Contribution to the Analysis of the Influence of Climatic and Geographic Factors on the Average Mechanical Parameters of Cork Growing in North Africa: The Case of Algeria

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Abstract

As part of the Mediterranean basin, Algeria is distinguished by its invaluable wealth in arboriculture, including cork cultivation. Cork is extensively utilized in the construction sector for its effectiveness in acoustic, thermal, and vibrational insulation. Due to its anisotropic cellular texture, cork possesses unique physicochemical properties that are undoubtedly influenced by both climatic and geographic factors. The objective of this study is to identify the optimal climatic and geographic conditions for obtaining high-quality cork with superior insulating properties. The analysis focuses on determining the mass diffusion coefficient of cork from plantations located across northern Algeria (Bejaia, Chlef, Jijel, Medea, and Skikda). These regions are naturally influenced by standard climatic factors, including altitude, humidity, sunlight exposure, rainfall, and temperature. For each sample, the diffusion coefficient was estimated using a conductimetric method, assuming the mass diffusion process follows a transient regime governed by Fick's second law. The apparent diffusion coefficient (Dapp) by fitting experimental values to the analytical expression derived from Fick's diffusion model. Data fitting was optimized using the Bat Algorithm. Meteorological data spanning a decade were meticulously analyzed for each region, and average values were used to assess their influence on the diffusion coefficient. Using a multiple regression model, the data were numerically processed to extract the desired results. The variation range of the diffusion coefficient spans $1x10^{-12}$: $6x10^{-12}$ m^2s^{-1}. Results indicate that the cork grown in Chlef is the most suitable for insulation applications due to its low Dapp around 10^{-12} m^2s^{-1}, under meteorological conditions characterized by 2840<Sunlight <2900 hours and 16.5<T<20°C.

Keywords: Cork, Apparent diffusion coefficient, Conductimetric, Climatic-geographical factors, Bat Algorithm.

1. Introduction

In light of emerging environmental challenges, such as climate change and greenhouse gas emissions, coupled with the fluctuating costs of fossil resources, research efforts are increasingly fo-cused on developing innovative technologies utilizing alternative and renewable raw materials. The building sector, being one of the most energy-intensive industries, significantly exacerbates these con-cerns, emphasizing the necessity of adopting decision-support tools and advanced technologies to miti-gate the environmental impacts associated with fossil energy consumption.Within this framework, the implementation of alternative materials and structural solutions of-fers promising prospects for enhancing insulation properties, including thermal, mass, acoustic, and vibration insulation. A review of the current state of innovative insulating materials, derived from natu-ral, recycled, or synthetic sources, reveals sector-specific characterization parameters demanded by users. These include mass insulation (porosity, mass diffusivity) [1], thermal insulation (density, thermal conductivity, specific heat)[2], acoustic insulation (absorption coefficient) [3], and vibration insulation (attenuation coefficient) [4].Lignocellulosic biomass, such as cork, offers numerous advantages in addressing contemporary environmental and industrial challenges. It serves as a renewable, biodegradable, lightweight, abundant, and cost-effective raw material, making it highly appealing for the development of sustainable and durable products [5]. These attributes position cork as a key resource for advancing environmentally friendly technologies and promoting a circular economy.

Cork oak forests (Quercus suber L.) are exceptionally well-suited to the semi-arid regions of North Africa and Southern Europe. These forests are distributed across seven countries, with Algeria ranking third globally in cork production. The global distribution is as follows: Portugal (33%), Spain (23%), Algeria (21%), Morocco (15%), Italy (10%), Tunisia (3%), and France (1%) [6, 7].

Cork, the bark of the cork oak tree, is a natural cellular material with outstanding physical and chemical properties, including resilience, elasticity, and impermeability to liquids and gases. It is an excellent thermal, acoustic, and vibrational insulator, qualities attributed to its unique closed-cellular structure [8, 9, 10, 11]. These properties make cork a versa-tile raw material suitable for a wide range of applications across various industries. It is extensively used for producing bottle stoppers, fishing rods, buoys, building materials, footwear, and automotive components. Its exceptional physico-mechanical properties make it an excellent choice for thermal insulation (e.g., cold storage rooms), acoustic absorption (e.g., recording studios), and vibration damp-ing (e.g., machinery). Additionally, cork’s ability to recover from compression makes it ideal for gas-kets and seals in civil construction, wind instruments, and internal combustion engines [12, 13, 14, 15]. In recent years, innovative cork-based compo-sites have been developed for applications such as flooring, wall coverings, and other industrial [16]. The distinctive features of cork, such as high compressibility, flexibility under compression, low permeability, and chemical and biological inertness, are primarily attributed to its chemical composition [17, 18, 19, 20, 21]. Cork consists predominantly of suberin (~40%), lignin (~22%), carbohydrates (~18%), extracts (~15%), and inorganic components (~1%) [22, 23, 24].

