Closed-Form Analytical Formulation for Double-Diffusive Darcy-Brinkman Convection in an Anisotropic Porous Medium with Soret-Dufour Cross-Diffusion and a First-Order Homogeneous Chemical Reaction

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ABSTRACT

Double-diffusive convection in anisotropic porous media plays a pivotal role in subsurface contaminant transport, carbon dioxide sequestration, and catalytic packed-bed reactors, where fluid motion is strongly coupled with chemical reactions and thermodynamic cross-diffusion. The initial phase of double-diffusive stationary convection in a fluid-saturated anisotropic Darcy-Brinkman porous layer under the influence of Soret and Dufour cross-diffusion and a linear, first-order homogeneous chemical reaction is determined using an exact, closed-form analytical formulation. Brinkman viscous shear dissipation is combined with both mechanical permeability anisotropy (ξ) and thermal conductivity anisotropy (ψ). Applying linear stability analysis under the Darcy-Brinkman-Boussinesq framework, the coupled perturbation equations for vertical velocity, temperature, and solute concentration are solved across permeable, stress-free, isothermal, and isosolutal boundaries. A normal mode eigenfunction expansion transforms the boundary-value problem into a linear algebraic characteristic system, from which an exact determinant expansion yields the critical stability condition without numerical discretization. As a function of the horizontal wavenumber (a), solutal Rayleigh number (Rs), Lewis number (Le), Dufour number (Df), Soret number (Sr), reaction Damköhler parameter (γ), and anisotropy ratios, a closed-form expression for the Rayleigh number (Ra) is explicitly obtained. High chemical reaction rates ($\gamma \to \infty$) disconnect the solutal transport field from the flow dynamics, changing the onset threshold to that of conventional single-component thermal convection, according to asymptotic analysis. Moreover, higher mechanical anisotropy ($\xi > 1$) destabilizes the medium by reducing horizontal flow drag, whereas enhanced thermal anisotropy ($\psi > 1$) exerts a stabilizing influence through lateral thermal dispersion. A critical singularity condition $\gamma^* = (Df - Le)(\pi^2 + a^2)$ is established, defining the theoretical boundary separating stationary overturning from oscillatory bifurcations. This exact formulation establishes a fundamental theoretical benchmark for validating complex numerical codes and elucidating multi-physics transport mechanisms in anisotropic porous systems.

Keywords: reaction Damköhler, cross-diffusion, anisotrophy

INTRODUCTION

Double-diffusive convection in porous media, driven by opposing or cooperating density gradients induced by heat and mass transfer, plays an essential role in diverse geophysical and industrial processes, including geothermal reservoir management, carbon dioxide sequestration in deep saline aquifers, nuclear waste repositories, and catalytic packed-bed reactors. In many practical geomechanical systems, the underlying porous

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matrix exhibits structural orientation due to sedimentation or compaction, leading to anisotropic mechanical permeability and thermal conductivity.

When convective transport occurs in chemically active environments, such as during the in-situ remediation of contaminated groundwater or reactive synthesis in chemical reactors, the dissolved solute is rarely inert. Rather, it undergoes homogeneous consumption or decomposition, which alters the concentration distribution and modifies the density field. The inclusion of cross-diffusion effects, namely, the Dufour effect (energy flux driven by chemical gradients) and the Soret effect (mass flux driven by thermal gradients) further couples the momentum, thermal, and solutal fields into a highly non-linear system.

While numerous numerical investigations have addressed double-diffusive instability, analytical closed-form solutions remain critical for validating computational solvers and establishing exact asymptotic boundaries. The objective of this work is to present an exact, closed-form algebraic formulation for the marginal stability threshold of double-diffusive convection in an anisotropic Darcy-Brinkman medium in the presence of Soret–Dufour cross-diffusion and a first-order homogeneous chemical reaction.

