Numerical Study of the Electromagnetohydrodynamic Bioconvection Flow of Micropolar Nanofluid through a Stretching Sheet with Thermal Radiation and Stratification

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ABSTRACT: The current work explores the bioconvection micropolar nanofluid through a stretching surface subjected to thermal radiation, stratification, and heat and mass transmission. Bioconvection contains the gyrotactic (random movement of microorganism in the direction of gravity with weak horizontal verticity) unicellular microorganism in aqueous environments. Heat and mass transfer assists the bioconvection to occur. The aim of this research is to evaluate the heat transfer rate of nanofluid in the presence of a unicellular microorganism. Self-similar variables are induced to reduce the governing equations into a non-linear differential system which is further solved via the bvp4c algorithm to tackle the fluid problem. Using visual representations, the effects of a number of dimensional less factors arising from the dimensional less differential system are determined. For a range of limiting conditions, the obtained results of this model correspond precisely to those in the literature. This study’s findings are highly regarded in the evaluation of the impact of key design factors on heat transfer and, therefore, in the optimization of industrial processes. Skin friction, local Nusselt number, Sherwood number, and density of microorganism concentrations are also studied for various parameters. Buoyancy ratio factor supports skin friction and density of microorganism profile to increase. Local Nusselt number drops due to the thermal radiation factor. Brownian motion speeds up the Sherwood number.

1. INTRODUCTION

Improvements in heat transmission have piqued the attention of a number of technical and industrial organizations. Heat transfer efficiency has been improved using a variety of strategies. Examples include changes in flow shape, an increase in the heat capacity of working fluids, the integration of radiative heat transfer or a heat source, and a change in boundary conditions. Floating micro/nano solid particles with better thermal conductivity in the base fluid have been found in many experiments to considerably enhance heat transfer. Although solid particles’ high density, large size, and associated settling may cause clogging in microsystems, these issues can be solved by employing nanofluids with lower concentrations of tiny particles. The term nanofluid was coined by Choi in a seminal study he delivered at the ASME Winter Annual Meeting in 1995. Sub-micron-sized solid particles (nanoparticles) are dispersed in a liquid with a particle size range of 1–50 nanometers. The hybrid nanofluid containing magnesium oxide and nickel nanoparticles in the base fluid water taken for MHD stagnation point flow through a permeable elastic stretched surface in a porous medium is studied. Darcy law is imposed for the isotropic homogeneous medium, and the velocity slip condition is taken for the boundary layer. Both of the nanofluids excellently assist to enhance thermal conduction. In another study, the Cobalt oxide and Graphene nanoparticles in the base fluid water in the form of hybrid nanofluid flow through a circular elastic surface in permeable medium are investigated. This type of study has great impact on solar energy applications. Thermal conductivity and thermal transfer are two of nanofluids most distinguishing characteristics. Several methods that increase heat transfer and energy transmission in nanofluids have been explored in several articles. Wang was a pioneer in the development of Bejan's constructed approach for developing nanofluids. Thermal performance of the host fluids is enhanced using the nanoparticles, which can be constructed to have the best microstructure and thermal performance within a certain microstructure.

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In this work, the bioconvection with hydro-magnetic flow of micropolar bioconvective nanofluid is studied. Bioconvection begins when microbes congregate in the top portion of the fluid owing to the bacteria’ unstable density stratification. Bioconvection plumes form during this process, as microorganisms migrate from the top to deeper fluid zones owing to density differences. According to Kuznetsov, microbial creation and mixing in bio-microsystems can contribute significantly to mass transport elaboration and mixing. In addition, nanofluids improve heat conductivity. As both the nanofluid and microorganisms (bio-nanofluids) have a combined effect on heat transfer, the rate of heat transfer is expected to increase more significantly. Therefore, many researchers are going to explore the bioconvection phenomena with nanofluid in order to enhance their thermal stratification and stability. Kuznetsov modified the bioconvection’s idea suspended microorganism in nanofluid in the direction of oxygen region and Alsallami presented the activation energy and entropy anatomiization. These added suspensions improve the heat transfer, mixing micro-scale and used for improving the stability of nanofluid for long time. The computational assessment of hybrid nanofluid flow over a stretching surface is presented in. Oxytactic microbes are added in the peristaltic flow of a non-Newtonian nanofluid that is past in infinite co-axial conduits under a porous medium. This type of fluid is applicable in the hemodynamic structure in the human body. This is due to the fact that certain blood clotting problems, such as hemophilia, emerge when some blood components on the arterial wall are limited away from the wall connecting the circulatory system. MHD bioconvective nanofluid with mobile microorganisms is subjected to a numerical study in order to investigate its heat and mass transport capabilities. Bioconvection is made feasible by the interaction of a magnetic field with buoyancy. The stability of nanomaterials is boosted by microorganisms that display gyrotactic behavior and enhancing heat and heat transfer as well.

A bioconvection nanofluid flow across a horizontally moving plate is numerically explored for the impacts of Stefan blowing, velocity, temperature, and solutal slips. This type of models is applicable to new microbial fuel cells technologies that combine nanofluids and bioconvection. Magnetohydrodynamic stratified is discussed for the micro-polar Bioconvective nanofluid containing gyrotactic microorganism flow. Thermal radiation and Joule heating included in the model. Bioconvection phenomenon depends on the combined impacts of magnetic force and buoyancy force and is used to stabilize dispersed nanoparticles. The significance of gyrotactic bioconvection phenomena in the micropolar Maxwell type nanofluidic flow that past an extending sheet is discussed. The gyrotactic bioconvection phenomena are added in MHD Williamson Maxwell nanofluid flow past a stretchable surface in a permeable matrix sheet under the impact of activation energy. Bioconvection containing gyrotactic microbes is studied in nanofluidic squeezing flow through rotational circular plates. Similarly, bioconvection phenomena with nanofluid is presented for the chemical reaction-based flow through sheets in rotatory medium, for the non-Newtonian force with Darcy Forchheimer and electroosmosis forces, in non-Darcian micropolar fluid along various nanoparticles, in second grade nanofluid, in MHD Maxwell fluid based on SWCNTs-MECNTs types nanoparticles, and in other various fluid models in different situations.

As the electromagnetic field passes through a medium, it meets magnetic forces on moving charges and a drag (viscous) force on stationary charges. The quantity of electric field is enhanced to show the impacts on evaporation having light-driven processes taken gold, silver, and graphite type of nanoparticles. Numerical and experimental study is made for the re-dispersing nanoparticles in pool boiling created the instability in thermal transportation of nanofluid. This model electric field is induced for controlling the nanoparticle motion. Bioconvection steady nanofluid flow through the stretching sheet is taken in the existence of electric and magnetic force. Electroosmotic dissipation is observed for the electromagneto-hydrodynamic hybrid nanofluid flow that past a micro-channel. Wettability and interfacial tension have been studied taking multi-nanofluids named hybrid-nanofluid under the influence of electromagnetic force. Another beneficial research about MHD exists in literature.

