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A brief Literature survey pertaining to Bio- Convection

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The first detailed observations of bioconvection were carried out at the beginning of this century by Wager (1911) but the subject was not taken up again until the work of Platt (1961), who apparently coined the term `bioconvection'. Plesset and Winet (1974) made some measurements of the wavelengths of the bioconvection patterns at the onset of instability in a suspension of the ciliate, Tetrahymena pyriformis, which is negatively gravitactic (but not apparently gyrotactic (Kessler 1985*a*)) and showed agreement with the linear stability theory for a layer of dense fluid overlying a layer of light fluid. Kessler (1985*a*) demonstrated that many swimming micro-organisms are gyrotactic and made observations (Kessler 1985*b*) of both the almost regular patterns that occur in concentrated algal suspensions in shallow layers a few millimeters deep, and of gyrotactic plume formation in a tall narrow cylindrical tube.

Childress *et al.* (1975) modeled bioconvection for upswimming cells in the absence of gyrotaxis and used the model to predict the wavelengths of the initial instabilities. Their analysis predicted large pattern wavelengths limited only by the size of the experimental apparatus. At any point in space, a population of microorganisms has a random distribution of possible swimming directions, characterized by an average swimming direction and a direction- and flow-dependent diffusivity tensor.

In Pedly et al [1988] a continuum model for bioconvection in a suspension of swimming gyrotactic microorganisms is formulated. The formulation includes the Navier-Stokes equation for an incompressible fluid and the micro organisms conservation equation.

Using the continuum model of Pedley et al [1988], Ghorai and Hill [1999,2000] introduced stream function vorticity formulation. This made the problem more suitable for a numerical analysis. The cases with different initial conditions are compared for different width-to-height ratios of the deep chamber.

Kessler (1985, 1986) demonstrated experimentally as well as theoretically that gravitactic algal cells can be reoriented in a shear flow for balance between the viscous torque due to shear stress and the gravitational torque resulting from the asymmetrical mass distribution within the cell body. He argued that this orientation, termed 'gyrotaxis', causes bottom-heavy cells to swim away from regions of up flow toward those of down flow. This results in an accumulation of cells in the regions of down flow, which makes these regions denser than the ambient suspension, and thus increases the rate of down flow. This is an alternative mechanism for inducing a spontaneous growth of density fluctuation even in the absence of a global vertical density gradient. There have been several intensive theoretical analyses of this mechanism, leading to a quantitative model to explain the onset of the gyrotactic convection and also its initial pattern spacing (Kessler, 1986; Pedley et al., 1988; Hill et al., 1989; Pedley and Kessler, 1990).

A deterministic model for gyrotactic bioconvection using a constant diffusivity was first analyzed in layers of infinite and finite depth by Pedley *et al.* (1988) and Hill *et al.* (1989), respectively, and more realistic wavelengths were predicted. This model was further extended in a completely self-consistent fashion by Pedley and Kessler (1990) and Bees (1996), who modeled bioconvection using a probability distribution function for the cell swimming direction in a stochastic formulation of gyrotaxis. In all these works, it was found that the gyrotactic instability mechanism depends on the absolute cell concentration, unlike the overturning instability which depends on the gradient of the cell concentration.

Bees and Hill (1997) studied the wavelengths of biogonvection patterns and observed that bioconvection occurs as the result of the collective behavior of many micro-organisms swimming in a fluid and is realized as patterns similar to those of thermal convection which occur when a layer of water is heated from below. A methodology is developed to record the bioconvection patterns that are formed by aqueous cultures of the single-celled alga Chlamydomonas nivalis. The analysis that is used to quantify the patterns as a function of cell concentration, suspension depth and time is described and experimental results are presented.

Ja:nosi et al (1998) studied the onset of biogonvection in suspension of Bacillus subtilus and they observed that bioconvection occurs when upward swimming micro-organisms generate gravitational energy that initiates and maintains dissipative movement of the water in which they swim. Advection, and motion of the organisms relative to the fluid, generate patchiness in concentration that drives and shapes the geometry and rate of convection. The study presents a method for quantitatively analyzing the development of self-organization, and numerical estimates that connect and interpret theory and experiment. While the oxygen consuming, oxygen-gradient-guided bacteria Bacillus subtilis are the sole subject here, the methods developed will find application to the analysis and modeling of other complex dynamic systems that ineluctably combine physics and biology.

