physical Model

The geometric configuration under study is shown in Figure 1. The geometric shape of these materials is considered to be a rectangular prism (L × l × h). The external surfaces of these materials are subjected to a uniform heat flux of constant density and are the site of convective heat and mass exchange with the ambient environment. The horizontal walls are assumed to be adiabatic. We also assume that the width of this parallelepiped is sufficiently large compared to the other dimensions so that heat and mass transfers are two-dimensional. The vertical walls of these materials are subject to convective exchange with the air.

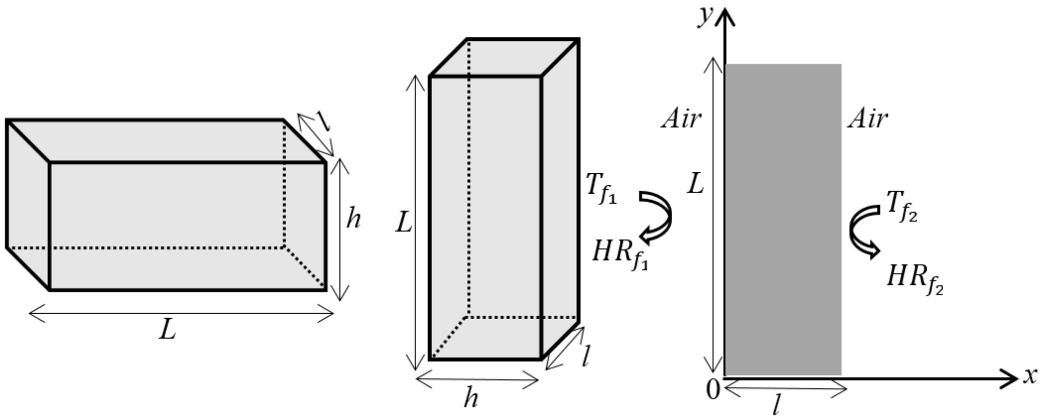

Figure 1. *Physical representation.*

2.2. Mathematical Formulation

A mathematical model consists of a system of equations, initial conditions, and boundary conditions. The first describes what happens within the domain. The second specifies, for transient problems, the initial state of the variables under study. The third describes the geometry of the domain and the thermal and mass conditions prevailing at the boundaries. It is currently not possible to describe all phenomena occurring within the porous medium using a system of equations that can be solved within reasonable computational time. It is therefore necessary to make simplifications and construct a model that will provide the best possible approximation.

2.3. Simplifying Assumptions of the Model

To simplify the physical problem, we make the following assumptions.

1) Heat and mass transfer are two-dimensional,
2) The materials are treated as homogeneous porous media,
3) The materials do not undergo deformation over time: the system is not subjected to significant external pressures,
4) Radiative heat transfer is negligible.

2.4. Heat and Mass Transfer Equations in Materials

Considering the simplifying assumptions described above, the equations for heat and mass transfer in materials, based on Luikov's model, are written as follows in the Cartesian coordinate system (oxy):

$$\begin{cases} \frac{\partial T_m}{\partial t} = \alpha_T \nabla^2 T_m + \phi \frac{\partial W_m}{\partial t} \\ \frac{\partial W_m}{\partial t} = \alpha_m \nabla^2 W_m + \alpha_m \delta_s \nabla^2 T_m \end{cases} \quad (1)$$

Where:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

$$\phi = \frac{L_v \varepsilon}{C_P}$$

α_m : mass diffusion coefficient of water in the material

α_T : thermal diffusivity coefficient of heat in the material

δ_s: thermal migration coefficient

L_v : latent heat of vaporization

ε : Phase change rate

C_P : specific heat

2.5. Initial and Boundary Conditions

Initial conditions

At $t \le t_0$; t_0 (being the time at which the interaction between the material and the surrounding environment begins).

$T_m = T_0$ *(Initial temperature of the material)*

$W_m = W_0$ *(Initial moisture content of the material)*

Boundary conditions

For all $t < t_0$: we have:

$$y = 0; 0 \prec x \prec l : \left.\frac{\partial T_m}{\partial y}\right|_{y=0} = 0 \quad (2)$$

$$\left.\frac{\partial W_m}{\partial y}\right|_{y=0} = 0 \quad (3)$$

$$y = L; 0 \prec x \prec l : \left.\frac{\partial T_m}{\partial y}\right|_{y=L} = 0 \quad (4)$$

$$\left.\frac{\partial W_m}{\partial y}\right|_{y=L} = 0 \quad (5)$$

Air-material interface: Continuity of heat and mass flux densities.