Fluid mechanics in micro-channels (such as pumps and valves) have been studied using Navier–Stokes equations. There are major disparities between fluid flow at the microscale and fluid movement at the macroscale. In numerous circumstances, the traditional continuum-derived Navier–Stokes equations fail to capture microscale fluid transport processes. Because when the diameter of a channel is equal to the diameter of a molecular molecule, it obviously affects the flow field in the case of spinning of molecules and the traditional Navier–Stokes equations do not take molecular spin into account. Later, the micro-continuum theory suggested by Eringen consists of three theories: micropolar, micro-morphic, and micro-continuum. There is a microstructure included in each 3 M particle that allows it to spin and deform independently of its centroid’s movement. The micropolar theory contains an additional degree of freedom—gyration—that determines the spin of the microstructure in its formulation. For solving gyration, the angular momentum balance law is presented. For the first time, molecule spins taken into consideration. Consequently, the micropolar theory offers a possible alternative to molecular dynamics simulations for numerically solving microscale fluid dynamics, which may be much faster and more efficient. Due to the importance of micropolar flow, it is added in nanofluid flow models. For instance, Ahmad et al. used the non-Fourier theory for stagnation point micropolar fluid flow that past over stretchable surface with slip condition. Khan et al. used the bioconvection gyrotactic microbes micro-polar nanofluid through circular disk under the impacts of heat radiation and activation energy. Darcy law and thermal radiation impacts has been observed in the bioconvection micropolar nanofluid flow that past an off-centered rotating disk. Bioconvection phenomena containing gyrotactic microorganisms with micropolar nanofluid flow has been studied through a thin movable needle. The flow is under the influence of viscous dissipation, Arrhenius activation energy, and chemical reaction. Casson micropolar nanofluid flow is taken, that flow through a porous stretchable curved surface within the stagnation region.

In this work, the bioconvection with hydro-magnetic flow of micropolar nanofluid is studied. Using the bvp4c approach, the numerical solution of altered governing equations is accomplished. The key points of the flow problems are as follows:

- The Bioconvection phenomena containing gyrotactic microbes with hydro-magnetic flow of micropolar nanofluid through a stretching inclined plate is taken.
• The conventional Navier–Stokes’s equations arising from fluid model are converted into the ODE form through the addition of non-dimensional variables.

• Bvp4c technique is taken to compute the solution of the flow model successfully.

• Various parameters related to flow model are studied for momentum, energy, nanofluid concentration, motile microorganism concentration, skin friction, Nusselt number, Sherwood number, and density of microorganism concentration profiles.

• The findings are visually shown and explained properly.

2. FLOW MODEL AND ITS MATHEMATICAL FORMULATION

The main objective is to investigate the incompressible, unsteady, two dimensional, electrically conducting magneto-hydrodynamic, combine convection micropolar nanofluid which is past on a stretchable plate. Bioconvection containing gyrotactic microorganisms is added with nanofluid for the stability purpose of nanoparticles in host fluid in such a way that the swimming direction of microbes and their momentum speed is not affected due to the existence of nanofluid. The flow is assumed under the influences of Ohm’s law, thermal stratification, and thermal radiation. The Cartesian coordinates in the flow section is assumed such that the velocity \( \mathbf{u}(\mathbf{x}) = a\mathbf{x} \) is in the horizontal direction of stretching sheet, whereas \( \mathbf{y} \) located in the vertical direction said normal stretching sheet. The Bioconvection nanofluid flow is considered limited beyond the region \( \mathbf{y} > 0 \). Constant magnetic and electric forces are applied in the region of positive \( \mathbf{y} \) with strengths \( B_0 \) and \( E_0 \), respectively. Whereas local Reynold number is considered so small that is negligible to apply. Figure 1 shows the flow structure in coordinate system.

\[
\begin{align*}
\frac{\partial \mathbf{u}}{\partial \mathbf{x}} + \nu \frac{\partial \mathbf{u}}{\partial \mathbf{y}} &= 0 \\
\frac{\partial \mathbf{v}}{\partial \mathbf{x}} + \nu \frac{\partial \mathbf{v}}{\partial \mathbf{y}} &= 0
\end{align*}
\]

\[
\begin{align*}
\frac{\partial^2 \mathbf{u}}{\partial \mathbf{x}^2} + v \frac{\partial^2 \mathbf{u}}{\partial \mathbf{y}^2} + \left( \frac{\partial \mathbf{E}_0 B_0^2}{\mathbf{y}} \right) \mathbf{u} &= \left( \mathbf{\hat{u}} + \hat{k}_f \right) \frac{\partial^2 \mathbf{u}}{\partial \mathbf{y}^2} + \left[ \mathbf{\hat{u}} \right] \frac{\partial \mathbf{N}}{\partial \mathbf{y}} \\
+ \frac{1}{\hat{\mathbf{r}}_f} \left( (1 - \mathbf{\hat{C}}) (\mathbf{\hat{T}} - \mathbf{\hat{T}}_\infty) \mathbf{\hat{p}} \mathbf{\hat{g}} - \mathbf{\hat{g}} (\mathbf{\hat{r}}_f - \mathbf{\hat{r}}_f) \right) \\
&= \left( \mathbf{\hat{u}} \right) \frac{\partial^2 \mathbf{N}}{\partial \mathbf{y}^2} + \frac{\partial \mathbf{N}}{\partial \mathbf{y}} (2 \mathbf{\hat{N}} + \frac{\partial \mathbf{u}}{\partial \mathbf{y}}) &= \left( \mathbf{\hat{u}} \right) \frac{\partial^2 \mathbf{N}}{\partial \mathbf{y}^2} + \frac{\partial \mathbf{N}}{\partial \mathbf{y}} (2 \mathbf{\hat{N}} + \frac{\partial \mathbf{u}}{\partial \mathbf{y}}) \\
\frac{\partial \mathbf{T}}{\partial \mathbf{x}} + v \frac{\partial \mathbf{T}}{\partial \mathbf{y}} &= \alpha \frac{\partial^2 \mathbf{T}}{\partial \mathbf{y}^2} + \tau \left\{ \frac{D_p}{T_\infty} (\mathbf{\hat{T}} - \mathbf{\hat{T}}_\infty) \right\} + \frac{D_n}{T_\infty} \frac{\partial \mathbf{C}}{\partial \mathbf{y}} + \frac{1}{\mathbf{\hat{r}}_f} \frac{\partial \mathbf{F}}{\partial \mathbf{y}} \\
&+ \frac{\mathbf{\hat{F}}}{(\mathbf{\hat{r}}_f) \mathbf{\hat{F}}} \mathbf{\hat{T}} - \mathbf{\hat{T}}_\infty \\
\frac{\partial \mathbf{C}}{\partial \mathbf{x}} + v \frac{\partial \mathbf{C}}{\partial \mathbf{y}} &= \frac{\partial \mathbf{C}}{\partial \mathbf{y}} (\mathbf{\hat{C}} - \mathbf{\hat{C}}_\infty) = \frac{D_n}{T_\infty} \frac{\partial \mathbf{C}}{\partial \mathbf{y}} + \frac{D_n}{T_\infty} \frac{\partial \mathbf{C}}{\partial \mathbf{y}} \\
\frac{\partial \mathbf{N}}{\partial \mathbf{x}} + v \frac{\partial \mathbf{N}}{\partial \mathbf{y}} &= \frac{\partial \mathbf{N}}{\partial \mathbf{y}} \left\{ \mathbf{\hat{N}} \frac{\partial \mathbf{C}}{\partial \mathbf{y}} \right\} = \frac{D_n}{T_\infty} \frac{\partial \mathbf{C}}{\partial \mathbf{y}}
\end{align*}
\]

