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Chapter

Wave Spectra in Dusty Plasmas of Nuclear Fusion Devices

*Aamir Shahzad, Muhammad Asif Shakoori
and Mao-Gang He*

Abstract

Wave's spectra are investigated through an equilibrium molecular dynamic (EMD) simulation of three-dimensional (3D) strongly-coupled complex-dusty plasmas (SCCDPs). In this chapter, we have analyzed the correlation functions over a wide range of plasma parameters of Γ ($\equiv 1, 100$) and of κ ($\equiv 4.5, 5.5$) along with a higher wave's numbers of k ($\equiv 1, 4$). In EMD simulations, we have examined the propagation modes of wave in the longitudinal $C_L(k, t)$ and transverse $C_T(k, t)$ current direction at higher screening (κ). We have also analyzed the wave's spectra in different regimes of plasma states of SCCDPs. A new simulation shows that the longitudinal (C_L) and transverse (C_T) waves in SCCDPs are damped for low values of Γ . However, these damping affects decrease comparatively with an increasing Γ . Outcomes show that amplitude and frequency modes of the C_L and C_T depend on κ , Γ , k and probably on a number of particles (N). The results obtained from EMD are in reasonable agreement with earlier known theoretical and experimental data. It has been shown that the present EMD method is the best tool for computing C_L and C_T in the SCCDPs over a suitable range of plasma parameters.

Keywords: wave properties, plasma parameters, longitudinal current correlation, transverse current correlation, strongly coupled dusty plasmas, equilibrium molecular dynamic

1. Introduction

A partially or fully ionized gas containing neutral atoms, electrons, ions and with the addition of dust particles is known as dusty plasma (DPs). This additional component (dust particle) increases the complexity in the behavior of the system, and thus refers to this system as "dusty" or complex plasma [1]. Nowadays the term "complex plasma" is commonly used in literature to differentiate the dusty plasma. Due to embedded dust particles in the plasma, these dust particles create changes in the charge composition. The new physical processes were introduced in the system such as the recombination of plasma on the particle surface and effects associated with the degeneracy, fluctuations of particle charges which also change the energy and transport phenomena. That's the way the DPs became a new type of non-Hamiltonian systems. The presence of dust particles in the complex plasma is vital for the collective processes. These micro size dust particles create very low-frequency wave mode, which represents charge particle oscillations against the quasi-equilibrium background of ions and electrons. Generally, a dynamical time

scale related to the dust component is in the range of 10–100 Hz. Recently the dusty plasma becomes an interesting field for researchers, technologists and scientists [2, 3]. The initial challenge of fusion in nuclear devices is to confine ionized isotopes of hydrogen atom known as plasma, increase the plasma pressure to initiate and sustain the fusion reaction [4].

Dusty plasma is classified on the basis of density, temperature, potential, and thermal energy. For classification of dusty plasma first, we define Coulomb coupling parameters. Coulomb coupling defines as “the ratio of average potential energy to the average thermal energy of neighboring charged particles” and mathematically written as $\Gamma = Q^2/4\pi\epsilon_0\alpha_{ws}k_B T$ [5].

1.1 Weakly coupled dusty plasmas (WCDPs)

Weakly coupled dusty plasmas have higher average thermal energy than average potential energy due to neighboring charged particles. WCDPs have a high temperature, low density and value of Coulomb coupling parameter less than 1 ($\Gamma < 1$). WCDPs have no structural form due to high temperatures. The background of WCDPs is considered as ionized gases. The temperature of dust particles is much higher than those of ions, electrons, and the neutral population in the system. Due to this, difference in temperature values, DPs becomes a particular interest in the research field of science and technology [6].