$x = 0$; $0 \le y \le L$ and $x = l$; $0 \le y \le L$

Heat flux density

$$-\lambda_m \left.\frac{\partial T_m}{\partial x}\right|_{x=0} = -\lambda_f \left.\frac{\partial T_f}{\partial x}\right|_{x=0} - (1-\varepsilon) L_v \rho_f \alpha_f \left.\frac{\partial W_f}{\partial x}\right|_{x=0} \quad (6)$$

$$-\lambda_m \left.\frac{\partial T_m}{\partial x}\right|_{x=0} = ht_1 \left(T_f - T_m(0,y)\right) + (1-\varepsilon) \rho_f L_v h_m \Delta W \quad (7)$$

$$\Delta W = W_{f_{S_1}} - W_{f_1}$$

λ_m : thermal conductivity of the material,

λ_f : thermal conductivity of the fluid (air),

ρ_f : density of the fluid (air),

W_{fs} : water vapor concentration or dry-basis water vapor content at the materials surface,

W_f : water vapor concentration or dry-basis water vapor content of the air,

ht : convective heat transfer coefficient,

hm : convective mass transfer coefficient,

α_{f_1} : water vapor mass diffusion coefficient ($m^2 s^{-1}$).

Mass flux density

$$\rho_m \alpha_m \left[\left.\frac{\partial W_m}{\partial x}\right|_{x=0} + \delta \left.\frac{\partial T_m}{\partial x}\right|_{x=0} \right] = \rho_{f_1} \alpha_{f_1} \left.\frac{\partial W_{f_1}}{\partial x}\right|_{x=0} \quad (8)$$

$$\rho_m \alpha_m \left[\left.\frac{\partial W_m}{\partial x}\right|_{x=0} + \delta \left.\frac{\partial T_m}{\partial x}\right|_{x=0} \right] = \rho_{f_1} hm_1 \Delta W \quad (9)$$

In Equations (4) and (5), we determined the water content W_{fs} using the Henderson-Huggins equation [12]:

$$H_r = 1 - \exp\ -k.T_m.W_m{}^n \quad (10)$$

Where Hr is the relative humidity, *k* and *n* are material-specific constants determined experimentally, and W_m is the water content on a dry basis.

$$W_m = \frac{C_v}{1 - C_v} \quad (11)$$

$$C_v = 0,622 \frac{P_v}{P - 0,378 H_r P_{vs}} \quad (12)$$

P: atmospheric pressure (Pa),

P_v: partial pressure of water vapor at the surface temperature of the porous material,

P_{vs}: saturated vapor pressure at the surface temperature of the porous material.

It is determined using Bertrand equation, which is valid for a temperature range between 0 ℃ and 200 ℃:

$$P_{vs}(T) = 10^{\left(17,442 - \frac{2790}{T} - 3,868 \log_{10}(T)\right)} \quad (13)$$

2.6. Surface Transfer Coefficients in Natural Convection

The heat transfer coefficient *ht* and mass transfer coefficient h_m are determined using the correlations proposed by (Lienhard, 2005) and (Jannot, 2003):

$$ht = \frac{Nu.\lambda_f}{L} = \frac{0,59.Ra^{1/4}.\lambda_f}{L} \quad (14)$$

$$Nu = 0,59.Ra^{1/4} \quad (15)$$

Nu: Nusselt number, Ra: Rayleigh number, λ_f: thermal conductivity of the fluid (air).

By analogy with heat transfer, the mass transfer coefficient h_m can be calculated using the following correlations:

$$hm = \frac{Sh.D_f}{L} \quad (16)$$

$$Sh = 0.59.(Gr_m.Sc)^{1/4} \quad (17)$$

Sh: Sherwood number, D_f: water-water vapor mass diffusion coefficient, Gr_m: Grashof mass number, Sc: Schmidt number.

2.7. Numerical Methodology

The heat and mass transfer equations, along with their associated initial boundary conditions, were discretized using the implicit finite difference method and solved using a Fortran code combined with the Thomas algorithm. The convergence criterion we selected is equal to 1.10^{-3} and a sub-relaxion coefficient of 8.10^{-1}.