Mendelson and Lega (1998) studied a complex pattern of traveling stripes produced by swimming cells of Bacillus subtilis. They observed that motile cells of Bacillus subtilis inadvertently escaped from the surface of an agar disk that was surrounded by a fluid growth medium and formed a migrating population in the fluid. When viewed from above, the population appeared as a cloud advancing unidirectionally into the fresh medium. The cell population became spontaneously organized into a series of stripes in a region behind the advancing cloud front. The number of stripes increased progressively until a saturation value of stripe density per unit area was reached. New stripes arose at a fixed distance behind the cloud front and also between stripes. The spacing between stripes underwent changes with time as stripes migrated towards and away from the cloud front. The global pattern appeared to be stretched by the advancing cloud front. At a time corresponding to approximately two cell doublings after pattern formation, the pattern decayed, suggesting that there is a maximum number of cells that can be maintained within the pattern. Stripes appear to consist of high concentrations of cells organized in sinking columns that are part of a bioconvection system. Their behavior reveals interplay between bacterial swimming, bioconvection-driven fluid motion, and cell concentration. A mathematical model that reproduces the development and dynamics of the stripe pattern has been developed.

Czirok et al (1999) studied bioconvective dynamics : dependence on organism behaviour .They observed that bioconvection occurs when a macroscopic non uniformity of the concentration of microbial populations is generated and maintained by the directional swimming of the organisms. The authors investigated the properties of the patterns near the onset of the instability and later during its evolution into a fully nonlinear convection regime. In suspensions of the bacteria *Bacillus subtilis*, which tend to swim upwards in a gradient of oxygen concentration that they create by consumption, we discovered that the dominant wavelength at the onset of the instability is determined primarily by the cell density and is influenced only weakly by the fluid depth. This observation contrasts strongly with previous observations on the gravitactic alga *Chlamydomonas nivalis*, in which the opposite dependence was found. Considerable differences were also found in the long-term evolution of the convection patterns. These results demonstrate the existence of readily distinguishable types of bioconvection systems, even at early stages of the instability. The observed differences are clearly and causally correlated with disparate reasons for upward swimming by these microorganisms, leading to different geometric distributions of the density of the suspension.

Ghorai and Hill (1999) studied the development and stability of gyrotactic plumes in bioconvection.*By* using the continuum model of Pedley, Hill and Kessler (1988) for bioconvection in a suspension of swimming, gyrotactic micro-organisms; they investigated the existence and stability of a two-dimensional plume in tall, narrow chambers with stress-free sidewalls. The system is governed by the Navier Stokes equations for an incompressible fluid coupled with a micro-organism conservation equation. These equations are solved numerically by using a conservative fnite difference scheme. In suffciently deep chambers, the plume is always unstable to both varicose and meandering modes. A linear stability analysis for an infnitely long plume predicts the growth rates of these instabilities, explains the mechanisms, and is in good agreement with the numerical results.

Kuznetsov (2000) investigated the effect of heating from below on the stability of a suspension of motile gyrotactic microorganisms in a fluid layer of finite depth. This problem is relevant to a number of geophysical applications, such as investigation of the dynamics of some species of thermophiles (heat-loving microorganisms) living in hot springs. It is established that heating from below makes the system more unstable and helps the development of bioconvection. By performing a linear stability analysis, a correlation for the critical bioconvection Rayleigh number is obtained.

Kuznetsov and Jiang (2001) studied the numerical investigation of bioconvection of gravitactic microorganisms in an isotropic porous medium. They have formulated a new continuum model for bioconvection in a dilute suspension of swimming, gravitactic microorganisms in a porous medium. “Bioconvection” is the name given to pattern-forming convective motions set up in suspensions of swimming microorganisms. “Gravitaxis” means that microorganisms tend to swim against the gravity. The aim of this paper was to analyze collective behavior and pattern formation in populations of swimming microorganisms. The existence and stability of a two-dimensional plume in a tall, narrow chamber with stress-free sidewalls is investigated. Governing equations include Darcy law as well as microorganism conservation equation. A conservative finite-difference scheme is used to solve these equations numerically.