The physical properties of cork demonstrate its status as a high-quality insulating material. However, to compete with alternative materials across various insulation sectors, enhancements to its insulating characteristics are necessary, achieved by modifying its properties and physical structure. Such modifications influence transport properties (e.g., thermal conductivity and mass diffusivity) as well as acoustic and vibrational attenuation factors. Kermezli et al.[25, 26] showed that thermal treatment produces a novel material with improved mechanical properties, offering significant economic advantages and notable environmental benefits. To expand the scientific understanding of this field, research efforts by Costa et al.[27,28], Sánchez-González et al., Oliveira et al. and Paulo et al. [29, 30, 31]have explored the impact of climatic factors on cork growth and quality.

In this regard, Leite et al. [32] concluded that drought conditions have negligible effects on cork’s chemical composition, particularly in the ratio and composition of structural components such as suber-in relative to lignin. They determined that the tree's genetic heritage is the most critical factor influenc-ing the chemical variability of cork, minimizing the impact of drought conditions. Recent work by Paulo et al.[33] has developed mathematical models correlating cork thickness, tree age, and various climate change scenarios.

This study focuses on the characterization of native cork through experimental measurements of the apparent diffusion coefficient, analyzing the impact of climatic and geographic factors on its insulating properties. Targeting key cork oak plantation sites across Algeria (Bejaia, Chlef, Jijel, Me-dea, and Skikda), the research considers in-situ climatic-geographical factors such as altitude, humidity, sunlight, rainfall, and temperature to deepen understanding and optimize cork’s insulating capabilities.

2. Materals and methods

2.1 Modeling

In the transient regime of matter diffusion, the Dapp is a critical parameter for studying the intensity of mass transfer phenomena of a chemical species within a porous medium (Cork). It should be noted that this scenario can be addressed using both analytical and experimental approaches, based on Fick's law. The proposed inverse method is an indirect parameter estimation technique that involves three main steps: experimentation, theoretical modeling, and minimization of the objective function, which represents the discrepancy between experimental and theoretical results. This method allows for the indirect determination of the molecular diffusion coefficient using the conductometric technique by establishing the experimental basis for the reduced mass. It relies on an original experimental setup and has been successfully applied to transient regimes using analytical methods. The calculation process is based on a mass transfer model combined with an optimization algorithm (Bat Algorithm) to minimize the discrepancy between experimental data and simulations.

2.1.1 Physical model

For the external diffusion of matter in the composite material, it is assumed that its initial concentration is c0 independent of position. At time t=0, the chip is immersed in a stirred medium with a concentration of (c∞). For a given temperature and during the diffusion process, the surface concentration (cs) remains constant and equals (c*), which is in equilibrium with the concentration of the external medium according to Equation (Pereira. 2013)[23].

$$c^* = k_p . c_\infty \tag{1}$$

Given the complexity of the problem and to streamline the computational model, certain simplifying assumptions were made regarding the operational parameters and material properties.

2.1.2 Mathematical Model

The mathematical modeling is based on the mass balance of the diffusing chemical species *(i)* through an infinitesimal volume element *(dv)* of the composite. The objective is to determine, during the desorption process, the concentration distributions within the finite-geometry composite.

$$\begin{bmatrix} (i) entering \\ thesystem \end{bmatrix} - \begin{bmatrix} (i) leaving \\ thesystem \end{bmatrix} + \begin{bmatrix} Rateofmolar \\ formationof(i) \\ fromchemicalreaction \end{bmatrix} = \begin{bmatrix} Rateoftemporal \\ molarchange\ of\ (i) \\ withinthesystem \end{bmatrix} \tag{2}$$

