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Active matter and active turbulence: a review of mass flow phenomena in biological and synthetic systems

Dr. Manju Bala[1]
[1]Associate professor, Department of mathematics, S V college Aligarh, Uttar Pradesh

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Abstract

Active matter comprises a broad class of systems in which individual components continuously consume energy to generate movement and mechanical stress, resulting in complex emergent phenomena that are far from equilibrium This review focuses on the principles, mechanisms, and collective behaviour of active matter. Particular emphasis is placed on active turbulence in active nematic liquid crystals, Janus particles, and self-moving colloids Experimental observations are integrated with computational simulations and theoretical frameworks, including Toner dual theory, continuum hydrodynamics, active nematic models Comparative analysis of organic synthetic systems Highlighting similarities and differences between, and underlining the importance of defect-mediated dynamics, bonding effects, and energy injection mechanisms In the broader context of soft-material physics, materials science, and biophysics, this paper identifies key successes, unresolved questions, methodological challenges, and promising directions for future research
Keywords: Active matter, Active turbulence, Active nematic, Collective behaviour, soft matter physics

Introduction

Active matter is a very important and emerging field of study developed at the intersection of modern physics, materials science, and biology, allowing scientists to understand how microscopic units produce continuous motion and structure using energy stored within themselves or from the environment The units in it consume energy continuously and maintain their momentum which is why each unit of active substance is called an "automatic unit". Such particles or organisms do not just move like ordinary particles but collectively form a special pattern or structure, which makes them quite different from conventional physical systems

Many examples of active ingredients are found in organisms and artificial systems. Coordinated migration of epithelial cell layers in living systems, wound healing, bacterial colonization, or morphogenesis during embryonic development are all true manifestations of active substance in artificial systems, such as self-propelled colloid suspensions, artificial microrobots, or artificial reconstituted cell synaptic networks and understand the similarities and differences between synthetic systems

The most distinctive and complex state of active matter appears as active turbulence. The turbulence that arises in normal fluids arises from inertial cascades due to high Reynolds number, while the situation is quite different in active turbulence Here the turbulence arises from continuous internal energy injection by units at the microscopic level. In this state the system neither stops at zero nor reaches complete chaos, but it reaches a dynamic equilibrium or "dynamic steady state" where energy production and dissipation continue This equilibrium is characterized by its length scale and time scale determined by the interaction of activity, elasticity and dissipation

The importance of active turbulence is not limited to theoretical considerations. It also helps us understand the deep processes of biology and medicine. For example, the rapid growth of bacteria, the spread of infection, the natural process of wound healing, or the formation of tissues and organs in embryonic development (orogenesis) can all be better understood using active ingredient principles. Such materials can be designed in

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such a way that they have pre-programmed flow motion properties, which could lead to future development of smart materials, self-driving robots and controlled industrial flow systems

Researchers in this field have resorted to several methods to understand the complexity of the active ingredient. Besides trying to explain theoretically by continuous hydrodynamic models and kinetic models, where the motion of active units is analysed by equations and mathematical formulas, computational simulations have also proved very helpful in this field confirm the theory but also make the model more reliable by comparing it with actual experimental observations.

Finally, this review on active matter and especially active turbulence not only collects and presents various published research, but also structures current knowledge, identifies shared principles among different biological synthetic systems, and indicates which areas still need more in-depth research. Active matter has thus become a highly relevant and multifaceted field of study not only for statistical physics and physical sciences, but also for biology, medicine, chemistry, and technological innovation, which can profoundly influence the direction of science and technology in the coming years.

2. Principles of Active Matter

Active matter refers to systems composed of individual agents that continuously consume energy to generate mechanical work, resulting in persistent motion and stresses. Unlike passive matter, which obeys the principles of equilibrium statistical mechanics, active matter remains intrinsically out of equilibrium due to ongoing energy injection at the level of its constituents (Marchetti et al., 2013).

A defining feature of active matter is self-propulsion. Each particle—whether a bacterium, a molecular motor, or a synthetic Janus colloid transduces energy from chemical reactions, light, or other sources into directed motion. The combination of self-propulsion, local interactions, and environmental constraints can produce complex collective behaviours such as flocking, swarming, and turbulence-like flows (Vicsek et al., 1995; Ramaswamy, 2010).