LITERATURE REVIEW

The pioneering formulations of Horton and Rogers [1] and Lapwood [2], who identified the critical threshold for the beginning of convection in a horizontal layer governed by Darcy's law, formed the basic framework for buoyancy-driven convective instability in fluid-saturated porous media. The boundary-layer shearing effects and macroscopic viscous dissipation that appear close to solid boundaries or in high-porosity systems like metal foams, fibrous mats, and loose granular beds are not captured by the classical Darcy formulation, despite the fact that it effectively describes creeping flow in low-permeability, consolidated media. Brinkman [3] proposed an effective viscous shear term ($\mu_e \nabla^2 \mathrm{v}$) to account for these viscous boundary effects. The resulting Darcy-Brinkman formulation provides the required mathematical order to comply with physical no-slip conditions at solid rigid barriers, bridging the gap between clear-fluid Navier–Stokes dynamics and pure Darcy porous flow [4, 5].

The assumption of isotropic macroscopic transport qualities is rarely true in both manmade materials and natural geological formations. Directional dependency in hydraulic and thermal properties is naturally produced by sedimentation processes, preferred compaction, and structural stratification. One of the first studies on the impact of anisotropic permeability on thermal convective stability was carried out by Epherre [6], who showed that changes in the ratio of horizontal-to-vertical permeability considerably affect the critical Rayleigh number and the preferred planform geometry of convective cells. Mechanical permeability anisotropy ($\xi = K_h/K_v$) and thermal conductivity anisotropy ($\psi = \kappa_h/\kappa_v$) have been shown to have distinct, competing effects on hydrodynamic stability by Kvernvold and Tyvand [7] and Bera and Khalili [8]. Specifically, an elevated horizontal permeability ($\xi > 1$) reduces resistance to lateral recirculating flow, destabilizing the medium. Conversely, enhanced horizontal thermal conductivity ($\psi > 1$) dissipates lateral temperature fluctuations between rising and falling convective plumes, stabilizing the porous layer against convective overturning [9].

Due to varying molecular diffusion rates, the double-diffusive phenomena that results from buoyant forces arising concurrently from temperature and solutal gradients is significantly more complex. Nield [10] expanded the analysis of double-diffusive convection to porous layers by mapping the boundaries between oscillatory convective modes and stationary overturning. Thermodynamic cross-diffusion effects, including the Dufour effect (energy transfer caused by concentration gradients) and the Soret effect (mass transport caused by heat gradients), cannot be disregarded in dense multicomponent mixes or systems exposed to strong localised gradients [11]. Cross-diffusion mechanisms in anisotropic porous layers were studied by Postelnicu [12] and Malashetty and Gaikwad [13]. They showed that the Dufour effect modifies the internal thermal energy balance, which may cause subcritical instabilities or change marginal stability boundaries, while the Soret coefficient directly modulates the effective adverse solutal gradient. Further evidence that coupled Soret and Dufour fluxes can cause oscillatory convection even in situations where the principal solute gradient is intrinsically stabilising was provided by Gaikwad et al. [14].

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The transported chemical species is not inert but undergoes chemical modification in various industrial and geophysical contexts, including catalytic packed-bed reactors, deep subterranean CO_2 mineralisation, and in-situ environmental pollutant treatment. Transport timescales and reaction rates are directly correlated when chemical reaction kinetics are introduced. By demonstrating that a first-order homogeneous consumption response adds an efficient damping mechanism that constantly depletes solute perturbations, Brand and Steinberg [15, 16] established the theoretical foundation for convective instability in chemically reactive binary mixtures. Yadav et. al. [17] demonstrated chemical reactions can destabilise the fluid system by promoting convective motion and enhancing mass transfer, thereby influencing the overall transport processes in porous media.

Research indicates a significant gap despite significant advancements in the modelling of these distinct physical processes where previous studies have mostly focused on chemical reaction kinetics, cross-diffusion, or structural anisotropy, often using low-order Galerkin truncations, finite differences, or approximation numerical shooting techniques. The simultaneous coupling of Brinkman viscous shear, dual mechanical and thermal anisotropy (ξ, ψ), Soret–Dufour cross-diffusion (Sr, Df), and homogeneous chemical consumption (γ) has not been found in an exact, closed-form algebraic formulation. It is crucial to provide such a closed-form analytical benchmark in order to validate computational fluid dynamics algorithms and understand the conflicting physical causes leading to reactive porous stability. Current study extended research done by Abidin et al. [18, 19] where they showed that the Dufour effect modifies the internal thermal energy balance, which may cause subcritical instabilities or change marginal stability boundaries, while the Soret coefficient directly modulates the effective adverse solutal gradient.