Kuznetzov and Avramenko (2002) performed a 2D stability analysis of bioconvection in a suspension of motile gyrotactic microorganisms in a fluid saturated porous medium to obtain an analytical expression for the critical permeability of the porous medium. Recent numerical investigation by Kuznetsov and Jiang [2001] suggests that permeability is a very important parameter for bioconvection in porous media. Their numerical results indicate that for small permeability bioconvection is stable (the microorganisms swim in the upward direction), while for large permeability it is unstable (variations of density are enhanced and macroscopic fluid circulation is induced). In the present investigation, a simple but elegant criterion of stability of the bioconvection is obtained. This criterion gives the critical permeability of the porous medium through the cell eccentricity, average swimming velocity, fluid viscosity, and other relevant parameters.

Kuznetsov and Avramenko (2002) investigated the effect of deposition and declogging on the critical permeability in bioconvection in a porous medium. The goal of this research is to investigate the effect of deposition and declogging of motile microorganisms in a fluid saturated porous medium on the development of bioconvention. If permeability of the porous medium is infinitely large (this corresponds to the clear fluid case) an infinite suspension of gyrotactic microorganisms with uniform number density of the suspended cells is unstable (Pedley et al. [1988]). On the other hand, if permeability is very small, the system behaves as a solid body and therefore must be stable. This means that there is a critical permeability value that corresponds to marginal stability. Kuznetsov, Raleigh and Avramenko presents a model of bioconvection of gyrotactic motile microorganisms in a fluid saturated porous medium. The model takes into account the capturing of motile microorganisms by the porous matrix which results in their deposition on the matrix as well as their possible declogging. The focus of this research is the determination of how the rates of cell deposition and declogging affect the critical value of permeability

Ghorai and Hillz (2002) studied axisymmetric bioconvection in a cylinder and observed that in three-dimensional bioconvection, the regions of rising and sinking fluid are dissimilar. This geometrical effect is studied for axisymmetric bioconvection in a cylindrical cell with stressfree (i.e. normal velocity and tangential stress vanish) lateral and top boundaries, and rigid bottom bound array. Using the continuum model of Pedley et al. (1988) for bioconvection in a suspension of swimming, gyrotactic microorganisms, the structure and stability of an axisymmetric plume in a deep chamber are investigated. The systems are governed by the Navier–Stokes equations for an incompressible fluid coupled with a microorganism conservation equation. These equations are solved numerically using a conservative finite-difference scheme. Comparisons are made with two-dimensional bioconvection.

Jánosi et al (2002) studied the enhancement of bacterial growth in quiescent environments due to bioconvection. They observed that bioconvection is an intriguing pattern-forming phenomenon driven by the swimming activity of various aquatic microorganisms. It is generally assumed that bioconvection has a positive effect on the entire microbial population by carrying oxygen into deep layers of non-aerated suspensions. In order to examine the presence of such a biological benefit, they analysed the correlation between bioconvective pattern formation and population growth of several *Bacillus subtilis* and *Bacillus licheniformis* strains under non aerated conditions. Bioconvection is a robust phenomenon. The authors observed its development in numerous cultures of various strains and growth phases. Nevertheless, evaluation of the data has not revealed detectable positive effects on population growth, questioning the potential biological relevance of bioconvection in natural habitats.

Vladimirov et al (2003) studied the measurement of cell velocity distributions in populations of motile algae. They investigated the self-propulsion of unicellular algae in still ambient fluid by using a previously reported laser-based tracking method, supplemented by new tracking software. A few hundred swimming cells are observed simultaneously and the average parameters of the cells' motility are calculated. The time-dependent, two dimensional distribution of swimming velocities is measured and the three-dimensional distribution is recovered by assuming horizontal isotropy. The mean and variance of the cell turning angle are quantified, to estimate the reorientation time and rotational diffusivity of the bottom-heavy cell. The cells phototactic and photokinetic responses to the laser light are evaluated. The results are generally consistent both with earlier assumptions about the nature of cell swimming and quantitative measurements, appropriately adjusted. The laser-based tracking method, which makes it possible to average over a large number of motile objects, is shown to be a powerful tool for the study of microorganism motility.