Another key characteristic is momentum transfer through the surrounding medium, which can be significant in systems where the active agents are immersed in a fluid. In such cases, hydrodynamic interactions play a critical role in pattern formation and the onset of instabilities. For example, elongated "rod-like" active units can generate extensile or contractile stresses, leading to flow patterns reminiscent of turbulence even at low Reynolds numbers (Simha & Ramaswamy, 2002).

Active agents are divided into two classes mainly on the basis of their structure and internal symmetry. The first class are polar systems, in which each particle has a clear head tail distinction. Examples of such mechanisms include migratory cells or flocks of birds. These particles are characterized by collectively moving in the same direction and exhibiting cluster like dynamics, called cluster dynamics A second class is nonpolar mechanisms, in which particles are elongated, but do not distinguish heads and tails Examples of this are microtubule kinesin networks or active nematic liquid crystals. These systems develop nematic order and the specific structures they produce and their defect dynamics are very important scientifically the most distinctive characteristic of active matter is that it consumes constant energy and generates force, which clearly distinguishes it from inert matter. Thus, active matter is a field of study that leads to an understanding of physical phenomena that have no direct counterpart in conventional physics

Theoretical Frameworks

The theoretical formulation of the active substance is carried out with the aim of relating the microscopic automatic behaviour to the emerging macroscopic models at the macroscopic level Several frameworks have been developed so far in this direction, suitable for coarse graining and analysis at different levels. Each

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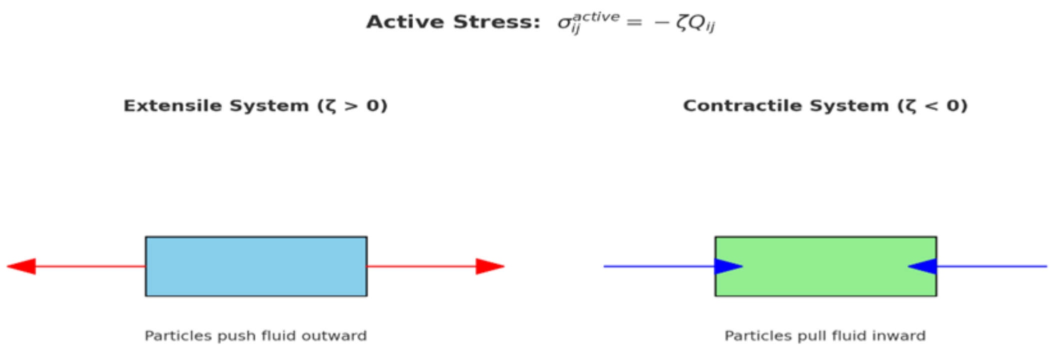
framework serves to understand and explain the complexity of the active substance according to the specific conditions and level of study.

Continuum Hydrodynamics

Continuum hydrodynamics provides one of the most widely used theoretical approaches to study active matter. In this framework, active matter is treated as if it were a continuous fluid, but unlike conventional fluids, it carries additional "active" stress terms that arise because its microscopic constituents are constantly consuming energy and generating mechanical forces. These forces, when averaged over many particles, can be expressed mathematically and incorporated into the equations of fluid motion.

The base equations here are extensions of the classical Navier Stokes or Stokes equations, which normally describe the flow of passive fluids like water or air. To adapt them for active systems, researchers introduce an *active stress tensor* that accounts for the extra stresses generated by the activity of the particles themselves (Simha & Ramaswamy, 2002; Marchetti et al., 2013). In this way, the hydrodynamic description captures both traditional fluid behaviours and the unique nonequilibrium dynamics created by continuous internal energy input.

A central example of this approach is found in active nematic systems. These are composed of elongated, rod-like particles that exhibit nematic order that is, the particles tend to align along a common axis, though they remain head–tail symmetric. The degree and direction of this alignment are captured mathematically by an order parameter, represented by the nematic director field n. In such systems, activity manifests itself through a stress term expressed as:



Extensile stresses (ζ > 0) push fluid outward, while Contractile stresses (ζ < 0) pull fluid inward.