Under isothermal conditions, the general mass transfer equation for the diffusion of the chemical species in different geometries of the composite, assuming the absence of chemical reactions and fluid flow within the composite, simplifies to the following mass balance equation (Amokrane et al. 2010):

$$\begin{pmatrix} Accmulation \\ term \end{pmatrix} - \begin{pmatrix} Diffusion \\ term \end{pmatrix} = 0 \tag{3}$$

Let:

$$\frac{\partial c_i(\zeta,t)}{\partial t} - D_{iapp}\left[\frac{\partial^2 c_i(\zeta,t)}{\partial \zeta^2} - \frac{\beta}{\zeta}.\frac{\partial c_i(\zeta,t)}{\partial \zeta}\right] = 0 \tag{4}$$

Where: *ci*, concentration of the diffusing chemical species *(i)* (mol/m³), t the diffusion time (s), ζ spatial coordinate (ζ=x for an axial coordinate from the center of the chip, and ζ=r for a radial coordinate), β a constant dependent on the geometry of the composite (β=0 for a plate-like geometry).The cork chips used in this study have a parallelepipedic shape, with a length (a), a thickness (2l), and a height (b).

Considering the studied phenomenon, the transient diffusion model, including the boundary and initial conditions, takes the following form (Amokrane et al. 2010):

$$\left.\begin{array}{c} \boldsymbol{D_{iapp}} \frac{\partial^2 c_i(x,t)}{\partial x^2} - \frac{\partial c_i(x,t)}{\partial t} = 0 \\ \boldsymbol{c_i(x,t)}|_{t=0}^{x>0} = \boldsymbol{c_{i0}} \\ \boldsymbol{c_i(x,t)}|_{t>0}^{x=l} = \boldsymbol{c_{ip}} \\ \left.\frac{\partial c_i(x,t)}{\partial x}\right|_{t>0}^{x=0} = 0 \end{array}\right\} \tag{5}$$

By using the Laplace transform, the variation in the concentration of the diffusing species is given by solving the partial differential equation. At the wall ($x=l$), the temporal variation of the diffusing mass is given by Pereira. (1988)[22]:

$$\frac{m_t}{m_\infty} = 1 - \frac{8}{\pi^2}\sum_{n=0}^{\infty}\left\{\frac{1}{(2n+1)^2}.exp\left(-\frac{(2n+1)^2.\pi^2.D_{i\ app}}{4l^2}.t\right)\right\} \quad (6)$$

Knowing that :

$$\frac{m_t}{m_\infty} = \frac{C_t}{C_\infty} \quad (7)$$

Where: m_t is the mass of the substance released at time t, m_∞ is the mass of the substance transferred after the total desorption of the chip at infinite time, c_t is the instantaneous concentration, and c_∞ is the concentration at equilibrium. A Matlab program was developed to calibrate the experimental results with the analytical expression of the solution obtained from the model, for the case of the selected plate geometry.

2.2 Sampling and plantation zones

To establish the impact of the geographical zone on the properties of cork, areas located in the North, Center, and East of Algeria, where cork oak grows under natural conditions, were targeted. Each zone is characterized by the altitude and longitude of the plantation site, as well as its geographical location. The data are summarized in Table 1:

Table 1 Geographical parameters of the cork oak plantation sites

Plantation Site	Bejaia	Chlef	Jijel	Medea	Skikda
Altitude(m)	2	43	8	1030	2
Latitude	36°43 N	36°12 N	36°48 N	36°17 N	36°53 N
Longitude	05°04 E	01°20 E	05°53 E	02°44 E	06°54 E

The cork oak (Quercus suber L.) thrives in a narrow geographical band located at similar latitudes, characterized by a Mediterranean climate. This includes the northern coastal regions and the Tell Atlas, which experience hot, dry summers and mild, wet winters. The northern, central, and eastern borders of this zone receive annual rainfall ranging from 600 to 1150 mm, making them significantly more watered compared to other parts of the country. Samples of cork oak growing in these regions were collected for experimental analysis. The apparent diffusion coefficients of these samples were determined using a specific protocol based on conductimetric analysis, allowing precise quantification of the material's mass transfer properties.