2.8. Mesh of the Domain

The study domain is divided into regular rectangular cells of dimensions Δx and Δy *(Figure 2)*. Δx and Δy are the spatial steps in the [Ox) and [Oy) directions. The material, treated as a porous medium, is divided into N×M regular rectangular cells of dimensions Δx and Δy. The width *l* is divided into (N-1) slices of thickness (Δx = l/(N-1)), and the length L into (M-1) slices of thickness (Δy = L/(M-1)). We denote by i the i^{-th} node counted in the positive *x*-direction and by *j* the j^{-th} node counted in the positive y-direction.

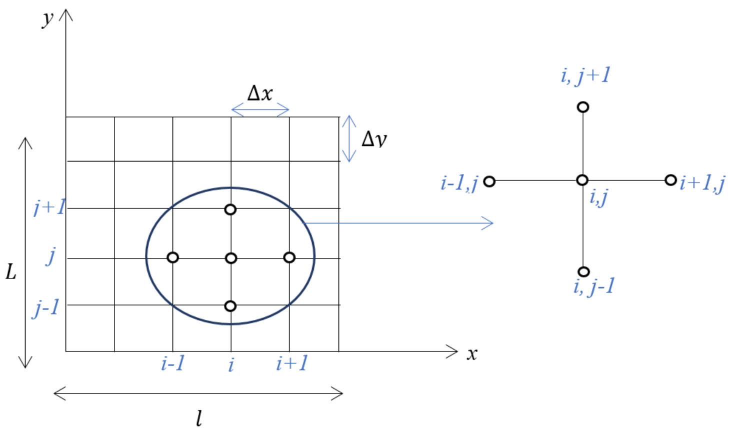

***Figure 2**. Mesh of the study area.*

***Table 1**. Thermophysical properties of the material [13].*

Materiel	λ(W/m K)	ρ(kg/m³)	C_P(J/kg K)	α (m²/s)
Concrete block	1.32(±0.22)	2150(±0.18)	1818(±0.05)	3.37×10^{-7}(±0.03)

Materiel	λ(W/m K)	ρ(kg/m³)	C_P(J/kg K)	α (m²/s)
Concrete	2.11 (±0.33)	2350 (±0.02)	1800 (±0.18)	4.98 × 10^{-7} (±0.11)
CEB	0.72 (±0.21)	1800 (±0.24)	1900 (±0.28)	2.10 × 10^{-7} (±0.06)
CLB	0.91 (±0.29)	2100 (±0.01)	1700 (±0.30)	2.54 × 10^{-7} (±0.16)