Mathematical Formulation

Consider a horizontal, fluid-saturated porous layer of thickness H bounded between planes at $z^* = 0$ and $z^* = H$. The porous medium is characterized by anisotropic mechanical permeability ($K_x = K_y = K_h,\ K_z = K_v$) and anisotropic effective thermal conductivity ($\kappa_{mx} = \kappa_{my} = \kappa_h, \kappa_{mz} = \kappa_v$). The fluid is subject to a constant downward gravitational acceleration $\mathbf{g} = -g\hat{\mathbf{k}}$. The boundaries are held at uniform temperatures T_0^* and T_1^* and solute concentrations C_0^* and C_1^*, with $\Delta T^* = T_0^* - T_1^* > 0$ and $\Delta C^* = C_0^* - C_1^* > 0$.

Under the Darcy–Brinkman–Boussinesq framework, the fluid density varies linearly as:

$$\rho^* = \rho_0[1 - \beta_T(T^* - T_0^*) - \beta_C(C^* - C_0^*)] \tag{1}$$

where β_T and β_C denote the thermal and solutal expansion coefficients, respectively.

The dimensional conservation equations for mass, momentum, thermal energy, and chemical solute with a first-order consumption reaction are:

$$\nabla^* \cdot \mathbf{v}^* = 0 \tag{2}$$

$$\frac{\rho_0}{\varepsilon}\frac{\partial \mathbf{v}^*}{\partial t^*} = -\nabla^* p^* + \mu_e \nabla^{*2}\mathbf{v}^* - \mu \mathbf{K}^{-1} \cdot \mathbf{v}^* + \rho^* \mathbf{g} \tag{3}$$

$$(\rho c)_m \frac{\partial T^*}{\partial t^*} + (\rho c)_f (\mathbf{v}^* \cdot \nabla^*) T^* = \nabla^* \cdot (\boldsymbol{\kappa}_m \cdot \nabla^* T^*) + D_{TC} \nabla^{*2} C^* \tag{4}$$

$$\varepsilon \frac{\partial C^*}{\partial t^*} + (\mathbf{v}^* \cdot \nabla^*) C^* = D_s \nabla^{*2} C^* + D_{CT} \nabla^{*2} T^* - k_r (C^* - C_1^*) \tag{5}$$

Here, $\mathbf{v}^* = (u^*, v^*, w^*)$ is the seepage velocity vector, μ is fluid dynamic viscosity, μ_e is effective Brinkman viscosity, ε is porosity, k_r is the reaction rate constant, D_s is solute diffusivity, D_{TC} is the Dufour coefficient, and D_{CT} is the Soret coefficient.

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Non-Dimensionalization

The variables are scaled using the characteristic dimensions:

$$(x,y,z)=\frac{(x^*,y^*,z^*)}{H},t=\frac{t^*\kappa_v}{(\rho c)_f H^2},\mathbf{v}=\frac{\mathbf{v}^*H}{\kappa_v/(\rho c)_f},p=\frac{p^*K_v}{\mu\kappa_v/(\rho c)_f},T=\frac{T^*-T_1^*}{\Delta T^*},C=\frac{C^*-C_1^*}{\Delta C^*}$$

This nondimensionalization produces the dimensionless governing system:

$$\nabla\cdot\mathbf{v}=0 \tag{6}$$

$$\frac{1}{\varepsilon Pr}\frac{\partial\mathbf{v}}{\partial t}=-\nabla p+\frac{\mu_e}{\mu}\nabla^2\mathbf{v}-\left(\frac{1}{\xi}u\hat{\mathbf{i}}+\frac{1}{\xi}v\hat{\mathbf{j}}+w\hat{\mathbf{k}}\right)+(RaT+RsC)\hat{\mathbf{k}} \tag{7}$$

$$\eta\frac{\partial T}{\partial t}+(\mathbf{v}\cdot\nabla)T=\left(\psi\nabla_h^2+\frac{\partial^2}{\partial z^2}\right)T+Df\nabla^2C \tag{8}$$

$$\varepsilon\frac{\partial C}{\partial t}+(\mathbf{v}\cdot\nabla)C=Le\nabla^2C+Sr\nabla^2T-\gamma C \tag{9}$$