2.3 Experimental Setup (Conductimetric Method)

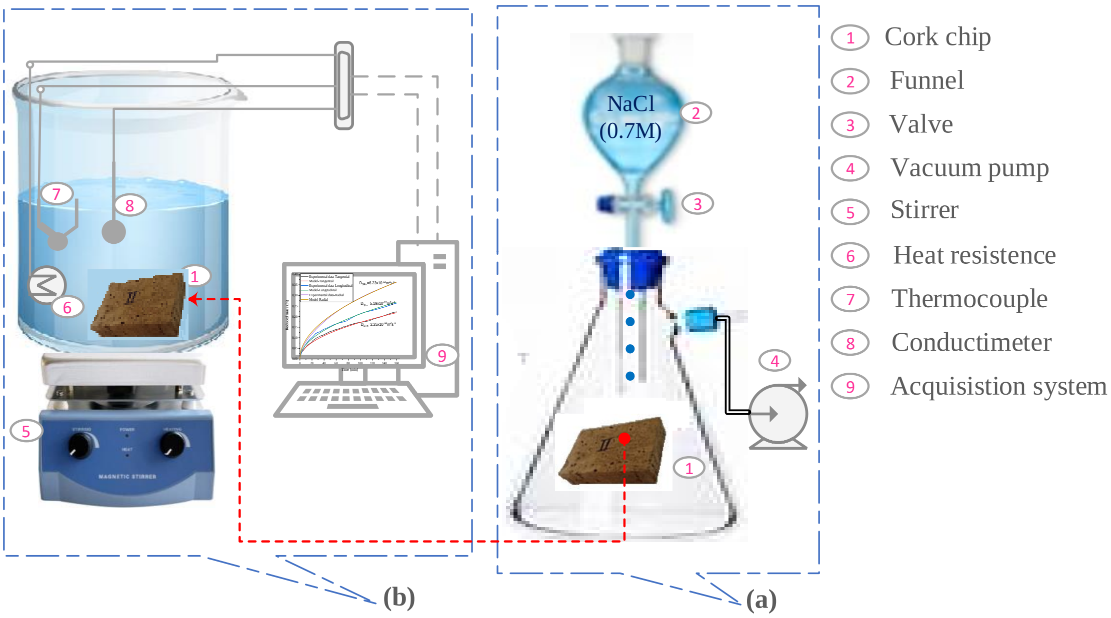
To analyze the diffusion process using the conductimetric method, we adopted the experi-mental protocol developed in previous studies by Kermezli et al. (2008)[25]. The experimental setup begins with the preparation of cork samples (Figure 1).

Figure 1 Cork Sample

For this purpose, the samples were cut along the radial direction, with an average facet area of 1.934×10^{-3} m^2 and an average thickness of 5.91×10^{-3} m measured along one direction.

Figure 2 Technical Diagram of the Conductimetric Method

(a) Vacuum Impregnation Process, (b) Conductivity Measurement



The conductimetric study of the cork samples was divided into two main stages:

1. Impregnation of the Samples with a KCl Solution: This step follows the operational procedure illustrated in Figure 2.a, where the cork samples are prepared and immersed in a potassium chloride (KCl) solution under controlled conditions.

2. Measurement of Conductivity in Distilled Ionized Water: The cork sample is immersed in ionized distilled water, agitated at a rotational speed ω\omegaω and maintained at a controlled temperature T. The initial conductivity of the water is measured beforehand using a data acquisition system to enable corrections to subsequent measurements. The temporal evolution of the water's conductivity, influenced by diffusion through the exposed lateral surfaces of the cork sample, is recorded in a transient regime using a dedicated acquisition system (Figure 2.b).

Phase (b) involves utilizing experimental data collected from the measurement block (9) to es-tablish the reduced mass profile in a transient regime. The Dapp is estimated by analyzing the evolution of the KCl concentration (ct)exp and fitting the data to the mathematical model developed in the preced-ing section. To refine the calculated values, optimization techniques inspired by biological system be-haviors, specifically metaheuristic algorithms, were employed. Genetic algorithms, such as the Bat Algorithm (BA) developed by Xin-She Yang (2012)[34], were used to minimize the error generated by dis-crepancies between the model's predicted transfer function and the experimental measurements.

The BA operates by adjusting the solution frequency range within a domain of [-10% : +10%] relative to the initial Dapp estimate. This calibration process follows the workflow depicted in Figure 6. The resulting diffusion coefficients are presented with a precision of 10^{-5}.