\( \mathbf{\hat{u}}, \mathbf{\hat{v}} \rightarrow \) components of velocity along the \((\mathbf{x}, \mathbf{y})\) direction, \( \mathbf{\hat{N}} \rightarrow \) angular velocity, \( \mathbf{\hat{T}} \rightarrow \) energy field, \( \mathbf{\hat{C}} \rightarrow \) nanofluid concentration, \( \mathbf{\hat{n}} \rightarrow \) bioconvection concentration, \( \mathbf{\hat{t}} \rightarrow \) ambient nanoparticle concentration, \( \mathbf{\hat{t}}_\infty \rightarrow \) ambient microorganism concentration, \( \mathbf{\hat{r}} \rightarrow \) electrical conduction, \( \mathbf{\hat{r}}_\infty \rightarrow \) chemical reaction coefficient, \( \tau = \frac{\langle \mathbf{\hat{r}} \mathbf{\hat{r}} \rangle_{\mathbf{\hat{r}}} \rangle_{\mathbf{\hat{r}}} \rangle_{\mathbf{\hat{r}}} \rightarrow \) effective heat content of nanoparticles to heat capacity of liquid, \( g \rightarrow \) gravitational force, \( \mathbf{\hat{Q}}_0 \rightarrow \) heat source/sink quantity, and \( \mathbf{\hat{r}} = \frac{\langle \mathbf{\hat{T}} \mathbf{\hat{T}} \rangle_{\mathbf{\hat{T}}} \rangle_{\mathbf{\hat{T}}} \rightarrow \) thermal diffusivity parameter. \( \mathbf{\hat{p}}, \mathbf{\hat{p}}_\infty, \mathbf{\hat{p}} \rightarrow \) densities of fluid, microorganism, and nanoparticle, respectively. \( \mathbf{\hat{D}}_\mathbf{p}, \mathbf{\hat{D}}_\mathbf{T}, \mathbf{\hat{D}}_\mathbf{C} \rightarrow \) diffusivities of nanofluid concentration, temperature, and microorganism concentration, \( \frac{\partial \mathbf{W}}{\partial \mathbf{y}} \rightarrow \) average velocity of microorganism swimming, in which \( \mathbf{W}_c \rightarrow \) maximum speed of swimming microorganism.

The boundary constraints are

\[
\begin{align*}
\mathbf{\hat{u}} &= \mathbf{\hat{u}}_\infty (\mathbf{x}) = a\mathbf{x} \\
\mathbf{\hat{v}} &= 0, \\
\mathbf{\hat{N}} &= 0, \\
\mathbf{\hat{T}} &= \mathbf{\hat{T}}_\infty = T_0 + b_2\mathbf{C}, \\
\mathbf{\hat{C}} &= \mathbf{\hat{C}}_\infty = C_0 + c_2\mathbf{C}, \\
\mathbf{\hat{n}} &= \mathbf{\hat{n}}_\infty = n_0 + n_2\mathbf{C}, \\
\mathbf{\hat{r}} &= \mathbf{\hat{r}}_\infty = r_0 + r_2\mathbf{C}, \\
&\text{at } \mathbf{y} \rightarrow \infty
\end{align*}
\]
Here, \( b_1,b_2,c_1,c_2,n_1 \), and \( n_2 \) are constants coefficient, \( \hat{T}_0 \rightarrow \) reference energy, \( \hat{C}_p \rightarrow \) reference density of nanofluid, \( \hat{h}_0 \rightarrow \) reference concentration of gyrotactic microbes, \( \hat{T}_w, \hat{C}_w, \hat{h}_w \rightarrow \) temperature at surface, nanoparticles concentration at surface, and microorganism concentration at the surface, respectively.

In angular velocity eq 3, the term spin gradient viscosity \( \gamma_f^* \) is defined as

\[
\gamma_f^* = \left( \mu_f^* + \frac{K_f^*}{2} \right)
\]

(8)

where \( j \rightarrow \omega \) micro-inertia-density, \( K_f^* \rightarrow \) vertex viscosity.

In eq 4, the thermal radiation is defined as

\[
q_r = 4/3 \sigma^* \hat{T}_4 \delta^* f
\]

(9)

Here, \( \sigma^* \rightarrow \) constant (Stefan–Boltzmann), \( k^* \rightarrow \) average absorption coefficient. For \( \hat{T}_4 \) Taylor expansion about \( \hat{T}_\infty \) is given as

\[
\hat{T}_4 = \hat{T}_\infty + 2(\hat{T} - \hat{T}_\infty)(2\hat{T}_\infty^3 + 3\hat{T} - 3\hat{T}_\infty) + ...
\]

(10)

2.1. Conversion of Navier–Stokes to Dimensional less Differential System. The stream function \( \psi = \psi(x,y) \) is defined as

\[
\hat{u} = \frac{\partial \psi}{\partial y}, \quad \hat{v} = -\frac{\partial \psi}{\partial x}
\]

(11)

The stream function is identically satisfying eq 1. For the given micropolar bioconvection nanofluid problem, the following similarity transformation variables are defined as

\[
\eta = -\sqrt{\frac{a}{\nu}} \quad \hat{u} = a \hat{f}'(\eta) \quad \hat{v} = -(\alpha \nu)^{1/2} f'(\eta)
\]

\[
\hat{N} = a \sqrt{\frac{a}{\nu}} g(\eta) \quad \hat{\theta}(\eta) = \frac{(\hat{T} - \hat{T}_\infty)}{\hat{T}_w - \hat{T}_\infty}
\]

\[
\phi(\eta) = \frac{(\hat{C} - \hat{C}_\infty)}{(\hat{C}_w - \hat{C}_\infty)} \quad \Psi(\eta) = \frac{(\hat{n} - \hat{n}_0)}{n_w - n_0}
\]

(12)

In order to get the non-dimensional momentum equation, substitute eqs 12 into 2 to yield the following

\[
(1 + K)\hat{f}''(\eta) - \hat{f}'(\eta)^2 - M(\hat{f}'(\eta) - \hat{E}) + f(\eta)\hat{f}'(\eta) + K\hat{g}(\eta) + \lambda(\hat{\theta}(\eta) + N\hat{\phi}(\eta) - Rb) = 0
\]

(13)

dimensional less angular velocity field is obtained through substituting eqs 12 into 3 as follows

\[
(1 + 0.5 K)\hat{g}''(\eta) - K(\hat{f}'(\eta) + 2\hat{g}(\eta)) - \hat{f}'(\eta)\hat{g}(\eta) + f(\eta)\hat{g}(\eta) = 0
\]

(14)

The dimensional less temperature distribution is obtained through substituting eqs 12 into 4 as follow

\[
(1 + 0.75 Rb)\hat{\theta}''(\eta) + Pr f(\eta)\theta'(\eta) + Pr(Nb\phi'(\eta) + Nt\varphi(\eta))\hat{\theta}'(\eta) - Pr(\theta(\eta) + S + Me\varphi'(\eta))\hat{f}'(\eta) + Pr\delta\theta(\eta) = 0
\]

(15)

The dimensional less nanoparticle concentration field is obtained through substituting eqs 12 into 5 as follows

\[
\phi''(\eta) + (\frac{Nt}{Nb})\hat{\phi}'(\eta) + Sc(f(\eta)\phi'(\eta) - f'(\eta)\phi(\eta) - Qf'(\eta)) = 0
\]

(16)

The dimensional less microorganism concentration field is obtained through substituting eqs 12 into 6 as follows

\[
\Psi''(\eta) - Lb(\Psi(\eta)\phi'(\eta) + Bf'(\eta) - \Psi(\eta)f'(\eta)) - Pr\Psi'(\eta)\phi'(\eta) = 0
\]