Hill and Pedley (2005) studied bioconvection patterns which are usually observed in the laboratory in shallow suspensions of randomly, but on average upwardly, swimming micro-organisms which are a little denser than water, but have also been found in situ in micro patches of zooplankton (Kils 1993). The mechanism of upswimming differs between bottom-heavy algae and oxytactic bacteria. Rational continuum models have been formulated and analysed in each of these cases for low cell volume fraction. These will be described, as will new theoretical and experimental developments, including nonlinear analysis of the patterns, dispersion in shear flows, measurements of algal cell swimming behaviour and new attempts to set up a model for more concentrated suspensions. The study reviews all work in this area since 1992.

Ghorai and Hill (2005) studied penetrative phototactic bioconvection.by using the generic model of Vincent and Hill (1996) for phototaxis in a suspension of swimming algae. The authors investigate two-dimensional phototactic bioconvection in a suspension confined between a rigid bottom boundary, and stress-free top and lateral boundaries. Phototaxis denotes swimming towards the (positive) or away (negative) from light. The model of Vincent and Hill also incorporates the effect of shading where microorganisms close to the light source absorb and scatter light before it reaches those further away. The system is governed by the Navier–Stokes equations for an incompressible fluid coupled with a microorganism conservation equation. These equations are solved numerically using a conservative finite-difference scheme. Convection driven by phototactic microorganisms, which are slightly denser than water, has been investigated in a series of numerical experiments. The solutions show transition from steady state to periodic oscillations, and periodic oscillations to steady state to periodic oscillations again, as the governing parameters are varied. The mechanism driving the oscillatory solution just above the critical parameter values is explained.

Simkus and Medkiene (2005) studied unstably stratified cultures of luminous cells.They observed that dense and open to air cultures of *luxCDABE*-gene fused *Ralstonia eutropha* in a cylindrical vessel exhibit bioconvection, which accounts for fluctuating bioluminescence. The characteristic period of fluctuations is ~10 min, when an unstable oxic–anoxic interface develops in close proximity (~1 mm) to the meniscus. Formation of a particular interface in the deeper layers (~2–3 mm) results in a noise which is close to Brownian.

Bearon and Grünbaum (2006) made an experimental and a theoretical study of bioconvection in a stratified environment. They observed bioconvection patterns which is a fascinating phenomenon of fluid mechanics that is driven by the swimming motion of micro-organisms. Typically the velocity and spatial scale of the fluid motions are much larger than those associated with the swimming speed and size of an individual cell, resulting in rapid transport of cells and the formation of complex spatial patterns in cell concentration. Motile micro-algae are ubiquitous in aquatic systems, and understanding how they are spatially distributed at a wide range of length and time scales is an important ecological task. In the natural environment, bioconvection is a little studied but potentially important mechanism influencing the vertical distribution, and therefore the growth and productivity, of motile micro-algae at centimeter to meter scales. However, in order to make predictions about when and where bioconvection might occur, one has to to understand how other physical factors, such as salinity stratification, will affect swimming behavior, fluid flow, and the resultant spatial distribution of cells. Bearson and Grünbaum present laboratory experiments that demonstrate the importance of swimming in generating large scale, persistent spatial structure in stratified water. In the first experiment, cells in a weakly stratified fluid environment first aggregate at the surface, and then form a bioconvective plume that descends to the bottom of the tank over a distance of 20 cm, equivalent to 104 cell body lengths. In the second experiment, addition of a low-salinity surface layer enables cells, initially well mixed due to bioconvection, to form a dense surface aggregation. Motivated by these experiments, we present a linear stability analysis for the onset of bioconvection in a stable linear salinity gradient. The concentration of cells is modeled by a continuous distribution and swimming is modeled as a constant upwards component combined with a diffusive component. The authors consider a deep chamber, where at equilibrium cells are concentrated in a thin boundary region. The ratio of chamber depth to boundary region depth is d. Using matched asymptotic analysis, they obtained the critical value of the cell Rayleigh number, Rcrit, for which the forcing due to a perturbation in cell concentration in the upper region drives flow. The experiments are then discussed in the light of the derived theoretical results.

Hu (2007) studied bioconvection patterns which are a collective phenomenon, usually appear due to upswimming of micro-organisms that are a little denser than water in suspensions. When the upper surface of the suspensions becomes too dense due to the gathering of micro-organisms, it becomes unstable and micro-organisms fall down to cause bioconvection. The reviews descuss the theoretical models and simulations, as well as experiments of bioconvection patterns.