3. Results and discussion

Thus, for each region and for the selected cutting direction, namely the radial direction, the conductometric process combined with the data fitting optimization technique allowed for the experimental determination of the Dapp. The obtained results are summarized in Table 2.

Table 2 Numerical val

ues of the Dapp as a function of the plantation zone

	Bejaia	Chlef	Jijel	Medea	Skikda
$D_{app}(m^2/s)$ **Calibration**	$5.40 x 10^{-12}$	$1.01 x 10^{-12}$	$3.95 x 10^{-12}$	$1.90 x 10^{-12}$	$6.23 x 10^{-12}$
$D_{app}(m^2/s)$ **Bat-Algorithm**	$5.41 x 10^{-12}$	$1.11 x 10^{-12}$	$3.96 x 10^{-12}$	$1.88 x 10^{-12}$	$6.19 x 10^{-12}$

It is observed in figure 3 that D_{app} is affected by the plantation region, and its value spans a rather narrow range from [1.11×10⁻¹², 6.19×10⁻¹²]. Among various factors, it stands out that the regional factor influences the performance and quality of the cork. Furthermore, it is important to consider the impact of geo-meteorological factors on the Dapp coefficient. In this regard, and without being exhaustive, the meteorological factors counted include relative humidity, sunlight duration, rainfall, and temperature. The numerical values of these factors represent the average data over a period of about ten years, from 1999 to 2009, and are recorded in Table 3.

Figure 3:Impact of the plantation region on the quality ofmass insulation

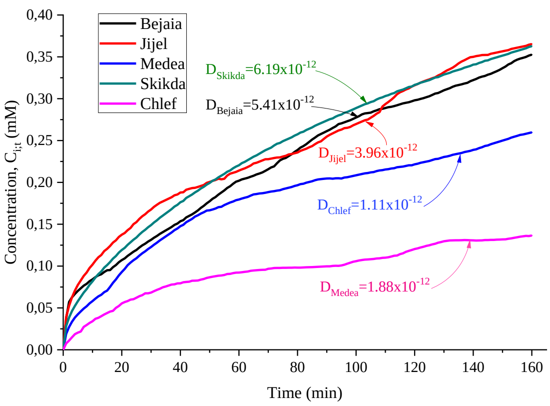


Table 3: Values of operational parameters at different levels of analysis

Province	Altitude (m)	Humidity (%)	Sunlight (h)	Cumulative Rainfall (mm)	Temperature (°C)	Dapp (m^2s^{-1})
BEJAIA	2	76	2718.6	782.5	18.5	$5.41 x 10^{-12}$
CHLEF	143	60	2844.8	368.3	19.9	$1.11 x 10^{-12}$
JIJEL	8	75	2747.7	985	18	$3.96 x 10^{-12}$
Medea	1030	68	2888.6	667.1	15.5	$1.88 x 10^{-12}$
Skikda	2	70	2687.6	727	19.2	$6.19 x 10^{-12}$

To study the influence of climatic factors on the apparent diffusion coefficient across different sites, a numerical model based on multiple regression was developed and processed computationally. By selecting a determination coefficient (R^2) value greater than 95%, the least squares method was used to establish a regression between the following factors:

1) Temperature, 2) Altitudeand3) Humidity.

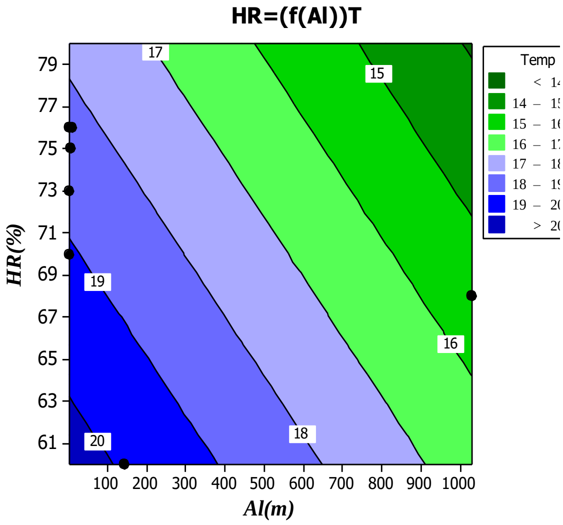
As well as their interactions. The regression is expressed by the following analytical relation:

$$T = 28.377 - 0.132 * \text{Humd} - 3.759 * 10^{-3} * \text{Alt} \quad (8)$$

$$R^2 = 97{,}62\%$$

From a meteorological perspective, it can be observed that for low altitudes, variations in ambient temperature are nearly negligible, as reflected by the low coefficient value of the altitude factor. Furthermore, it can be stated that temperature is negatively influenced by the relative humidity of the environment within a narrow temperature range. For a given altitude, this result can be confirmed by a simple reading of the Mollier hygrometric diagram, Humd=Humd(T).