(17)

where

\[
Sc = \frac{\nu_j}{D_h}, \quad Pe = \frac{bW}{D_h}, \quad \lambda = \frac{Gr}{Re_x}, \quad Pr = \frac{\nu_j}{\alpha_r}, \quad M = \frac{\partial\beta_0^2}{\alpha_r^2}, \quad Lb = \frac{\nu_j}{D_m}, \quad Nt = \frac{(\dot{\beta}^*_{p,\alpha})^{(p)}}{(\dot{\beta}^*_{p,\alpha})^{(0)}} = \frac{\nu_j}{\mu_j}, \quad Gr = \frac{g\beta_{p,\alpha}(1 - \hat{C}_\infty)\Delta \hat{v}^3}{v_j^2}, \quad Nb = \frac{\nu\nu_j}{\mu_j}, \quad Gc_\alpha = \frac{g\beta(\hat{C}_w - \hat{C}_\infty)}{\rho \alpha^2}, \quad \lambda_1 = \frac{Q_0}{\alpha R_p Ec}
\]

\[
= \frac{\nu_j^2}{(\dot{\beta}^*_{p,\alpha})^{(0)}(\hat{T}_w - \hat{T}_\infty)}, \quad K = \frac{\nu_j^2}{\mu_j}, \quad S = \frac{b_1}{b_2}, \quad Q = \frac{c_2}{c_1}, \quad Nr = \frac{(\hat{\beta}_w - \hat{\beta}_0)(\hat{C}_w - \hat{C}_0)}{\beta\beta_p(\hat{T}_w - \hat{T}_0)}, \quad Re_x = \frac{\alpha_0(\hat{v})\hat{v}}{\nu}, \quad Rb = \frac{\gamma^*}{(1 - \hat{C}_\infty)(\hat{T}_w - \hat{T}_\infty)}, \quad \delta = \frac{Q_0}{\alpha(\dot{\beta}^*_{p,\alpha})^{(0)}}, \quad \Omega = \frac{n_2}{n_1}
\]

(18)

Here, \( Pe \rightarrow \) Peclet number, \( \lambda \rightarrow \) mixed convection parameter, \( Pr \rightarrow \) Prandtl number, \( Sc \rightarrow \) Schmidt number, \( Lb \rightarrow \) Lewis bioconvection number, \( Nt \rightarrow \) thermophoretic factor, \( Gr \rightarrow \) local Grashof number, \( Nb \rightarrow \) Brownian motion factor, \( Gc_\alpha \rightarrow \) modified local Grashof number, \( \lambda_1 \rightarrow \) heat generation/absorption parameter, \( Ec \rightarrow \) Eckert number parameter, \( K \rightarrow \) dimensionless vertex viscosity, \( S \rightarrow \) chemical reaction parameter, \( Q \rightarrow \) mass stratification, \( Nr \rightarrow \) buoyancy ratio parameter, \( Re_x \rightarrow \) Reynolds number, \( Rb \rightarrow \) bioconvection Rayleigh number, \( \delta \rightarrow \) \( \Omega \rightarrow \) microorganism concentration difference parameter, \( B \rightarrow \) motile density stratification, and \( E \rightarrow \) activation energy.
Their corresponding non-dimensional boundary conditions are obtained through substitute eqs 12 in 7 to yield the following
\[
\begin{align*}
g(0) &= 0, \\
f(0) &= 0, \\
f'(0) &= 1, \\
\phi(0) &= 1 - Q, \\
\theta(0) &= 1 - S, \\
\Psi(0) &= 1 - B,
\end{align*}
\]
\[f'('\eta') \rightarrow 0, \quad g('\eta') \rightarrow 0, \quad \phi('\eta') \rightarrow 0, \quad \theta('\eta') \rightarrow 0, \quad \text{as } \eta \rightarrow \infty
\]
(19)

It is noticed that to eliminate the vertex viscosity, that is, \((K = 0)\), then the micropolar effects are not included in the nanofluid model.

2.2. Physical Quantities of Interest. The physical quantities of interest for the governing flow problem are microorganism density number \((\text{Nu}_x)\)
\[\text{Nu}_x = \frac{\dot{\xi}_m}{\dot{D}_k(\eta_k - \eta_0)}
\]
Sherwood number \((Sh_x)\)
\[Sh_x = \frac{\dot{\xi}_m}{\dot{D}_k(C_w - \dot{C}_0)}
\]
Nusselt number \((\text{Nu}_x)\)
\[\text{Nu}_x = \frac{\dot{\xi}_m}{k(\dot{T}_w - \dot{T}_0)}
\]
and skin friction \((C_{f})\) are
\[C_{f} = \frac{\tau_w}{\dot{\rho}_f}
\]
where
\[q_n = -\dot{D}_k \left( \frac{\partial \phi(\eta)}{\partial \eta} \right)_{\eta \rightarrow 0}, \quad q_m = -\dot{D}_k \left( \frac{\partial \phi(\eta)}{\partial \eta} \right)_{\eta \rightarrow 0}
\]
\[q_w = \mu \left( 1 + K \right) \frac{\partial T(\eta)}{\partial \eta} \right)_{\eta \rightarrow 0}
\]
\[= \mu \left( 1 + K \right) \frac{\partial T(\eta)}{\partial \eta} \right)_{\eta \rightarrow 0}
\]
(24)
Through the self-similar transformation in eq 12, the associated physical quantities are
\[\text{Nu}_x(0) = -\frac{\Psi'(0)}{\sqrt{Re_x}}, \quad \text{Sh}_x = \phi'(0) - \frac{1}{\sqrt{Re_x}}, \quad \text{Nu}_x = -\theta'(0)\frac{1}{\sqrt{Re_x}}, \quad C_{f} = (1 + K)\sqrt{Re_x}f''(0),
\]
(25)
where \(Re_x = \frac{\dot{\xi}_m \eta}{v}\) is the Reynolds number relative to the stretching velocity.

3. NUMERICAL SOLUTION METHODOLOGY
The non-linear coupled and non-dimensional transformed ODEs eqs 13–17 along with the boundary conditions 19 are tackled numerically with the help of MATLAB built-in function “bvp-4c” solver. The leading equations are solved with a step size of \(\Delta \eta = 0.01\) which is proposed to be suitable for inner convergence condition with error tolerance \(10^{-6}\) in all cases. The asymptotically limiting condition in 19 at \(\eta \rightarrow \infty\) were stored to the domain of the problem by finite inputs of \(\eta_f\), say \(\eta_f\)finite, that is, \([0,30]\) instead of \([0,\infty]\), where no remarkable deviation in velocity distribution, fluid temperature, and concentration occurs. The nonlinear ODE system is transferred into linear first-order differential equation in order to convert the boundary value problem into initial problem. The newly defined variables are given as follows
\[f''(\eta) = \left( f'(\eta) \right)^2 + M(f'(\eta) - E) - f(\eta)g(\eta) - \lambda g(\eta) - \lambda(\theta(\eta) + N\phi(\eta) - Rd) \right)
\]
\[\left( 1 + K \right)
\]
\[g''(\eta) = \frac{K(f''(\eta) + 2g(\eta)) + f'(\eta)g(\eta) - f(\eta)g'(\eta)}{(1 + 0.5K)}
\]
\[\left( 1 + 0.75Rd \right)
\]
\[\left( 1 + 0.75Rd \right)
\]
\[\phi''(\eta) = -N_{f}\frac{\Psi'(\eta) - \lambda g(\eta) - \lambda(\phi(\eta) + N\phi(\eta) - Rd))}{\Psi(\eta) + J(q''(\eta))}
\]
\[\frac{\Psi(\eta) + J(q''(\eta))}{\Psi(\eta) + J(q''(\eta))}
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\[\frac{\Psi(\eta) + J(q''(\eta))}{\Psi(\eta) + J(q''(\eta))}
\]
\[\frac{\Psi(\eta) + J(q''(\eta))}{\Psi(\eta) + J(q''(\eta))}
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\[\frac{\Psi(\eta) + J(q''(\eta))}{\Psi(\eta) + J(q''(\eta))}
\]
\[\frac{\Psi(\eta) + J(q''(\eta))}{\Psi(\eta) + J(q''(\eta))}
\]
\[\frac{\Psi(\eta) + J(q''(\eta))}{\Psi(\eta) + J(q''(\eta))}
\]
\[
\gamma_{i}^{'}(\eta) = \left( \frac{-Pr(\gamma_{i}^{'} - Pr(Nb\gamma_{i} + Nt\gamma_{i})\gamma_{i})}{1 + 0.75Rd} + Pr(\gamma_{i}^{'} - S - M Ec\gamma_{i}^{'} - Pr \delta\gamma_{i}) \right) \frac{(1 + 0.75Rd)}{1 + 0.75Rd} \]
\[
\gamma_{i}^{'} = \left( \frac{-Pr(\gamma_{i}^{'} - Pr(Nb\gamma_{i} + Nt\gamma_{i})\gamma_{i})}{1 + 0.75Rd} + Pr(\gamma_{i}^{'} - S - M Ec\gamma_{i}^{'} - Pr \delta\gamma_{i}) \right) \frac{(1 + 0.75Rd)}{1 + 0.75Rd} \]
\[
\gamma_{i}^{'} = \left( \frac{-Pr(\gamma_{i}^{'} - Pr(Nb\gamma_{i} + Nt\gamma_{i})\gamma_{i})}{1 + 0.75Rd} + Pr(\gamma_{i}^{'} - S - M Ec\gamma_{i}^{'} - Pr \delta\gamma_{i}) \right) \frac{(1 + 0.75Rd)}{1 + 0.75Rd} \]
\[
\gamma_{i}^{'} = \left( \frac{-Pr(\gamma_{i}^{'} - Pr(Nb\gamma_{i} + Nt\gamma_{i})\gamma_{i})}{1 + 0.75Rd} + Pr(\gamma_{i}^{'} - S - M Ec\gamma_{i}^{'} - Pr \delta\gamma_{i}) \right) \frac{(1 + 0.75Rd)}{1 + 0.75Rd} \]