Here, ζ (zeta) is known as the *activity coefficient*, which sets the strength and type of the active stress. A positive ζ represents *extensile stresses* (particles pushing fluid outward along their long axis, like microtubule–kinesin bundles), whereas a negative ζ corresponds to *contractile stresses* (particles pulling inward along their axis, as seen in actomyosin networks). Qij is the nematic order tensor, which encodes information about the local orientation of the particles.

What makes this formulation powerful is that it naturally explains phenomena that cannot be captured by equilibrium fluid models. For example, in active nematic, the system is prone to the spontaneous creation and annihilation of topological defects localized regions where the orientation field breaks down. These defects, often of charge +1/2 and –1/2, move, interact, and self-organize, leading to a constantly changing but statistically steady pattern of flows and vortices. This process is now recognized as a defining feature of active turbulence a chaotic but self-sustained flow state that occurs even at very low Reynolds numbers (Doostmohammadi et al., 2018).

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In short, the continuum hydrodynamic approach provides a bridge between the microscopic world of self-propelled particles and the macroscopic world of emergent fluid-like behaviours. By adding active stress terms into well-established fluid equations, it allows researchers to capture the rich and complex dynamics of active matter, including defect proliferation, spontaneous flow generation, and turbulence-like states that have no analogue in passive systems

Toner–Tu Theory

The Toner–Tu theory is one of the foundational frameworks for understanding polar active matter, that is, systems made up of self-driven units that have a clear head–tail distinction and thus move in a preferred direction. Examples of such systems range from bacterial colonies and migrating cells to flocks of birds and schools of fish. What makes this theory remarkable is that it adapts the principles of fluid dynamics and statistical physics to explain how collective motion can emerge and persist even in two-dimensional systems, where long-range order is normally prohibited by equilibrium physics.

In its essence, Toner and Tu (1995) proposed a continuum description where the macroscopic state of the system is captured not only by density but also by a velocity (or polarization) field that represents the average direction of motion of the active units. Unlike equilibrium fluids, these fields are governed by modified hydrodynamic-like equations that incorporate self-propulsion, alignment interactions, and stochastic noise. This framework successfully predicts several unusual features of active matter.

One of the most striking predictions is the occurrence of giant number fluctuations. In equilibrium systems, the variance in particle number typically grows in proportion to the square root of the mean. However, Toner–Tu theory shows that in active polar systems the fluctuations can be much larger, scaling nearly linearly with the mean. Such anomalous behaviour has since been verified in experiments on dense bacterial suspensions and synthetic active colloids, confirming the relevance of the model.

Another important result of the Toner–Tu framework is that it allows for the existence of true long-range orientational order in two dimensions. In passive systems, long-range order is destroyed by thermal fluctuations (as explained by the Mermin–Wagner theorem). Yet, in polar active matter, continuous energy consumption and self-driven alignment overcome these fluctuations, enabling persistent collective motion. This insight explains why bird flocks or microbial swarms can maintain coordinated movement over large scales.

Beyond order and fluctuations, the theory also provides tools to analyse long-wavelength excitations, or fluctuations in density and orientation that propagate through the system like waves. These modes help explain how information about direction or speed can spread rapidly across a flock without requiring direct communication between all individuals.

Over the years, the Toner–Tu model has been extended and refined (Toner, Tu & Ramaswamy, 2005) to capture additional complexities such as phase transitions between ordered and disordered states, the influence of confinement, and the effects of varying alignment rules. Its predictions continue to be tested in laboratory and field studies, making it one of the most influential and versatile theoretical tools in active matter research.

In summary, the Toner–Tu theory bridges microscopic self-propelled behaviour with macroscopic collective phenomena, explaining why large groups of polar active agents can display robust order, giant fluctuations, and dynamic patterns that have no analogues in passive equilibrium systems.