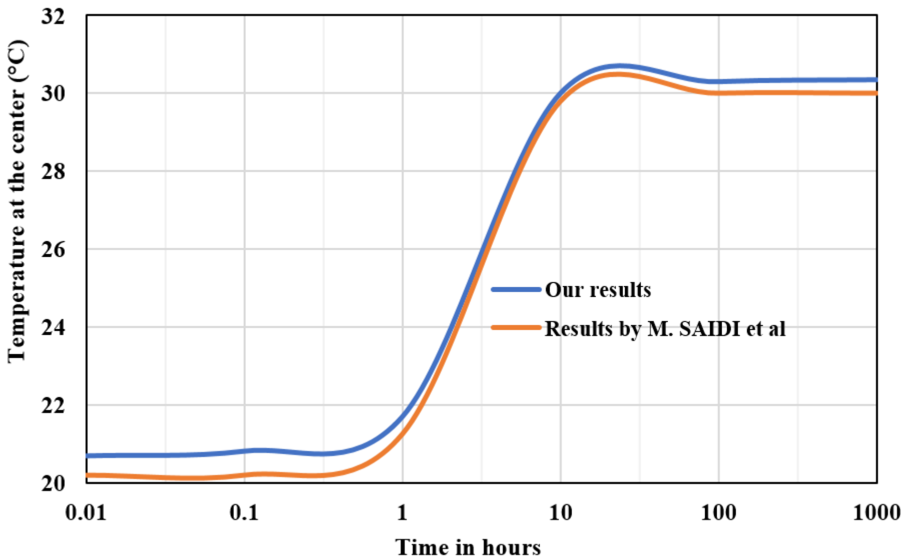

Figure 3. *Temperature at the center of the material.*

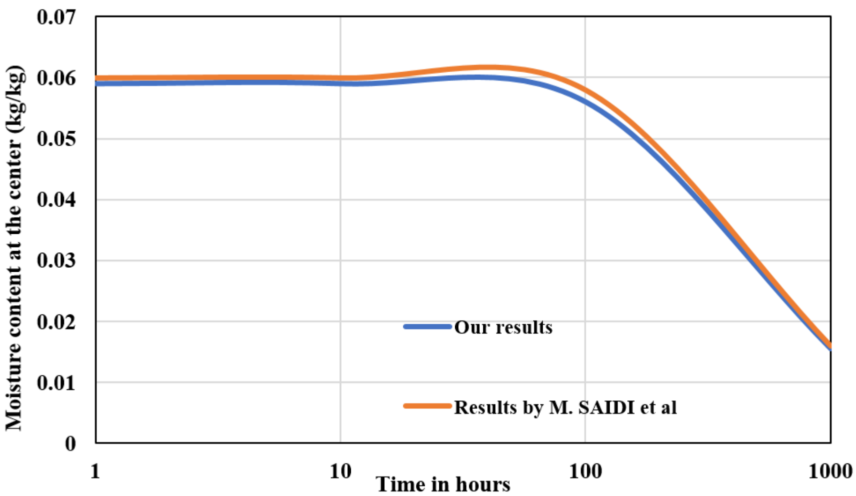

Figure 4. *Moisture content at the center of the material.*

3. Results and Discussion

3.1. Thermophysical Properties of the Studied Material

Most of the thermophysical properties (*Table 1*) of the material under study were determined using the KD2-Pro device in our previous work [13].

3.2. Validation of Numerical Results

To ensure the validity of our program, we compared our results with some results from the literature. The temperature and moisture content distributions determined numerically by the Luikov model for a heat and mass transfer problem are compared with those obtained by M. SAIDI et al.,[14] in a biobased construction material of the CEB (compressed earth brick) type. The agreement between our results and those of M. SAIDI et al confirms the validity of our numerical code for estimating temperature and moisture content distributions in our porous material.

3.3. Mesh Sensitivity

A sensitivity study was conducted for three different meshes: 201 x 201, 201 x 251, and 201 x 301. The results of this study were obtained by comparing the temperature and water content values at the outer surface (*x=0*) and the inner surface (*x=1*) of the material, where the temperature and moisture gradients are greatest. The results show that the maximum error between the temperature and moisture content values is on the order of 10^{-3} across these three meshes. Consequently, we selected 201 x 251 mesh because it provides the highest accuracy in the calculations.

3.4. Initial Conditions for the Simulation

At the initial time, the temperature T_0 and the moisture content of the material W_0 are set to T_0=10 ℃ and W_0=0.12 kg of water/kg, respectively. The two vertical faces of the material are maintained at temperatures T_{f1} =35 ℃ and T_{f2} =30 ℃. The relative humidity of the air in contact with these faces is 25%. The desorption isotherm coefficients according to the Henderson model for the material used in our calculations were determined in previous work by B. Kiema et al., [15, 16].