(34)

\[
\gamma_{i}^{'} = \left( \frac{-Pr(\gamma_{i}^{'} - Pr(Nb\gamma_{i} + Nt\gamma_{i})\gamma_{i})}{1 + 0.75Rd} + Pr(\gamma_{i}^{'} - S - M Ec\gamma_{i}^{'} - Pr \delta\gamma_{i}) \right) \frac{(1 + 0.75Rd)}{1 + 0.75Rd} \]

(35)

\[
\gamma_{i}^{'} = \left( \frac{-Pr(\gamma_{i}^{'} - Pr(Nb\gamma_{i} + Nt\gamma_{i})\gamma_{i})}{1 + 0.75Rd} + Pr(\gamma_{i}^{'} - S - M Ec\gamma_{i}^{'} - Pr \delta\gamma_{i}) \right) \frac{(1 + 0.75Rd)}{1 + 0.75Rd} \]

(36)

with corresponding boundary conditions in the bvp-4c approach as

\[
\gamma_{i}(1) = 0, \quad \gamma_{i}(2) = 1, \quad \gamma_{i}(4) = 0, \quad \gamma_{i}(6) = 1 - S, \quad \gamma_{i}(8) = 1 \quad \gamma_{i}(10) = 1 - B, \quad \gamma_{i}(2) = 0, \quad \gamma_{i}(4) = 0, \quad \gamma_{i}(6) = 0, \quad \gamma_{i}(8) = 0, \quad \gamma_{i}(10) = 0 \]

(37)

Taking into account both

\[
f''(\eta) = \gamma_{i}^{'}(\eta), \quad g''(\eta) = \gamma_{i}^{'}(\eta), \quad \theta''(\eta) = \gamma_{i}^{'}(\eta), \quad \phi''(\eta) = \gamma_{i}^{'}(\eta), \quad \xi''(\eta) = \gamma_{i}^{'}(\eta) \]

(38)

4. RESULT INTERPRETATION

To scrutinize the effect of various governing parameters arising in the micropolar-type nanofluidic flow problem, the non-dimensional velocity \( f'(\eta) \), angular velocity \( g'(\eta) \), the non-dimensional temperature \( \theta(\eta) \), the non-dimensional concentration \( \phi(\eta) \), and the motile density \( \Psi(\eta) \) profiles are graphically illustrated in Figures 2−39. These Figures describe the different values of micropolar constant \( K \), Prandtl number \( Pr \), magnetic number \( M \), mixed convection parameter \( \lambda \), Grashof number \( Gr \), heat generation coefficient \( \delta \), Reynolds number \( Re \), bioconvection Peclet and Lewis numbers \( Pe, Lb \), microorganism concentration difference factor \( \Omega \), motile density stratification \( B \), mass stratification, and thermal stratification parameters \( Q, S \) in these \( f'(\eta), g'(\eta), \theta(\eta), \phi(\eta), \Psi(\eta) \) profiles. The impact of magnetic field parameter on velocity profile is seen in Figure 2. It is demonstrated that the velocity profile and the thickness of the boundary layer (BL) are both reduced in response to a minor increase in the magnetic field, providing more evidence for the regular convection of the magnetic field effect. The fluid velocity is lowered due to significant Lorentz force that hampers the flow of the fluid. For this reason, it can be proven that as \( M \) becomes larger, the value of \( M \) slows down the velocity because the drag force generated by the magnetic effect drop the velocity field. It can be seen in Figure 3 that enhancing material parameter \( K \) increases the flow field \( f'(\eta) \), resulting an increase in resistance causing a declining effect in velocity profile. Figure 4 displays the impacts

Figure 2. Magnetic parameter impacts on velocity.

Figure 3. Vortex viscosity factor effect on the velocity profile.

Figure 4. Mixed convection factor \( \lambda \) for the velocity profile.

Figure 5. Buoyancy ratio factor \( Nr \) for the velocity field.
of mixed convection factor ($\lambda$) on velocity field. It is perceived that the associated boundary layer (BL) thickness and the fluid velocity greater by gradually growing the range of convection parameter. Combine convection parameter ($\lambda$) is directly proportional to buoyancy force, which means an increase in one parameter causes an increment in other and that is why the speed of the flow is higher in the fluid regime. Figure 5 displays the influence of buoyancy ratio parameter for the flow field which is seen as an altered behavior for different values of ($Nr$). From the graphical illustration, it can be seen that increasing the range of ($Nr$) diminishes the $f'(\eta)$ shape. Buoyancy effect might rise in the case when the particles and fluid densities are considerably different. The particles may either sink or float causing changes in their stability and hence may disturb the velocity of nanofluid flow. Figure 6 depicts the change in velocity profile caused by an increase in the bioconvection Rayleigh number ($Rb$). The buoyancy force increases as ($Rb$) increases, causing a retardation effect in the velocity of the fluid. Figure 7 shows the influence of thermal stratification ($S$) parameter on $f'(\eta)$ profile. In the lower regime the fluid density enhances rapidly compared to upper regime when the values of ($S$) escalates. It causes a decreasing effect in the velocity field $f'(\eta)$.
by reducing the convective flow between the ambient flow and the surface. The effect of material parameter ($K$) on angular field $g(\eta)$ velocity is elucidated in Figure 8. The curvature of effect of this graphical illustration indicates that $g(\eta)$ is enhanced for the enhancing values of ($K$). It is because acclivity in the material parameter produces an increase in the nanofluid viscosity, causing the angular flow speed $g(\eta)$ to increase. In Figure 9, the angular velocity $g(\eta)$ is explored for the influence of magnetic field number ($M$). The non-dimensional rotational field velocity $g(\eta)$ diminishes by escalating the values of magnetic number. An increase in the magnetic force ($M$) physically signifies an increment in the drag force, is an opposite force due to which the angular velocity is reduced. The variation in velocity field profile $f'(\eta)$ via an electric parameter ($E1$) is shown in Figure 10. The velocity function is increasing by enhancing the electric parameter. The electric field works as a reducing force, lowering the frictional strength of the fluid and thus enhancing the fluid velocity. Figures 11−20 represents the graphical results of various parameters on non-dimensional temperature profile $\theta(\eta)$ simultaneously. The plot for material parameter ($K$) on temperature $\theta(\eta)$ field is carried out in Figure 11. It can be observed from the graphical presentation that enhancement in ($K$) causes a depreciation in the fluid temperature $\theta(\eta)$ profile.
Figure 12. Brownian motion $Nb$ for energy distribution.