Kinetic and Agent-Based Models

At the mesoscopic scale, active matter theory is enriched by two complementary approaches—kinetic theories and agent-based models that link individual particle dynamics to emergent collective behaviour. Kinetic theories derive governing equations for coarse-grained fields such as density and polarization from the

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microscopic rules of self-propelled particles. A landmark example is the Boltzmann-like kinetic framework developed by Bertin, Droz, and Grégoire (2006), which demonstrated that hydrodynamic equations for density and velocity can be obtained systematically from particle-level interactions, thereby providing a microscopic foundation for continuum theories. Their analysis revealed that collective motion emerges below a critical threshold in the noise density parameter space, although this ordered state becomes unstable to spatial perturbations, producing density waves and band structures consistent with simulation and experimental results. Extensions of kinetic theory, including Enskog-like approaches at higher densities, further capture invasion waves and steep density modulations near the flocking transition (Ihle, 2011). Complementing these analytical models, agent-based simulations explicitly represent the behaviour of each particle. The most influential example is the Vicsek model (Vicsek et al., 1995), where particles move at constant speed, align with local neighbours, and are subject to random noise. Despite its simplicity, this model exhibits rich behaviour, including a phase transition from disordered random motion to ordered flocking, typically of first-order nature and accompanied by density band formation. Variants of the Vicsek model that incorporate inertia, attraction–repulsion forces, chemotaxis, or coupling with fluids further reveal turbulence-like flows and complex spatiotemporal patterns (Chaté et al., 2008). Together, kinetic and agent-based models provide complementary perspectives: the former offers analytical insights into the onset and stability of collective order, while the latter numerically explores parameter regimes and validates predictions, thereby jointly advancing our understanding of emergent structures in active matter systems.

Elasticity and Defect Dynamics

In active nematic systems, the dynamics of topological defects are central to the emergence of turbulence. These systems are characterized primarily by two types of defects: +1/2+1/2+1/2 defects, which behave like self-propelled particles capable of directed motion, and −1/2-1/2−1/2 defects, which are relatively immobile and act more like passive structures. The continual creation, annihilation, and nonlinear interactions between these defects drive sustained chaotic flows, giving rise to the phenomenon of active turbulence (Giomi et al., 2013). The interplay between the elastic forces inherent to the nematic medium, the strength of activity within the system, and the effects of confinement geometry collectively determine the emergent flow states. For example, when activity dominates over elasticity, defects proliferate and turbulence emerges, whereas stronger elasticity can stabilize ordered configurations. Similarly, confinement and boundary conditions can reorient or stabilize defect trajectories, leading to distinct collective patterns (Doostmohammadi et al., 2018). Taken together, frameworks based on elasticity and defect dynamics complement continuum hydrodynamics, Toner–Tu theory, and kinetic models, and form an essential foundation for interpreting both experimental and simulation studies of biological and synthetic active turbulence systems.

Experimental Observations in Biological Systems

Biological active matter systems provide some of the most compelling examples of active turbulence. Their constituents—cells, microorganisms, or protein filaments—convert chemical energy into motion, generating complex flows over multiple scales.

Bacterial Colonies and Swarms

Dense suspensions of motile bacteria such as *Bacillus subtilis* exhibit chaotic flow fields with continuously forming and decaying vortices, even at low Reynolds numbers (Dombrowski et al., 2004; Wensink et al., 2012). Particle image velocimetry (PIV) analyses have revealed characteristic vortex sizes on the order of tens of micrometres, with energy spectra distinct from inertial turbulence (Dunkel et al., 2013).

These "living fluids" demonstrate that turbulence-like flows can emerge purely from self-propulsion and steric/hydrodynamic interactions, without inertial effects. Bacterial turbulence has also been shown to enhance nutrient mixing and material transport within the colony (Wioland et al., 2013).

Cytoskeletal Filaments and Motor Proteins

In vitro reconstituted networks of microtubules driven by kinesin molecular motors represent another archetype of biological active matter. Sanchez et al. (2012) demonstrated that such systems self-organize into an active nematic phase exhibiting spontaneous streaming, defect proliferation, and turbulent-like dynamics.

The energy input comes from ATP hydrolysis by kinesin, which generates extensile stresses in the filament network. The resulting flows are highly dynamic and can be tuned by controlling motor activity, filament density, and boundary conditions (Henkin et al., 2014)

Epithelial Cell Monolayers

Active turbulence has also been observed in confluent epithelial tissues. Saw et al. (2017) showed that the proliferation and movement of cells in a monolayer can lead to nematic ordering, with cell elongation acting as the order parameter. Topological defects in the nematic field were found to correlate with sites of cell extrusion and apoptosis, suggesting that defect dynamics are not merely mechanical but also influence biological function.