The dimensionless parameters are defined as:

$Ra=\frac{\rho_0 g\beta_T\Delta T^*HK_v}{\mu\alpha_v}$ (Thermal Rayleigh number), $Rs=\frac{\rho_0 g\beta_C\Delta C^*HK_v}{\mu\alpha_v}$ (Solutal Rayleigh number), $Pr=\frac{\nu}{\alpha_v}$ (Prandtl number), $Le=\frac{D_s}{\alpha_v}$ (Lewis number), $Df=\frac{D_{TC}\Delta C^*}{\alpha_v\Delta T^*}$ (Dufour number), $Sr=\frac{D_{CT}\Delta T^*}{\alpha_v\Delta C^*}$ (Soret number), $\gamma=\frac{k_rH^2}{\alpha_v}$ (Damköhler reaction parameter), $\xi=\frac{K_h}{K_v}$ (Mechanical permeability anisotropy ratio), $\psi=\frac{\kappa_h}{\kappa_v}$ (Thermal conductivity anisotropy ratio), $\nabla_h^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$ (Horizontal Laplacian operator).

The quiescent, steady base state is given by:

$$\mathbf{v}_b=(0,0,0),\quad T_b(z)=1-z,\quad C_b(z)=1-z,\quad \frac{dp_b}{dz}=Ra(1-z)+Rs(1-z) \tag{10}$$

Infinitesimal perturbations are superimposed onto the base state:

$$\mathbf{v}=\mathbf{v}_b+\mathbf{v}',\quad T=T_b(z)+T',\quad C=C_b(z)+C',\quad p=p_b(z)+p' \tag{11}$$

Substituting Equation (11) into Equations (6) – (9), neglecting non-linear products of perturbed quantities, and focusing on the onset of stationary convection ($\frac{\partial}{\partial t}=0$), the linearized system becomes

$$\frac{\mu_e}{\mu}\nabla^4w'-\left(\frac{1}{\xi}\nabla_h^2+\frac{\partial^2}{\partial z^2}\right)w'-Ra\nabla_h^2T'-Rs\nabla_h^2C'=0 \tag{12}$$

$$\left(\psi\nabla_h^2+\frac{\partial^2}{\partial z^2}\right)T'+Df\nabla^2C'+w'=0 \tag{13}$$

$$Le\nabla^2C'+Sr\nabla^2T'-\gamma C'+w'=0 \tag{14}$$

where w' is the vertical perturbation velocity, T' is the temperature perturbation, C' is the solute perturbation, and $\nabla_h^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$.

Applying the operator $\nabla_h^2\left(\frac{\partial}{\partial z}\right)$ to the horizontal momentum components and utilizing the continuity equation eliminates the pressure perturbation p' and horizontal velocity components (u',v'), yielding the governing equation for the vertical perturbation velocity w':

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$$\frac{\mu_e}{\mu}\nabla^4 w' - \left(\frac{1}{\xi}\nabla_h^2 + \frac{\partial^2}{\partial z^2}\right)w' - Ra\nabla_h^2 T' - Rs\nabla_h^2 C' = 0 \quad (15)$$

Analytical Solution

Boundary Conditions & Eigenfunction Expansion

For permeable, stress-free boundaries maintained at constant temperature and concentration:

$$w' = \frac{\partial^2 w'}{\partial z^2} = T' = C' = 0 \quad \text{at} \quad z = 0,1 \quad (16)$$

The exact normal mode representations satisfying these boundary conditions are:

$$[w'(x,y,z),\, T'(x,y,z),\, C'(x,y,z)] = [W_0 \sin(\pi z)\,,\, \Theta_0 \sin(\pi z)\,,\, \Phi_0 \sin(\pi z)]e^{i(a_x x + a_y y)} \quad (17)$$

where $a^2 = a_x^2 + a_y^2$, and W_0, Θ_0, Φ_0 are arbitrary constant perturbation amplitudes.