Figure 19. Impact of $E1$ for temperature profile.

Figure 20. Microbe’s densities difference factor for temperature distribution.

Figure 18. Brownian motion $Nb$ for energy distribution.

Figure 21. Impact of vortex viscosity $K$ for nanofluid concentration $\phi(\eta)$.

Figure 22. Eckert number $Ec$ for $\phi(\eta)$.

Figure 23. Thermal radiation $Rd$ effect for nanofluid $\phi(\eta)$.

Figure 21. Impact of buoyancy ratio $(Nr)$ parameters on temperature profile $\theta(\eta)$. Graphical representation shows that increasing factor $(Nr)$ causes the energy profile to enhance. The non-dimensional temperature $\theta(\eta)$ field is enhanced by increasing the thermal radiation factor $(Rd)$, as depicted in Figure 13. The result reveals that even with a slight change in thermal radiation bases a large change in energy profile in the associated boundary-layer formulation. The impact of thermal stratification $(S)$ parameter on energy $\theta(\eta)$ field is depicted in Figure 14. In comparison to the upper region, an increase in heat stratification improves the nano-fluid density in the inferior section. As a result, the difference in temperature among the heated exterior and ambient declines, which produces depreciation in the energy field of the nano-fluid. The dissimilarity in the non-dimensional energy profile $\theta(\eta)$ with respect to thermal cohort constant $(\delta)$ is enhanced gradually, as shown in Figure 15. The heat source factor physically releases energy into the fluid, enhancing the energy of the fluid. The impact of viscous dissipation factor such that Eckert number $(Ec)$ on the non-dimensional energy $\theta(\eta)$ field is illustrated in Figure 16. It may be seen that enhancing the range of $(Ec)$ number leads to upsurge energy field of the fluid.
throughout the boundary region. The ratio of the kinetic energy to enthalpy is known as Eckert number ($Ec$). However, the effect of ($Ec$) on the $\theta(\eta)$ profile is perceived only due to the enhancing trend of joule and viscous dissipation. Heat formation is due to the friction between two vicinal electrically conducting fluid boundary layers in the case Ohmic heating and viscous process as a result of dissipation effects, and hereby, the fluid temperature enhances. Figure 17 portrays the effect of various values of thermophoretic factor ($Nt$) on energy $\theta(\eta)$ field. It can be shown that parameter ($Nt$) has an enhancing effect on temperature field distribution. As a result, the thickness of the thermal boundary layer (TBL) improves considerably. The increase in ($Nt$) is physically due to an improvement in the thermophoretic process. Thermophoresis is a sort of particle mobility that occurs when heat gradients are applied and it is closely related to the Soret effect. Due to particle diffusion mediated by the thermophoretic effect, within the boundary layer, the heated particles transfer heat from the warmer to the colder areas. The fluid’s temperature therefore skyrocket.

**Figure 24.** Schmidt number $Sc$ for nanofluid density profile $\phi(\eta)$.

**Figure 25.** Thermophoresis effect $Nt$ for $\phi(\eta)$.

**Figure 26.** Brownian motion $Nb$ for $\phi(\eta)$.

**Figure 27.** Mass stratification $Q$ for nanofluid density $\phi(\eta)$.

**Figure 28.** Impact of vortex viscosity $K$ for $\psi(\eta)$.

**Figure 29.** Magnetic factor $M$ for $\psi(\eta)$. 
them to accelerate. Figure 18 illustrates the energy $\theta(\eta)$ outline for disparate range of Brownian motion factor ($Nb$). It is depicted graphically that the raise in ($Nb$) leads to an increase in the energy of the fluid. This phenomenon exemplifies an increment of Brownian motion, which exhibits the zigzag movement of particles swaying in the fluid. As result of the increased collision between fluid particles, increasing Brownian motion significantly increases temperature throughout the boundary layer. Figure 19 revealed that the increment of electric parameter ($E1$) results in depreciation of temperature field $\theta(\eta)$ at a particular point of the flow regime. The reason is that reducing of the thermal boundary layer (TBL) wideness through the enhancement of the electric parameter. The results have depicted those larger values of ($E1$) will generate a lower heat transfer effect. In Figure 20, the influence of microbe's concentration difference ($\Omega$) factor on a non-dimensional energy field $\theta(\eta)$ distribution is examined. It is noted that the upsurge in ($\Omega$) factor results a declination effect in temperature.
Figures 21−27 represent the graphical results of various parameters on non-dimensional concentration profile \( \phi(\eta) \). The time interval between rising and falling in a curve is relatively short. As a result, with growing range of the radiation factor, a shorter but incremental trend is observed. The concentration behavior via altered values of Schmidt number \((Sc)\) is given in Figure 24. Ratio between viscosity and mass diffusivity is termed as Schmidt number \((Sc)\). Because the mass diffusion function is against the Schmidt number, that is why enhancing the range of \((Sc)\) takes a reduction in mass-diffusion as consequence of nanoparticles density \(\phi(\eta)\) declined. The influence of thermophoresis factor \((Nt)\) on nanofluid density behavior \(\phi(\eta)\) is depicted in Figure 25. An increasing trend is observed for \((Nt)\) via \(\phi(\eta)\). Larger values of thermophoresis parameter improve the movement of particles and it drastically enhances the concentration behavior. Figure 26 shows the Brownian motion influence against the nanofluid concentration field. Higher magnitude results in a lower concentration behavior and vice versa. In the boundary layer (BL), Brownian motion may increase the temperature of the fluid and exacerbate the particles that are outside the fluid regime, leading to a drop in the concentration boundary layer profile \(\phi(\eta)\). When the values of mass stratification \((Q)\) factor increase, it lessens the absorption boundary-layer behavior and the related BLT as displayed in Figure 27. Figures 28−39 represent the graphical results of various parameters on motile density profile \(\Psi(\eta)\), respectively. Figure 28 depicts the decline impact on motile density profile \(\Psi(\eta)\) due to the increasing range of material parameter \((K)\). Figure 29 is presented to examine the \(\Psi(\eta)\) field for the escalating range of magnetic factor \((M)\). The curve of the graph reflects an increase in motile density behavior. In Figure 30, both the related boundary layer thickness (BLT) and motile density profile are enhanced by accumulative range of parameter \((Pr)\). The influence of combine convective \((\lambda)\) factor on the unicellular microbes’ density \(\Psi(\eta)\) field is depicted in Figure 31. It is evident that \(\Psi(\eta)\) gets decreased for enhancing the values of mixed convection parameter. As the ratio between buoyancy force and viscous force is mixed convection by means of increasing \((\lambda)\) has a tendency to reduce motile density behavior. Figure 32 is sketched to view the variational change in motile density \(\Psi(\eta)\) profile via buoyancy ratio \((Nr)\) factor. \((Nr)\), escalates the \(\Psi(\eta)\) profile when it governs throughout the domain. The increase in fluid density occurs because the buoyancy ratio \((Nr)\) has direct relation with solutal buoyancy force. Figure 33 is depicted to illustrate the Schmidt \((Sc)\) number’s inverse impact on microbe’s density profile \(\Psi(\eta)\). Figure 34 is arranged to demonstrate the influence of

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**Figure 36.** Brownian motion \(Nb\) for the microorganism concentration profile \(\psi(\eta)\).