Such observations connect active turbulence to morphogenetic processes, where the interplay of mechanical forces, biochemical signalling, and defect structures may regulate tissue development and homeostasis.

Experimental Observations in Synthetic Systems

Synthetic active matter offers controlled platforms for exploring active turbulence, allowing systematic variation of particle properties, interaction strengths, and boundary conditions.

Janus Particles and Self-Propelled Colloids

Janus particles colloids with asymmetric surface chemistry—can be driven into motion by self-generated chemical gradients (self-diffusiophoresis) or by light-induced heating (self-thermophoresis). While dilute suspensions typically display random walks, higher densities can lead to collective motion and vortex formation (Howse et al., 2007; Palacci et al., 2013).

These systems permit precise control over propulsion speed, particle–particle interactions, and activity duration, making them ideal for testing theoretical predictions of active turbulence.

Active Nematics in Liquid Crystals

Doostmohammadi et al. (2018) reviewed numerous experiments in which passive nematic liquid crystals are doped with active components—such as microtubules or catalytic particles—transforming them into active nematic. In these systems, the extensile or contractile stresses destabilize the uniform nematic alignment, producing a dynamic state filled with motile topological defects.

By tuning activity, elasticity, and confinement, researchers have mapped transitions between ordered, weakly turbulent, and strongly turbulent regimes. This has provided insights into how defect dynamics govern large-scale flow structures (Guillamat et al., 2017).

Microtubule–Kinesin Suspensions in Confined Geometries

Synthetic assemblies of microtubules and kinesin motors, when confined to thin films or patterned substrates, display vortex lattices, defect ordering, or chaotic turbulence depending on system geometry (Keber et al., 2014). Such confinement-induced phenomena mirror observations in biological contexts, highlighting the universality of active turbulence mechanisms.

Computational and Simulation Studies

Computational modelling has played a pivotal role in advancing the understanding of active turbulence by enabling systematic variation of parameters, access to regimes beyond current experimental capabilities, and precise control over boundary conditions.

Continuum Simulations

Numerical solutions of continuum hydrodynamic equations for active nematic reproduce many qualitative features of experimentally observed active turbulence. Simulations incorporating active stress terms capture spontaneous flow generation, defect proliferation, and the characteristic length scale of vortices (Thampi et al., 2014). The defect creation–annihilation cycles observed in simulations mirror experimental measurements in microtubule–kinesin systems and bacterial colonies.

Activity strength (ζ\zetaζ) and elastic constants are key parameters controlling the transition between ordered nematic, weakly turbulent, and strongly turbulent states. Increasing activity beyond a critical threshold destabilizes the nematic order, leading to chaotic flows dominated by motile +1/2+1/2+1/2 defects (Giomi et al., 2013).

Lattice Boltzmann Methods (LBM)

LBM approaches have been widely employed for simulating active fluids due to their efficiency in handling complex boundary conditions and hydrodynamic interactions (Mirandize et al., 2007). These simulations have elucidated the effects of confinement, substrate friction, and flow–order parameter coupling on the onset and structure of active turbulence.

Particle-Based Simulations

Agent-based simulations, such as Vicsek-type models (Vicsek et al., 1995) and their extensions, reproduce collective motion and turbulence-like patterns in polar active matter. By adjusting alignment rules, noise, and density, researchers can generate transitions between disordered motion, polar order, and mesoscale turbulence (Grossmann et al., 2014).

Molecular dynamics simulations of self-propelled rods have provided insight into steric and hydrodynamic contributions to turbulence onset (Wensink et al., 2012). These studies highlight the universality of active turbulence features across different modelling frameworks.

Hybrid Approaches

Coupling continuum hydrodynamics with explicit particle simulations offers a multiscale view, capturing microscopic propulsion mechanisms while resolving macroscopic flow patterns. Such approaches are particularly promising for bridging the gap between synthetic and biological systems (Fielding, 2021).

