Chapter 6

Conclusion and future prospects

Dusty plasmas represent a fascinating and captivating field of study within the realm of plasma physics, and this thesis undertakes a comprehensive exploration of their intricacies, particularly within the confines of the strong coupling limit. These highly chaotic systems, consisting of ions, electrons, neutral particles, and solid particles, have long ignited the curiosity of researchers due to their ubiquity in diverse environments, ranging from space and planetary rings to the controlled environments of laboratory experiments. Through a comprehensive examination of interaction mechanisms, self-diffusion processes, and rheological behaviors, this thesis contributes insights into unraveling the intricate nature of these complex systems.

Chapter 1 of the thesis presented a comprehensive introduction to the field of plasma physics, with a specific focus on the intriguing domain of dusty plasmas. This chapter commenced by providing a definition of plasma and then explored the unique realm of dusty plasmas, characterized by the presence of solid dust particles that introduced intricate dynamics into the system. It proceeded to elucidate the essential characteristics of dusty plasmas, highlighting their relevance in astrophysics and laboratory settings. Furthermore, the chapter explored the dynamic behavior of dust particles within plasma environments and examined various types of waves that propagated through these fascinating media. Moreover, it introduced strongly coupled dusty plasmas, highlighting their distinct characteristics and their presence in both natural and laboratory settings. This chapter also laid the groundwork for the following chapters by introducing the concept of interaction potential in complex plasma systems.

Chapter 2 of the thesis covered the methodologies employed in this work to investigate the interaction mechanisms, transport coefficients, and rheological behaviors of complex plasmas. It began by establishing Fluid Theory as the foundational framework for understanding interaction potential within plasma systems. The chapter included a detailed explanation of the simulation technique, outlining the principles and procedures involved in conducting Molecular Dynamics (MD) simulations for dusty plasmas. Furthermore, it delved into the theoretical background of the Green-Kubo formalism, which served as the basis for calculating transport coefficients in molecular systems. The chapter offered a comprehensive exploration of the fundamental principles and concepts underlying this formalism, including the core ideas of the fluctuation-dissipation theorem and its connection to equilibrium fluctuations and transport properties.

In a dusty plasma system, the introduction of ion flow and a magnetic field has a substantial impact on the electrostatic potential between dust grains. These external factors fundamentally change the nature of the interactions between the dust particles, leading to significant modifications in the electrostatic potential they experience. In **Chapter 3** of the thesis, the wakefield phenomena around a charged dust grain in a streaming complex plasma in the presence of an external magnetic field were examined. Previous research had primarily focused on the effects of a magnetic field aligned with the ion flow direction, leading to significant suppression of wakefields. However, the influence of a transverse magnetic field, perpendicular to the ion flow direction, on the wakefield had received less attention. In this study, we conducted a comprehensive examination of wakefield characteristics when exposed to a transverse magnetic field relative to the ion flow direction, utilizing Linear Response Theory. In our study, we investigated the effects of various factors on the wake potential profile. Specifically, we analyzed how alterations in the strength of the magnetic field influenced this profile. Furthermore, we examined the impact of ion flow velocity on the wakefield characteristics. Additionally, we explored the effects of ion-neutral collision frequency on the overall behavior of the wakefield characteristics.

In **Chapter 4,** our primary focus was on examining the diffusive behavior of a strongly correlated dusty plasma within magnetized flowing conditions. We discussed in detail the effect of the magnetized wake on the diffusion and phase behavior of a strongly coupled 3-D dusty plasma system using Langevin Dynamics simulation. For a range of normalized ion flow velocity (M) that lay between 1.0 and 1.2, the attractive wake potential was predominant, and the dust ensemble exhibited super-diffusion. We also observed super-diffusion when the magnetic field was increased beyond 0.09 T for suitable values of the Mach number in the supersonic regime. The dust ensemble showed sub-diffusion when the effective potential was Yuwawa dominant and super-diffusion when it was wake dominant. It was apparent that the magnetized wake played a crucial role in driving the system from sub-diffusion to super-diffusion. Both cross-field ($D_{\perp}$) and parallel ($D_{\|}$) diffusion coefficients were sensitive to the magnetic field, even when the field strength was weak. The nature of the dependence of the perpendicular ($D_{\perp}$) and parallel ($D_{\|}$) diffusion coefficients on B depended on several factors, such as the state of the system, ion flow velocity, and effective interaction potential. A novel regime of dependence of cross-field diffusion coefficient $D_{\perp}$ as B^{γ} with γ > 2 is observed for ultra-low magnetic field B (< 0.01 T). On the other hand, the combined effects of Lorentz force and wake potential lead the system to exhibit B^{-2} variation for a relatively large magnetic field (> 0.09 T).

In **Chapter 5** of the thesis, we explored how an external magnetic field influences the rheological properties of complex plasma via anisotropic wake potential. Here, the shear viscosity (η) of a 3D liquid dusty plasma has been estimated from the simulation data using the Green-Kubo formalism with the help of Langevin dynamics simulation. The dependence of shear viscosity on magnetic field and ion flow velocity has been analyzed. The novel feature of this work is that the viscosity of complex plasma is found to be sensitive even to small changes in magnetic field because of the role of tunable wake potential with magnetic field. Here, we have modeled our system considering a binary Yukawa inter-particle interaction together with particle-wake interaction. In our work, we found 3 different regions that show different trends of viscosity with the external magnetic field, which can be explained based on the kinetic and potential parts of the shear stress under the external magnetic field. In the Yukawa-dominant, strongly coupled liquid state, the viscosity is found to vary as B^7 with a magnetic field in the range 0.001 T–0.05 T and B^4 in the range 0.05 T–0.09 T. This unique behavior is observed due to the role of tunable wake potential with magnetic field. On the other hand, in the gaseous state, the viscosity is found to vary as $\frac{1}{B^2}$ with a magnetic field in the range 0.09 T–0.3 T. Therefore, the viscosity is crucially related to the phase state of the dusty plasma system. We also observed the effect of the drift velocity of ions on viscosity, and it was found that viscosity changes very rapidly in the supersonic regime for normalized ion flow velocity M $>$ 1.5 for the range of parameters studied here. Due to this unique property, complex plasma may be used as a platform to study the magneto-rheological characteristics of soft matter, and there is a possibility of using dusty plasma as a magneto-rheological material in the near future. The tunable and anisotropic inter-grain interaction among the dust grains makes complex plasma an ideal candidate for soft matter, such that its structural and transport properties can be suitably designed. In the presence of a magnetic field, the amplitude of wake potential is modulated, and as a result, there is a possibility of controlling the rheological behavior of complex plasma by tuning the external magnetic field, thus resembling the magneto-rheological properties of conventional soft matter.

In continuation of this thesis, there are several intriguing avenues for future research:

1. Study of ion-wake formation with dust charge fluctuation in complex plasma: The charging dynamics within complex plasma systems play a pivotal role in modifying the plasma's dielectric response function. Future investigations could explore further the intricate relationship between ion wake formation and dust charge fluctuation.

2. Exploration of Non-Linear Regimes: Expanding on the established theories of interaction mechanisms, future research can broaden its focus to non-linear regimes. Investigating how the system behaves beyond linear approximations can uncover novel phenomena and offer a more comprehensive understanding of complex plasma dynamics.

3. Study of Longitudinal and Transverse Wave Modes: An interesting avenue for research involves a detailed exploration of longitudinal and transverse wave modes across a broad parameter range. This investigation can shed light on the intricate interplay of various physical effects in the system's evolution, providing a holistic view of complex plasma behavior.