**Figure 37.** Lewis number \(Lb\) for \(\psi(\eta)\).

**Figure 38.** Motile density stratification \(B\) for concentration \(\psi(\eta)\).

**Figure 39.** Peclet number \(Pe\) for \(\psi(\eta)\).
thermophoresis \((Nt)\) factor over density of microbe’s \(Ψ(η)\) field. An acclivity curve behavior in \((Nt)\) yields an increase in the \(Ψ(η)\) profile. The gradually and slowly escalating rang of mass stratification \((Q)\) factor increase the behavior of microbe’s density field \(Ψ(η)\) as portrayed in Figure 35. The impact of Brownian motion \((Nb)\) factor on motile density \(Ψ(η)\) profile is depicted in Figure 36. An increase in the \((Nb)\) parameter results in a decrease in the \(Ψ(η)\) profile of fluid due to an increase in the irregular motion of nanofluid’s nanoparticle particles. Figure 37 illustrates to highlight the microbe density \(Ψ(η)\) profile for various values of the bioconvection Lewis \((Lb)\) number. Higher magnitude of \((Lb)\) number indicates a decrease in diffusion of microbes and so a reduction is observed in the density profile. Figure 38 illustrates to highlight the motile density \(Ψ(η)\) profile

Table 1. Comparison of Drag Force and Micro-Rotational Results with Existing Literature, \(^{32}\) when \(Ec = 0.02, δ = 0.1, Nb = 0.1, Q = 0.1, Pr = 1.2, Nt = 0.1, \Ω = 0.2, Sc = 0.2, E1 = 0.1, B = 0.1, \) and \(Rd = 1.0\)

| \(M\) | \(K\) | \(Λ\) | \(Nr\) | \(Rb\) | \((C_JRe_x)\) \(\text{(present results)}\) | \((C_JRe_x)\) \(\text{(compared results)}\) | \(g'(0)\) \(\text{(present results)}\) | \(g'(0)\) \(\text{(compared results)}\) |
|---|---|---|---|---|---|---|---|---|
| 0.05 | 0.2 | 0.1 | 0.1 | 0.1 | 1.0468 | 0.909737 | 0.0926 | 0.094997 |
| 0.5 | | | | | 1.2823 | 1.114376 | 0.1014 | 0.105090 |
| 1.0 | | | | | 1.4849 | 1.287152 | 0.1079 | 0.112061 |
| 0.0 | | | | | 1.2889 | 1.414216 | 0.1021 | 0 |
| 1.0 | | | | | 1.1446 | 1.140786 | 0.1915 | 0.211162 |
| 2.0 | | | | | 0.7761 | 0.769757 | 0.3217 | 0.358664 |
| 0.1 | | | | | 1.2823 | | 0.1014 | |
| 0.3 | | | | | 1.2404 | | 0.0993 | |
| 0.5 | | | | | 1.1999 | | 0.0974 | |
| 0.1 | | | | | 1.2904 | | 0.1020 | |
| 0.3 | | | | | 1.3068 | | 0.1033 | |
| 0.5 | | | | | 1.3232 | | 0.1046 | |
| 0.1 | | | | | 1.2860 | | 0.1015 | |
| 2.0 | | | | | 1.2936 | | 0.1017 | |
| 4.0 | | | | | 1.3011 | | 0.1020 | |

Table 2. Numerical Values of the Local Nusselt Number for Various Factors when \(Rb = 0.1, Nr = 0.1, \Ω = 0.2, \Lambda = 0.1, Sc = 0.2, E1 = 0.1, \) and \(B = 0.1\)

| \(M\) | \(K\) | \(Rd\) | \(S\) | \(δ\) | \(Nb\) | \(Ec\) | \(Nt\) | \(Q\) | \(Pr\) | \(\theta'(0)\) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.05 | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 1.2 | 1.9394 | 1.2909 |
| 0.5 | | | | | | | | 1.2079 | 1.2909 |
| 1.0 | | | | | | | | 1.3435 | 1.4075 |
| 0.0 | | | | | | | | 1.0 | 0.9746 |
| 1.0 | | | | | | | | 0.8173 | 0.7232 |
| 2.0 | | | | | | | | 1.1358 | 1.2395 |
| 3.0 | | | | | | | | 1.1878 | 1.1627 |
| 0.1 | | | | | | | | 1.1040 | 1.0197 |
| 0.2 | | | | | | | | 1.2767 | 1.2462 |
| 0.3 | | | | | | | | 1.2159 | 1.2159 |
| 0.1 | | | | | | | | 1.2515 | 1.2297 |
| 0.2 | | | | | | | | 1.2078 | 1.2297 |
| 0.3 | | | | | | | | 1.2763 | 1.2763 |
| 0.02 | | | | | | | | 1.2474 | 1.2474 |
| 0.1 | | | | | | | | 1.2190 | 1.2190 |
| 0.5 | | | | | | | | 1.3842 | 1.3842 |
| 1.0 | | | | | | | | 1.3883 | 1.3883 |
| 2.0 | | | | | | | | 1.3925 | 1.3925 |
| 3.0 | | | | | | | | 1.9133 | 1.9133 |
| 4.0 | | | | | | | | 3.3300 | 3.3300 |

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4.1. Drag Force Physical Quantity and Micro-Rotational Factor. The impact of several different factors on the skin friction coefficient \( (C_f R_e) \) and microrotation parameter \( (g'(0)) \) is presented in Table 1. It is visualized that for the gradually increasing values of magnetic number \( (M) \), Bioconvection Rayleigh number \( (Rb) \), the buoyancy ratio parameter \( (Nr) \), and both the skin friction coefficient \( (C_f R_e) \) and microrotation parameter \( (g'(0)) \) are enhanced, while the micropolar parameter \( (K) \) and mixed convection parameter \( (\lambda) \) are reducing via skin friction and microrotation behavior simultaneously.

4.2. Nusselt Number. The impact of several different factors on the Nusselt number \( (Nu R_e^{1/2}) \) is presented in Table 2. It is observed that the Prandtl number \( (Pr) \), micropolar parameter \( (K) \), and mass stratification parameter \( (\Omega) \) cause the enhancement in local Nusselt number. While on the other side, the Nusselt number declined for an enhancement in each of the thermal stratification \( (S) \), heat generation coefficient \( (\delta) \), magnetic number \( (M) \), thermophoretic parameter \( (Nt) \), Brownian motion parameter \( (Nb) \), and the Eckert number \( (Ec) \).

4.3. Sherwood Number. The influence of various parameters on the local Sherwood number \( (Sh R_e^{1/2}) \) is presented in Table 3. It is observed from the table that an increase in heat generation coefficient \( (\delta) \), Schmidt number \( (Sc) \), thermal stratification parameter \( (S) \), and the Brownian-faction \( (Nb) \) causes an escalating effect in mass transfer, while an conflicting influence is observed for the increasing range of the mass stratification factor \( (Q) \) and the thermophoresis motion factor \( (Nt) \).

4.4. Density Number. The impact of various factor on the local density \( (Nn R_e^{1/2}) \) is illustrated in Table 4. The tabulated form of results influence that gradually escalating values of bioconvection Lewis number \( (Lb) \), microorganism density difference \( (\Omega) \), and Schmidt number \( (Sc) \) effects gave an increase in the concentration of microbes, while the opposite trend is observed for escalating range of buoyancy ratio factor \( (Nr) \), Rayleigh number \( (Rb) \), Schmidt number \( (Sc) \), concentration of microbe’s stratification \( (B) \), and bioconvection Peclet number \( (Pe) \). The graphical representation of these physical interest parameters is depicted in Figures 40–47.