The differential operators transform under this expansion as:

$$\nabla_h^2 \to -a^2, \quad \frac{\partial^2}{\partial z^2} \to -\pi^2, \quad \nabla^2 \to -(\pi^2 + a^2), \quad \nabla^4 \to (\pi^2 + a^2)^2$$

Substituting Equation (17) into Equations (12)–(16) produces a system of three linear homogeneous algebraic equations:

$$\left[\frac{\mu_e}{\mu}(\pi^2 + a^2)^2 + \left(\pi^2 + \frac{a^2}{\xi}\right)\right] W_0 - a^2 Ra\,\Theta_0 - a^2 Rs\,\Phi_0 = 0 \quad (18)$$

$$-W_0 + (\pi^2 + \psi a^2)\Theta_0 + Df(\pi^2 + a^2)\Phi_0 = 0 \quad (19)$$

$$-W_0 + Sr(\pi^2 + a^2)\Theta_0 + [Le(\pi^2 + a^2) + \gamma]\Phi_0 = 0 \quad (20)$$

For non-trivial solutions $(W_0, \Theta_0, \Phi_0)^T \neq \mathbf{0}$, the determinant of the coefficient matrix must vanish and yields the exact closed-form expression for the Rayleigh number:

$$Ra = \frac{M11\{(\pi^2 + \psi a^2)[Le(\pi^2 + a^2) + \gamma] - Df \cdot Sr(\pi^2 + a^2)^2\} - a^2 Rs[M22 - Sr(\pi^2 + a^2)]}{a^2[(\pi^2 + a^2)(Le - Df) + \gamma]} \quad (21)$$

where

$$M11 = \left[\frac{\mu_e}{\mu}(\pi^2 + a^2)^2 + \left(\pi^2 + \frac{a^2}{\xi}\right)\right]$$

$$M22 = (\pi^2 + \psi a^2)$$

Analytical Results

Corollary 1: Non-Reactive Limit ($\gamma \to 0$)

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In the absence of chemical consumption ($\gamma = 0$), the solutal transfer is governed purely by molecular and cross-diffusion. Substituting $\gamma = 0$ reduces Equation (20) to:

$$Ra_{\text{inert}} = \frac{\left[\frac{\mu_e}{\mu}(\pi^2 + a^2)^2 + \left(\pi^2 + \frac{a^2}{\xi}\right)\right][(\pi^2 + \psi a^2)Le - Df \cdot Sr(\pi^2 + a^2)] - a^2 Rs[(\pi^2 + \psi a^2) - Sr(\pi^2 + a^2)]}{a^2(\pi^2 + a^2)(Le - Df)}$$

(21)

This recovers the standard baseline for coupled Soret–Dufour thermosolutal Darcy–Brinkman convection.

Corollary 2: Asymptotic Fast-Reaction Decoupling ($\gamma \to \infty$)

Taking the asymptotic limit as the reaction rate parameter becomes arbitrarily large:

$$\lim_{\gamma\to\infty} \Delta_0 = \lim_{\gamma\to\infty}\{(\pi^2 + \psi a^2)\gamma + \mathcal{O}(1)\} = \gamma(\pi^2 + \psi a^2)$$

$$\lim_{\gamma\to\infty}[Le(\pi^2 + a^2) + \gamma - Df(\pi^2 + a^2)] = \gamma$$

Evaluating the limit of Equation (20) as $\gamma \to \infty$:

$$\lim_{\gamma\to\infty} R\,a = \lim_{\gamma\to\infty} \frac{M_{11}[\gamma(\pi^2 + \psi a^2)] - \mathcal{O}(1)}{a^2\gamma} = \frac{\left[\frac{\mu_e}{\mu}(\pi^2 + a^2)^2 + \left(\pi^2 + \frac{a^2}{\xi}\right)\right](\pi^2 + \psi a^2)}{a^2}$$

(22)

Physical Insight:: When the chemical consumption rate is arbitrarily high, any solutal perturbation is decomposed immediately upon inception ($\Phi_0 \to 0$). The concentration field is completely decoupled from the fluid dynamics, and the critical Rayleigh number becomes independent of Rs, Le, Df, and Sr, matching single-component thermal convection in an anisotropic Darcy–Brinkman layer.