Figure 4: Interaction curve of humidity and altitude on the temperature iso-response



Having noted the variation of the D_{app}, with the different factors (temperature, sunlight, and rainfall), we similarly developed a predictive model based on multiple linear regression with quadratic terms, using the determination coefficient as the significance criterion. The analytical expression of the regression is as follows:

$$\mathcal{D}_{app} = 214{,}637 - 13{,}868\mathrm{T} + 0{,}373\,\mathrm{T}^2 - 0{,}0304\,\mathrm{Sunl} + 0{,}0028\,\mathrm{Rainf} \quad (9)$$

$$R^2 = 99{,}87\%$$

Based on the coefficients of the factors and their algebraic signs, we can determine the positive effect of rainfall on the D_{app}. However, the relatively low value of its factor suggests an almost negligible effect of rainfall on D_{app}. Ultimately, it can be stated unequivocally that the factors : temperature, sunlight, and rainfall ; significantly influence Dapp. To highlight the impact of the factors on the Dapp, and to determine the climatic and geographical conditions that lead to cork production meeting the criteria of low apparent diffusion coefficients, iso-response curves were presented. The key results are discussed in this analysis.

For constant rainfall, Figures 5.a,b and c show iso-response curves (D_{app}=Cst) obtained by analyzing the combined impact of temperature and sunlight on the diffusion coefficient. These analyses were conducted under rainfall conditions matching those prevailing in the plantation zones.

Based on this analysis and considering the combined effect of rainfall, temperature, and sunlight, it is clear that the low diffusion coefficients suitable for use in insulation can be defined by the ranges presented in Summary Table 4.

Figure 5: Curve of the interaction between temperature and sunlight on the iso-response of the diffusion coefficient:

a) PI=360mm; b) PI=670mm; c) PI=990mm

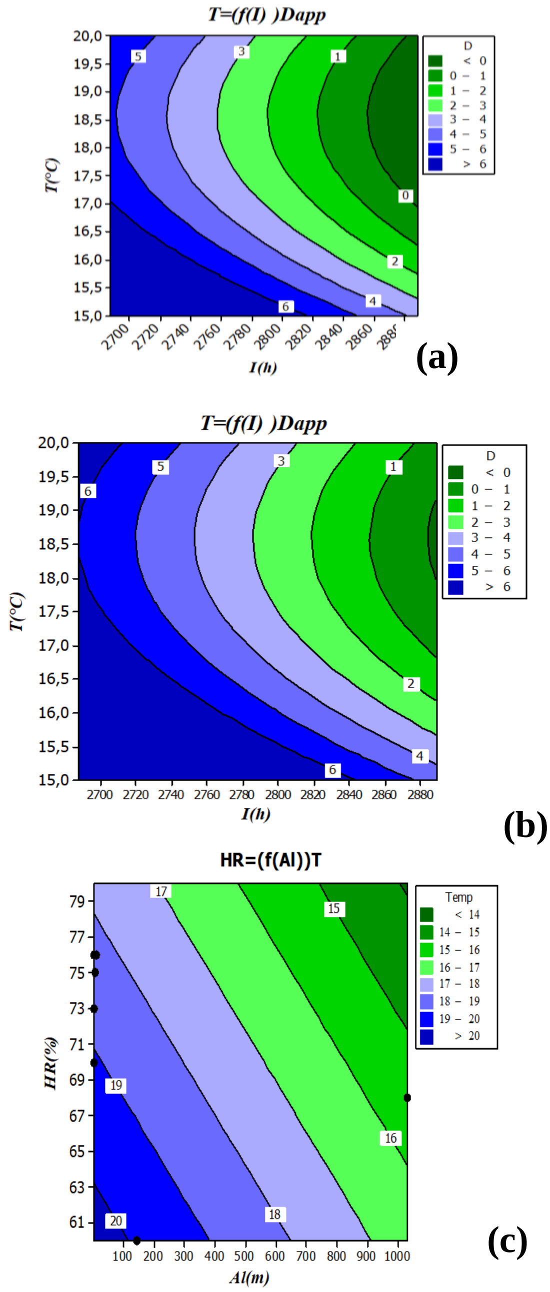


Table 4: Meteorological ranges for producing cork with insulating properties

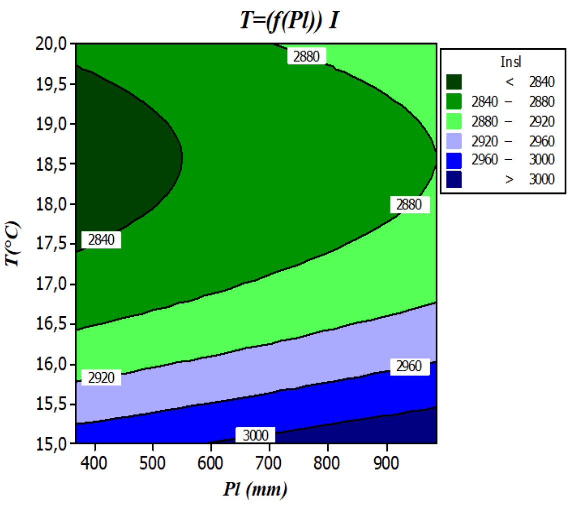
Rainfall (mm)	Temperature (°C)	Sunlight (h)
360	$16,5 < T < 20$	$2840 < Sunlight < 2900$
670	$17 < T < 20$	$2860 < Sunlight < 2900$
990	$17,5 < T < 19.5$	$2880 < Sunlight < 2900$

The intersection of these ranges identifies the favorable conditions for producing cork with low transfer parameters. The common range between these domains is:

Sunlight (h) : $2840 < Sunl < 2900$

Temperature (°C) :$16,5 < T < 20$

Figure 6: Identification of the climatic and geographical conditions for obtaining cork with superior insulating quality



With low rainfall levels. Given the mixed influence of rainfall on the transfer coefficient Dapp, it appears more insightful to examine its interaction with sunlight and temperature for Dapp values close to those limiting its application in insulation, i.e., around Dapp=10^{-12}m^{2}s^{-1}.

In this context, iso-response curves were plotted for a diffusion coefficient of this magnitude, as shown in Figure 6. This figure outlines the climatic and geographical conditions conducive to producing cork of higher quality for insulation purposes.

4. Conclusion

The objective of this study was to analyze the influence of climatic and geographical factors on the mass insulation performance of cork harvested in regions with specific hygrometric and thermal conditions. It focused on identifying the optimal climatic and geographical profile to produce cork that meets market demands for quality.

The study investigated the influence of various climatic factors, namely altitude, humidity, sunlight, rainfall, and temperature, on the Dapp of cork from different sites (Bejaia, Chlef, Jijel, Medea, and Skikda). The key property responsible for the insulation characteristics of the biomaterial is the Dapp. Given that insulation is a mass transfer phenomenon, its spatiotemporal variation was analyzed using a mathematical model derived from the solution of Fick's second law under transient conditions, tracking the evolution of KCl concentration through the conductometric method. By calibrating experimental results of reduced mass with the model obtained from solving Fick's law, the Dapp values were approximated. These results were further refined using the Bat Algorithm with a precision of 10^{-5}. It was found that the diffusion coefficient values ranged between 1×10^{-12} m^{2}s^{-1} and 6×10^{-12} m^{2}s^{-1}, with the lowest apparent diffusion coefficient of 1.11×10^{-12} m^{2}s^{-1} obtained in the Chlef region.

To analyze the influence of the factors on the Dapp coefficient, a numerical model based on multiple regression was developed, highlighting the impact of the various factors considered in this study. Through graphical analyses, it was determined that low apparent diffusion coefficients were achieved for 2840<Sunlight<2880 h and 16.5<T<20°C.

In conclusion, it can be stated that cork from the Chlef region exhibits superior quality, making it more suitable for insulation purposes compared to cork from the other regions analyzed in this study.

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