### Table 3. Numerical Values of the Local Sherwood Number for Different Quantities when \( K = 0.2, M = 0.2, Rb = 0.1, Pr = 1.2, Nr = 0.1, \Omega = 0.2, \lambda = 0.1, E1 = 0.1, B = 0.1, \) and \( Rd = 1.0 \)

| \( S \) | \( \delta \) | \( Ec \) | \( Sc \) | \( Nr \) | \( Q \) | \( Nb \) | \( \phi'(0) \) |
|---|---|---|---|---|---|---|---|
| 0.2 | 0.1 | 0.02 | 0.1 | 0.1 | -0.0477 |
| 0.6 | 0.1 | 0.02 | 0.1 | 0.1 | -0.0389 |
| 0.2 | 0.02 | 0.1 | 0.1 | 0.1 | -0.0477 |
| 0.3 | 0.02 | 0.1 | 0.1 | 0.1 | -0.0389 |
| 0.2 | 0.02 | 0.1 | 0.1 | 0.1 | -0.0429 |
| 0.3 | 0.0518 | 0.1 | 0.1 | 0.1 | -0.0429 |
| 0.4 | 0.0653 | 0.1 | 0.1 | 0.1 | -0.0429 |
| 0.5 | 0.1713 | 0.1 | 0.1 | 0.1 | -0.0429 |
| 0.6 | 0.2702 | 0.1 | 0.1 | 0.1 | -0.0429 |
| 0.2 | 0.01 | 0.1 | 0.1 | 0.1 | -0.0449 |
| 0.02 | 0.1 | 0.1 | 0.1 | 0.1 | -0.0449 |
| 0.03 | 0.2 | 0.1 | 0.1 | 0.1 | -0.0449 |

### Table 4. Local Concentration of Microbes for Various Quantities is \( K = 0.2, M = 0.2, \delta = 0.1, Nb = 0.1, Q = 0.1, S = 0.1, Pr = 1.2, Nt = 0.1, \lambda = 0.1, E1 = 0.1, \) and \( Rd = 1.0 \)

| \( Rb \) | \( Ec \) | \( \Omega \) | \( Sc \) | \( Nr \) | \( Lb \) | \( B \) | \( Pe \) | \( \Psi(0) \) |
|---|---|---|---|---|---|---|---|---|
| 0.1 | 0.02 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.9868 |
| 2.0 | 0.02 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.9858 |
| 4.0 | 0.02 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.9847 |

This exploration discussed the MHD flow of Bioconvection micropolar nanofluid comprising gyrotactic microbes under the effects thermal radiation, stratification, and viscous dissipation. The flow is past on a stretching surface within the porous medium. This model is investigated via numerical scheme bvp4c solver.

Several significant findings show briefly the effects of leading parameters, as outlined below:

- Velocity profile drops with the high range of buoyancy ratio parameter, magnetic field, bioconvection Rayleigh number, and chemical reaction parameter, whereas it is enhanced due to dimensionless vertex viscosity, electric parameter, and heat generation coefficient.
- Angular velocity drops with magnetic parameter, whereas it rises with material parameter.
Figure 40. Variation of $f''(0)$ with $M$.

Figure 41. Variation of $f''(0)$ with $K$.

Figure 42. Variation of $\theta'(0)$ with $Pr$.

Figure 43. Variation of $\theta'(0)$ with $Rd$.

Figure 44. Variation of $\phi'(0)$ with $Sc$.

Figure 45. Variation of $\phi'(0)$ with $Nb$. 
The local Nusselt number decreases with magnetic parameter, thermal radiation parameter, and Brownian motion factor.

Sherwood number escalated with the thermal stratification, heat generation, Eckert number, and Schmidt number, but diminishes due to the increasing range of mass stratification, and Brownian motion factor.

Density of microorganism evaluated with buoyancy ratio parameter and Eckert number and decreased with bioconvection Rayleigh number, Schmidt number, buoyancy ratio parameter, and Peclet number.

The flow problem is applicable in bio-engineering and technologies, especially used in pharmaceutical industry, biological polymer synthesis, biological polymeric solution, and biological lubricant fluids.

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**NOMENCLATURE**

\( \bar{u}, \bar{v} \)
velocity components in \((\hat{x}, \hat{y})\) directions [m/s]

\( \bar{u}_\infty = a_0 \hat{x} \)
velocity of free stream

\( \mu_c = a_\xi \)
velocity at plate

\( E_0 \)
constant electric force

\( T, T_\infty \)
fluid temperature [K], temperature at plate

\( T_\infty, T_\infty \)
ambient temperature

\( B_0 \)
constant magnetic field,

\( N_\eta \)
angular velocity

\( \hat{C}, \hat{C}_\infty \)
nanofluid concentration [mol/m³], Ambien nanofluid concentration
\[ \dot{n}_s, \text{ bioconvection concentration} \]
\[ \dot{n}^{\infty}_s, \text{ ambient microbe concentration} \]
\[ \tau = \left( \frac{\dot{\rho}}{\dot{\rho}^*} \right), \text{ effective heat capacity of nanoparticles to heat capacity of liquid} \]
\[ Q_{\text{m}}, \text{ coefficient of heat source/sink for temperature-dependent mass transfer at wall} \]
\[ \frac{kT}{\Delta C}, \text{ average velocity of microbes} \]
\[ \tilde{D}_B, \tilde{D}_p, \tilde{D}_T, \text{ nano-fluid concentration diffusion, temperature diffusion, and motile microbe concentration} \]
\[ q_r, \text{ radiative heat flux [kg m}^{-1} \text{s}^{-1} \text{K}] \]
\[ Q, \text{ mass stratification} \]
\[ \lambda, \text{ combine convection parameter} \]
\[ S, \text{ chemical reaction factor} \]
\[ S_c, \text{ Schmidt number} \]
\[ L_b, \text{ bioconvection Lewis number} \]
\[ E, \text{ activation energy} \]
\[ C_{\text{fis}}, \text{ local skin friction coefficient} \]
\[ N_{\text{Re}}, \text{ local Reynolds number} \]
\[ N_{\text{Hu}}, \text{ Nusselt number} \]
\[ Pr, \text{ Prandtl number} \]
\[ N_r, \text{ Buoyancy ratio parameter} \]
\[ R = \frac{16\rho' k'}{3k}, \text{ thermal radiation coefficient} \]
\[ R_{\text{by}}, \text{ bioconvection Rayleigh number} \]
\[ f, \text{ dimensionless stream function} \]
\[ k, \text{ thermal conductivity [W m}^{-1} \text{K}^{-1}] \]
\[ k^*, \text{ Rosseland mean absorption coefficient [m}^{-1} \text{]} \]
\[ N_{\text{It}}, \text{ thermostophoresis parameter} \]
\[ Re, \text{ Reynolds number} \]
\[ B, \text{ motile density stratification} \]
\[ Sh_{\text{f}}, \text{ local Sherwood number} \]

**GREEK SYMBOLS**

- \( \varphi \): stream function [m$^2$ s$^{-1}$]
- \( \alpha \): thermal diffusivity [m$^2$ s$^{-1}$]
- \( \xi \): similarity variable
- \( \gamma_f \): spin gradient viscosity
- \( \eta_f \): kinematic viscosity of fluid [kg m/s]
- \( \bar{\mu} \): dynamic viscosity of nanofluid [m$^2$/s]
- \( \rho \): density [kg m$^{-3}$]
- \( \nu_{\text{had}} \): coefficient of kinematic viscosity of hybrid nanofluid
- \( \sigma^* \): Boltzmann constant [J/K]
- \( \varepsilon \): specific heat capacity nanofluid [J/kg K]
- \( \theta \): dimensionless temperature
- \( \phi \): dimensionless nano-fluid concentration
- \( \Psi \): dimensionless bioconvection concentration

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