Ghorai and Hill (2007) studied gyrotactic bioconvection in three dimensions. They considered the bioconvection equations, based on the continuum model of Pedley et al. (1988) which consist of the Navier-Stokes equations for an incompressible fluid coupled with a micro-organism conservation equation. These equations are solved efficiently using a semi-implicit second-order accurate conservative finite-difference method. The structure and stability of a three-dimensional plume in deep rectangular boxes with stress-free sidewalls are investigated. Comparisons are made with the two-dimensional and axisymmetric bioconvection. In deep chambers, the three-dimensional plume that forms initially along the central axis of the chamber typically breaks down via a meandering instability.

Nguyen-Quang et al (2009) studied two dimensional gravitactic bioconvection in a protozoan (Tetrahymena pyriformis) culture. They observed that gravitactic bioconvective patterns created by *Tetrahymena pyriformis* in a Hele-Shaw apparatus were realized and compared with theoretical results. They found two thresholds for bio-convection development: the first indicates the transition from the diffusion to the steady convection state; the second corresponds to the transition from the steady to the unsteady convection state. The results showed that the Hele-Shaw apparatus may be used as a physical analogy of porous media to study 2D bioconvection, with possible extensions to larger scale biological systems where population growth and distribution are driven by similar bio-physical interactions.

Suematsu et al (2010) studied localized bioconvection of *Euglena* caused by phototaxis in the lateral direction. They observed that *Euglena*, a swimming micro-organism, exhibited a characteristic bioconvection that was localized at the center of a sealed chamber under bright illumination to induce negative phototaxis. This localized pattern consisted of high-density spots, in which convection was found. These observations were reproduced by a mathematical model that was based on the photo taxis of individual cells in both the vertical and lateral directions. The results indicate that this convection is maintained by upward swimming, as with general bioconvection, and the localization originates from lateral phototaxis. **(Ashraf (2010)** has made a study of advanced bioconvection and the hydrodynamics of bounded biagellate iocomotion. The recent developments in using micro-organisms e®ectively for biofuels is the main motivation to carry out this research work. In this thesis, investigated two main aspects related to micro-organisms are investigated: swimming behavior and bioconvection pattern formation.

(Kuznetsov (2011)) has developed a theory describing the onset of convection instability (called here nanofluid bioconvecion) that is induced by simultaneous effects produced by oxytactic microorganisms, nanoparticles, and vertical temperature variation. The theory is developed for the situation when the nanofluid occupies a shallow horizontal layer of finite depth. The layer is defined as shallow as long as oxygen concentration at the bottom of the layer is above the minimum concentration required for the bacteria to be active (to actively swim up the oxygen gradient). The lower boundary of the layer is assumed rigid, while at the upper boundary both situations when the boundary is rigid or stress free are considered. Physical mechanisms responsible for the slip velocity between the nanoparticles and the base fluid, such as Brownian motion and thermophoresis, are accounted for in the model. A linear instability analysis is performed, and the resulting eigenvalue problem is solved analytically using the Galerkin method.

Nobuhiko et al., (2011) observed Localized pattern of bioconvection in a suspension of *Euglena gracilis*, which was a photosensitive micro-organism. The suspension was exposed to bright illumination from the bottom, in which the cells swam away from the light source. Then high-density spots, i.e., settling the cells, were formed at a part of a sealed chamber. This localized pattern was contrast with a general bioconvection where pattern was generated whole of a chamber. The experimental observations were reproduced by a mathematical model that was based on the phototaxis of individual cells in both vertical and lateral directions. The results indicate that convection is maintained by upward swimming, as with general bioconvection, and the localization originates from lateral phototaxis.

(Williams and Bees (2011)) has discussed three novel and mechanistically distinct models of the interaction of the two dominant taxes in suspensions of swimming phototrophic algae : phototaxis, swimming towards or away from light, and gyrotaxis, a balance between viscous and gravitational torques. Results indicate that the first two models, despite their different roots, remarkably are in agreement. Penetrative and oscillatory modes are found and explained. Dramatically different behaviour is obtained for the model with phototactic torques: instabilities arise even in the absence of fluid motion due to induced gradients of light intensity.

(Kuznetsov (2011)) has discussed the possibility of oscillatory instability in bioconvection.