Corollary 3: Pure Darcy Medium Limit ($\frac{\mu_e}{\mu} \to 0$)

Setting the Brinkman viscosity ratio to zero recovers the governing criterion for a pure anisotropic Darcy porous medium:

$$Ra_{\text{Darcy}} = \frac{\left(\pi^2 + \frac{a^2}{\xi}\right)\{(\pi^2 + \psi a^2)[Le(\pi^2 + a^2) + \gamma] - Df \cdot Sr(\pi^2 + a^2)^2\} - a^2 Rs[(\pi^2 + \psi a^2) - Sr(\pi^2 + a^2)]}{a^2[(\pi^2 + a^2)(Le - Df) + \gamma]}$$

DISCUSSION

The analytical closed-form relationship for the Rayleigh number provides direct insight into how chemical reaction kinetics, cross-diffusion, and structural anisotropy govern the onset of stationary double-diffusive instability.

Influence of the Chemical Reaction Parameter (γ)

The Damköhler parameter γ appears linearly in both the numerator and the denominator of Equation (20). Differentiating Ra with respect to γ reveals that for stabilizing solutal gradients ($Rs > 0$), $\frac{\partial Ra}{\partial \gamma} < 0$. This indicates

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that chemical consumption reduces the stabilizing capacity of the solutal gradient by eliminating solute perturbations, thereby facilitating earlier convective onset relative to an inert solutal state. Conversely, for destabilizing solutal gradients ($Rs < 0$), chemical consumption stabilizes the layer by destroying solutal buoyancy plumes.

Role of Mechanical and Thermal Anisotropy (ξ and ψ)

Mechanical Permeability Anisotropy (ξ): The parameter ξ is confined entirely to the hydrodynamic resistance term M_{11}. Because $\frac{\partial M_{11}}{\partial \xi} = -\frac{a^2}{\xi^2} < 0$, an increase in horizontal permeability ($\xi > 1$) reduces flow resistance to horizontal recirculation, directly lowering Ra and destabilizing the layer.

Thermal Conductivity Anisotropy (ψ): The parameter ψ enters the thermal diffusion term $M_{22} = \pi^2 + \psi a^2$. Because $\frac{\partial \Delta_0}{\partial \psi} = a^2[Le(\pi^2 + a^2) + \gamma] > 0$, increasing lateral thermal conduction ($\psi > 1$) dissipates horizontal thermal perturbations across rising and falling plumes, increasing Ra and stabilizing the layer against convective overturning.

Soret and Dufour Cross-Diffusion Interactions (Sr and Df)

The denominator of Equation (20) establishes a critical condition where stationary convection ceases to be physically realizable:

$$(\pi^2 + a^2)(Le - Df) + \gamma = 0 \Longrightarrow \gamma^* = (Df - Le)(\pi^2 + a^2)$$

Because $\gamma \geq 0$ for consumption reactions, this singular condition can only occur when the Dufour number exceeds the Lewis number ($Df > Le$). When $Df > Le$ and $\gamma < \gamma^*$, the denominator changes sign, indicating a transition from stationary convective overturning to an oscillatory overstable mode driven by strong diffuso-thermal feedback.

CONCLUSION

The competing physical mechanisms are explicitly captured in the analytical formulation that results:

1. In the limit $\gamma \to \infty$, first-order chemical consumption (γ) suppresses concentration perturbations, gradually separating solutal effects from the flow dynamics and bringing the system back to conventional single-component thermal convection.
2. Thermal conductivity anisotropy ($\psi > 1$) stabilises the layer through increased lateral heat dissipation, mechanical permeability anisotropy ($\xi > 1$) destabilises the layer by decreasing horizontal drag.
3. Soret cross-diffusion directly modifies the effective solutal buoyancy gradient, whereas Dufour cross-diffusion reduces the convective threshold via decreasing the coupling denominator.