3.5. Temperature and Moisture Content Profiles Within the Materials

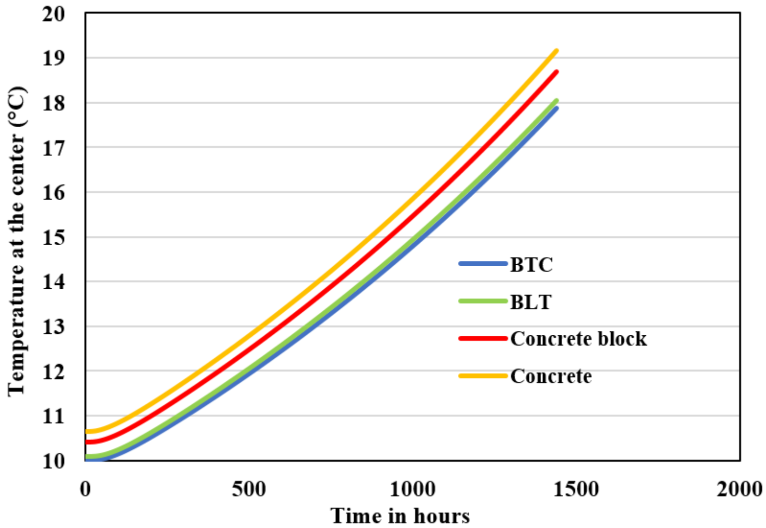

Figure 5. *Temperature evolution at the center according to material type.*

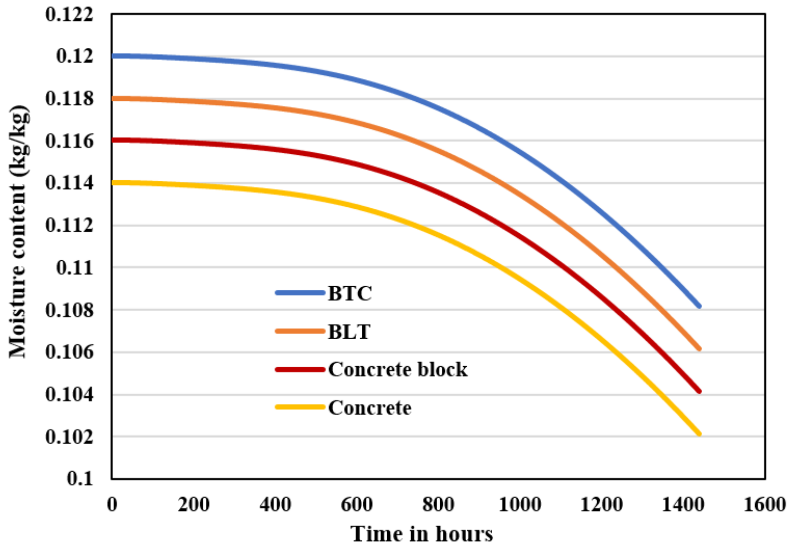

Figure 6. *Moisture content at the center according to material type.*

Figure 5 shows the temperature evolution over time at the center of the materials. It can be seen that temperatures rise over time until they reach a constant value approaching the temperature of the fluid (air). This temperature evolution is due to heat transfer by natural convection between the fluids and the material. Overall, the water content in the center of the materials decreases. This decrease is particularly pronounced in materials with high thermal conductivity, such as concrete and cement blocks.

Figure 5 illustrates the evolution of the temperature at the center (x=l/2; y=L/2) for the four construction materials. It can be observed that for each material, the temperature at the center increases over time, tending toward the temperature of the fluid in (Tf=40 °C) which they are placed. This increase in material temperature is due to heat transfer via natural convection between the fluid and the materials, since the initial temperature of the materials (T_0=10 °C) is assumed to be lower than that of the fluid (air). Analysis of the Figure 5 shows that the temperature rise at the center of the concrete is faster than that of the other materials. This trend could be due to the thermal conductivity of concrete, which ranges from 1.4 to 3.6 W/m·K and is higher than that of the other materials. This is because thermal conductivity is an important parameter in the heat transfer process. These results were confirmed in the studies by Guo et al., [17], and R. Kodur et al., [18], where the authors analyzed the heat transfer mechanism conductivity. The results show that certain additives can improve thermal conductivity and affect the temperature within the material. *Figure 6* illustrates the moisture content at the center of the materials over time. For all four materials, the moisture content at the center decreases over time. This decrease could be explained by the effect of the fluid temperature (air) on the materials. Over time, the free water contained within the materials gradually evaporates from the surface toward the center. It is observed that the water content within the Compressed Earth Brick (CEB) over 24 hours is higher than in the other materials because, without additives, the CEB material is more hygroscopic than the other materials and promotes the retention of mixing water within it. Unlike cementitious materials, the presence of the binder (cement) promotes the evaporation of free water, which affects the moisture content at the center of these materials. This premature evaporation can cause these materials to dry out too quickly, thereby affecting their mechanical properties. Under these conditions, when used as building materials, this impacts the building's energy consumption as well as its thermal comfort [19, 20].

4. Conclusion

This comparative study highlights the importance of heat and mass transfer in the behavior of building materials. The results emphasize that porous materials, particularly earth-based ones, offer significant advantages in terms of thermal performance and moisture regulation. The use of these materials represents a promising solution for reducing the energy needs of buildings while promoting renewable resources. A better understanding of coupled transfer phenomena allows for the optimization of material selection and the design of buildings that are more efficient, sustainable, and adapted to local climatic conditions.

Abbreviations

CEB	Compressed Earth Bricks
CLB	Cut Laterite Blocks

Author Contributions

Benjamin Kiema: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing

Salifou Cisse: Conceptualization, Writing – original draft, Writing – review & editing

Hermann Kabore: Conceptualization, Writing – original draft, Writing – review & editing

Ousmane Coulibaly: Software, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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