Comparative Analysis: Biological vs. Synthetic Active Turbulence

Biological and artificial active turbulence share many common fundamental features despite differences in scale, driving mechanisms, and constituent properties. Defect-mediated dynamics plays an important role in both systems. Biological systems such as epithelial tissues and bacterial films, and artificial systems such as active nematic and colloidal systems, have dynamic +1/2 defects and stable −1/2 defects whose interactions maintain turbulent and chaotic flow states (Doostmohammadi et al., 2018). Additionally, both types of active turbulence have characteristic length scales, where the distance between vortices and defects is determined by the balance of active forces and elastic/restorative forces, and does not depend on the overall size of the system. Also, in both cases there is a continuous injection of energy at the microscale. Whether it is the conversion of chemical energy into mechanical work or the use of light energy at the level of particles and fibres, the resulting flows become chaotic and disordered. Thus, the basic basis of active turbulence is the same in both

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biological and artificial forms, and this is what makes it a distinct phenomenon from equilibrium-based physical systems.

Differences

There are also many differences between biological and artificial active turbulence, mainly related to the properties of their components, controllability, and functional consequences. In terms of component properties, biological systems are often composed of soft, deformable, and multi-dispersed units that can adaptively respond to their environment. In contrast, artificial systems are mostly based on rigid, monodispersed particles whose dynamic properties are fixed and predetermined. Similarly, artificial systems are more precise in terms of controllability and adaptability, as researchers can control the size of the particles, their movement, and interactions, allowing systematic testing of different parameter spaces. While biological systems are bound by physical limitations and do not offer as much flexibility. Finally, differences are also observed in functional consequences. Active turbulence in biological systems has adaptive significance such as enabling more efficient transport of nutrients or regulating cell transformation. In contrast, active turbulence in artificial systems often appears only as an emergent phenomenon with no intrinsic "purpose." Thus, while biological active turbulence is an integral part of life processes, artificial active turbulence is mostly considered as a unique model for experimental and theoretical studies.

Cross-Learning Opportunities

Synthetic systems provide platforms for the study of active matter where various theoretical models can be tested and situations can be investigated that are difficult to directly observe in biological contexts. In these systems, the size of particles, their activity, and interactions can be controlled, allowing researchers to systematically explore the parameter space and validate complex kinetic phenomena. On the other hand, biological systems become a source of inspiration as they help us understand how properties such as self-organization and adaptability work in real life. For example, the group behaviour of cells, the collective motion of bacteria, or the reorganization of tissues serve as models for the creation of new active matter-based artificial materials. Thus, a reciprocal relationship is established between the two, where artificial systems validate theoretical and experimental assumptions, while biological systems inspire the design of new active materials with self-organization and adaptive properties. This bilateral relationship underlines the interdisciplinary nature of active materials research, which involves contributions from physics, biology, chemistry and materials science.

Key Breakthroughs and Unresolved Questions

In recent years, several important achievements have been made in understanding active turbulence. First, universal defect dynamics were elucidated, where experiments and theoretical studies demonstrated that both +1/2 dynamic and -1/2 static topological defects play a central role in maintaining turbulence in biological and artificial systems (Giomi et al., 2013; Doostmohammadi et al., 2018). On the other hand, continuum-experiment agreement was established, where hydrodynamic models incorporating active stress accurately reproduced experimental findings. These models gave credible explanations of important features such as the growth rate of defects, the size distribution of vortices, and the energy spectrum (Thampi et al., 2014). Finally, this research also revealed biological relevance. Studies on epithelial monolayers and bacterial colonies have proven that active turbulence is not only a physical phenomenon but also has functional significance. It can affect the pattern of cell removal and increase the efficiency of biological processes by improving the mixing of nutrients (Saw et al., 2017; Violland et al., 2013). Thus, these studies have deeply elucidated the fundamental principles, theoretical-experimental consistency, and biological functionality of active turbulence.

Unresolved Questions

Despite the remarkable progress in understanding active turbulence, many questions still remain unresolved. The first challenge is quantitative predictability. Although qualitative agreement between models and experiments is strong, predictive frameworks capable of quantitatively understanding the full complexity of biological active turbulence are not yet available. The second major problem is multiscale coupling. The relationship between microscopic activities, such as the dynamics of molecular motor proteins, and macroscopic turbulence statistics is not yet fully clear. The third challenge is the role of heterogeneity. Structural and dynamical heterogeneities are abundant in real systems, but their influence on the dynamics of active turbulence is still poorly understood. Finally, control strategies are also in their infancy. Methods to control active turbulence in artificial materials or to use it for functional outcomes are still being developed and have achieved limited success at the experimental level. Thus, the next major advances in the study of active turbulence will depend on resolving these unresolved questions.