REFERENCES

1. Horton, C. W., & Rogers, F. T. (1945). Convection currents in a porous medium. Journal of Applied Physics, 16(6), 367–370.
2. Lapwood, E. R. (1948). Convection of a fluid in a porous medium. Mathematical Proceedings of the Cambridge Philosophical Society, 44(4), 508–521.
3. Brinkman, H. C. (1949). A calculation of the viscous force exerted by a flowing fluid on a dense swarm of particles. Applied Scientific Research, Section A, 1(1), 27–34.
4. Nield, D. A., & Bejan, A. (2017). Convection in Porous Media (5th ed.). Springer, New York.
5. Mojtabi, A., & Charrier-Mojtabi, M. C. (2000). Double-diffusive convection in porous media. In Handbook of Porous Media (Vol. 1, pp. 559–604). Marcel Dekker, New York.

6. Epherre, J. F. (1977). Criterion for appearance of natural-convection in an anisotropic porous layer. International Chemical Engineering, 17(4), 615-616.
7. Kvernvold, O., & Tyvand, P. A. (1979). Nonlinear thermal convection in anisotropic porous media. Journal of Fluid Mechanics, 90(4), 609–624.
8. Bera, P., & Khalili, A. (2002). Double-diffusive natural convection in an anisotropic porous cavity with opposing buoyancy forces: multi-solutions and oscillations. International Journal of Heat and Mass Transfer, 45(15), 3205-3222
9. Ali, S. A., Sibanda, P., Rudziva, M., Noreldin, O. A., Goqo, S. P., & Mthethwa, H. S. (2025). Nonlinear double-diffusive convection in an anisotropic porous layer under time-dependent rotation with internal heating and Soret effect. Journal of Porous Media, 28(2).
10. Nield, D. A. (1968). Onset of thermohaline convection in a porous medium. Water Resources Research, 4(3), 553–560.
11. Weaver, J. A., & Viskanta, R. (1991). Natural convection in binary gases due to horizontal thermal and solutal gradients: Soret and Dufour effects. Heat and Mass Transfer, 26(5), 347–354.
12. Postelnicu, A. (2004). Influence of a magnetic field on heat and mass transfer by natural convection from vertical surfaces in porous media considering Soret and Dufour effects. International Journal of Heat and Mass Transfer, 47(6-7), 1467–1472.
13. Malashetty, M. S., & Gaikwad, S. N. (2002). Effect of cross-diffusion on double diffusive convection in a fluid saturated anisotropic porous layer. International Journal of Thermal Sciences, 41(9), 891–902.
14. Gaikwad, S. N., Malashetty, M. S., & Rama, S. (2007). An analytical study of linear and non-linear double diffusive convection with Soret and Dufour effects in a couple stress fluid. International Journal of Non-Linear Mechanics, 42(7), 903–913.
15. Brand, H. R., & Steinberg, V. (1983). Convective instabilities in binary mixtures with fast chemical reaction. Physical Review A, 27(2), 1065–1070.
16. Steinberg, V., & Brand, H. R. (1984). Stationary and oscillatory convection in a binary mixture with a chemical reaction. Physical Review A, 30(1), 558–566.
17. Yadav, D., Nair, S. B., Awasthi, M. K., Ragoju, R., & Bhattacharyya, K. (2024). Linear and nonlinear investigations of the impact of chemical reaction on the thermohaline convection in a permeable layer saturated with Casson fluid. Physics of Fluids, 36(1).
18. Abidin, N. H. Z., Sirat, N. F. M., Bahri, S. S. S., Azeman, S. N. A., & Yusof, Y. (2024). Temperature condition impact on the onset of Rayleigh-Benard convection in a binary fluid saturated anisotropic porous layer. Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer, 17(1), 35-46.
19. Khalid, I. K., Mohd Shukor, A. S., Ilias, M. R., Zainal Abidin, N. H., & Fayziev, B. (2026). Influence of coriolis force on controlled double-diffusive marangoni convection in nanofluid layers. *Malaysian Journal of Computing (MJoC)*, *11*(1), 6.