(Rosie Williams (2011)) has studied the problems of a tale of three taxes: photo- gyro - gravitactic bioconvection. The aim of this study was to quantify experimentally the wavelength of the initial pattern to form from an initially well-mixed suspension of unicellular, swimming green algae as a function of concentration and illumination.

(Srimani and Sujatha (2011)) discuss the asymptotic analysis of Rotation Bio convection (RBC) in a suspension of phototactic algae. Bioconvection is an interesting pattern-forming phenomenon driven by the swimming activity of various aquatic micro organisms. In fact, bioconvection is a robust phenomenon and is one of the oldest documented collective behavior of independent microorganisms. Further, positive phototaxis consists of motions directed toward the source of illumination and negative phototaxis is, the motion directed away from it. The asymptotic analysis was carried up to the fourth order approximation and the cumulative effect of Taylor number and the other governing parameters on the stability conditions as well as on the different profiles was remarkable. The computed results were presented through graphs and are in excellent agreement with the available results in the limiting case.

Srimani & Roopa (2008) have studied the linear stability analysis of a suspension of gyrotactic micro-organisms in a horizontal fluid layer of finite depth subject to adverse temperature gradient and gravity modulation.The results have several geophysical applications. For example, this problem is relevant to certain species of thermophilic micro-organisms that live in hot environment.

Srimani & Roopa (2011a). have studied the effect of rotation on the onset of bioconvection in a suspension of gyrotactic bioconvection. The governing differential equations were complex nonlinear differential equations with boundary (velocity, temperature and cell) conditions. *Galerkin Technique* was employed and physically feasible trial functions were determined. The critical conditions for the onset of BPC were determined and the computed results were presented through graphs and were discussed. The effects of the rotational constraint on BPC were discussed in detail. The results suggested that rotation had strong influence on the BPC system the results more accurate when compared to the results of the earlier works. The results were in excellent agreement with those of the available results in the limiting cases. The methodology was found to be very efficient and elegant.There was a drastic change in the behaviour of the non-rotating and rotating bioconvective systems.

Srimani & Roopa (2011b) have investigated the effect of gravity inclination on the estimation of the critical permeability in a bio porous convection. Due to the extreme complexity of the problem the computational tools like Maple and Mathematica were used to get the analytic expressions. It is a well known fact that permeability of the porous medium is an important factor in the study of bioconvection. In the absence of gravity inclination, the results obtained were quite simple when compared to those of the inclined environment. It was found that the criterion for the existence of critical permeability was dominated by five parameters viz, cell eccentricity, gravity inclination, average swimming velocity, vertical disturbance and fluid velocity. The profiles of critical permeability vs cell eccentricity exhibited amazingly interesting features. The results were found to be in excellent agreement with the available results for the limiting cases.

(Srimani and Sujatha (2012) have studied studies the cumulative effect of uniform rotation of the system and the heating/cooling from below on the stability of a suspension of motile gravitactic microorganisms in a shallow sparsely packed horizontal porous layer. The bioconvective system is described by the continuity, momentum, cell conservation, flux of micro-organisms and thermal energy equations. The basic state solution is determined and the perturbed equations are solved using a fast computational technique. The Eigen value problem is solved and the profiles of the stream function, cell concentration, temperature along with the neutral stability curves are presented through graphs. The present results show an excellent agreement with the available results in the limiting cases.

Sharma and Virendrakumar (2012) investigated the effect of high-frequency vertical vibration in a suspension of negatively geotactic microorganisms in a horizontal fluid layer of finite depth saturating a porous medium. A single term Galerkin method is employed to solve the non- dimensional mathematical model developed for the considered case and a relation between the critical bioconvection Rayleigh number and its vibrational analogue (vibrational Rayleigh number) is established. Numerical computations are carried out and results are depicted graphically. It is observed that the high frequency, low amplitude vertical vibration and bioconvection Péclet number has a stabilizing effect on the system. It is also reported that the presence of porous medium results in decrease of the magnitude of critical bioconvection Rayleigh number in comparison with its non-existence; hence porous effect pre-pones the onset of instability**.**

(Srimani and Sujatha (2012)) discuss the cumulative effect of uniform rotation of the system and the heating/cooling from below on the stability of a suspension of motile gravitactic microorganisms in a shallow sparsely packed horizontal porous layer. The bioconvective system is described by the continuity, momentum, cell conservation, flux of micro-organisms and thermal energy equations.

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