Methodological Challenges

Researchers face several methodological challenges when studying active turbulence. To clearly visualize defect structures and flow fields, high-resolution imaging and advanced microscopy techniques that operate at high frame rates and large fields of view are required. Techniques used for quantitative measurements of flow, such as particle image velocimetry (PIV), when applied to dense and noisy systems, may interfere with the dynamics of tracer particles, affecting the reliability of the results. Similarly, extracting parameters such as activity coefficients and elastic constants from experiments is not easy, as it often depends on assumptions of data fitting. On the other hand, simulations have to simultaneously incorporate both microscopic dynamic activities and macroscopic flow patterns, which is computationally extremely expensive and time-consuming, especially in three-dimensional geometries. In addition, the lack of standardized protocols for data analysis and reporting is also a major challenge, as different research groups use different methodologies, making comparisons between different studies difficult and slowing down collective progress. Thus, the lack of high-level techniques, computational efficiency, and standardization makes the study of active turbulence complex and challenging.

Future Directions

Looking into the future of active turbulence, it is clear that in the coming years the field will develop in several new directions, allowing scientists to gain a deeper understanding as well as practical applications. First of all, special attention will be paid to multiscale modelling, which integrates particle-based and continuum models to cover phenomena ranging from microscopic propulsion processes on the nanometre scale to large-scale flows on the millimetre scale in a single framework. This will not only make theoretical predictions more accurate, but will also reveal the dynamics of complex biological systems more clearly. At the same time, there will be progress towards creating adaptive synthetic systems in which activity can be adjusted by external stimuli or through feedback control. Such systems will be able to adapt to the environment like biological cells or tissues and will form the basis for the creation of a new generation of active materials. Another big step will be the study of three-dimensional active turbulence, since most research so far has been limited to two dimensions (2-D). Three-dimensional studies will reveal new types of defect structures, flow states and energy flow patterns, which can completely change the current understanding. Similarly, confinement and geometry will also play an important role; it will be possible to direct, organize or suppress turbulence through patterned boundaries, topographical structures and controlled confinement, leading to the development of new types of functional materials. Future research will not be limited to basic science but will also leave its mark in interdisciplinary applications. In biomedical engineering it can make targeted drug delivery more efficient, while in soft robotics it can make self-organized and flexible movements possible. In addition, data-driven approaches and machine learning will play a key role in analysing the trajectories of defects, predicting the onset of turbulence and developing control strategies. In short, the future of active turbulence will not only deepen the convergence of physics and biology but will also open unprecedented opportunities in fields such as materials science, engineering and artificial intelligence.

Conclusion

The conclusion of this paper clarifies that the study of active turbulence is a highly multidisciplinary and emerging research field that lies at the juncture of physics, biology, materials science and computational modelling. The present review establishes, on the basis of various theoretical models, experimental results and comparative analyses, that the self-organised structure, energy flow, defect dynamics and multilevel interactions of active matter are fundamentally different from those of conventional turbulence. The active presence of $+1/2$ and $-1/2$ topological defects in both biological and artificial systems plays a central role in the generation and persistence of turbulence. Biological systems exhibit diverse patterns due to their multiplicity, adaptability and complex dynamics, while artificial systems facilitate systematic exploration on activity, shape and interactions in controlled environments. This interrelationship not only enriches active matter research from a theoretical point of view but also opens new horizons in applications such as smart materials, targeted drug delivery, soft robotics and advanced biomedical technology. Although significant progress has been made, several challenges still remain, such as the integration of multi-scale modelling, development of high-resolution imaging techniques, accurate estimation of activity coefficients, and complexities of data analysis in the absence of standardized protocols. The convergence of machine learning and data-driven approaches could prove extremely helpful in the prediction, control, and optimization of active turbulence in the future. Ultimately, continued research focused on active turbulence will not only deepen our fundamental scientific understanding but will also make unprecedented contributions to the advancement of society from practical and technological perspectives.

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