1.2 Strongly coupled complex dusty plasmas (SCCDPs)

In strongly coupled dusty plasma (SCDP), the average potential energy of neighboring charged particles is dominated on the average thermal energy of the same charged particles. This type of dusty plasma has high charged particles density and low temperature. The SCDPs speedily become emerging fields from last three decades. Due to the presence of dust particles in the atmosphere, the dusty plasma becomes a very significant research field of astrophysical plasma and also in nuclear fusion devices [7–9]. At higher density and low temperature, the SCDPs undergo in crystallization phase. In Coulomb coupling systems, the SCDPs change phase from liquid to crystal phase at specific values of the Coulomb coupling parameters. SCDPs known as a warm liquid at $\Gamma = 5$, liquefy at $\Gamma = 80$, it becomes cold liquid at $\Gamma = 100$, very cold ($\Gamma = 120$) and then liquid phase has a limitation at $\Gamma = 137$. The SCDP has a crystalline form at $\Gamma = 175$ value; it has very high density and very low temperature [10, 11]. SCDPs appear in many astrophysical objects such as neutron star crusts, white dwarf interiors, supernova cores, and giant planetary interiors. Charged particles in dusty plasma are also found in many physical systems such as condensed matter systems of liquid metals and molten salts, cryogenic traps, electrons trapped on the free surface of the helium. DPs play a very important progressing role in laboratory experiments. Nowadays, recently the dusty plasma plays a very significant role in the nuclear fusion devices for plasma confinement and to control the fusion reaction [39]. For basic experiments in the laboratory, the DPs shows very interesting phenomena such as melting and formation of crystals, collective modes excitation with reference to dust component. Nanostructure layered, and colloidal suspension of dusty plasma was also investigated in these set of references [12–14].

1.3 Properties of dust particles

Dust is present everywhere in the space and environment. Dust particles are much larger than electrons, ions, and neutral particles. Their sizes of dust particles

vary from hundreds of millimeters to 10 nm and the mass of dust particle is approximately 7.53×10^{-10} kg. Their dynamic behaviors are easily observed through a CCD camera because of temporal and spatial scale. These dust particles are mostly negatively charged; however, sometimes they have positive charged also, that depends upon the charging phenomena. The large shielding clouds are created for balance the ion thermal current and electron thermal current. Charging phenomena of dust particles are photoionization, electron bombardment, sputtering, etc. The amount of charge at dust particles depends upon shape and size. Most often, they have spherical shape; however, sometimes they are of the form of rod type and or irregular shape [12, 15]. Dust particles are exposed to ion and electron currents from discharge plasma that's why reached quickly in dynamical equilibrium. The electric charge on the dust particle depends upon their radius (size) and shape, and the charge amount is in the order of 10^3 – 10^4 electrons. Increasing the charge on the particles increases the electrostatic repulsion between them in a confined system and may lead to crystallization [16]. The dust particles are strongly coupled due to high electric charges and unable to move easily so that they look like a solid and liquid phase in the DPs. The phonon spectra in the DPs are easily calculated due to the thermal motion of dust particles [17]. The motion of dust particles generates the longitudinal and transverse waves in the dusty plasma. Due to the complex behavior of a dust particle in DPs, it becomes an independent field for researchers whose study dusty plasma with strong correlation. The charged dust particles are highly susceptible to the different forces in the plasma such as the electric field, neutral and ion drag and can serve as sensitive diagnostic tools [18].

1.4 The existence of DPs in nature and laboratory

DPS are found in the ionosphere, that's a lower part of the earth. Noctilucent clouds (NLs) are composed of ice and dust from manmade pollution and heavy clusters. In the space environment, the examples of dusty (complex) plasma are Jupiter rings, were first observed in 1779, comets, planetary rings and spokes, Saturn's rings and Neptune. The size of dust particles in Saturn ring varies from micron to sub-micron. The radial spokes also consist of micron and submicron sized dust charged particles that are electrostatically levitated. The presence of dust particles in the atmosphere at the altitudes in the range of 80 and 90 km was observed during polar summer mesopause [19]. The presence of dust particles was observed in the nuclear fusion devices, both Tokamaks and stellarators. Due to the presence of dust particles in these devices may disturb the performance and stop working on it. Nowadays, study of dust particles in fusion devices becomes very important. The charging mechanisms of dust particles in these devices are also investigated by Liu et al. [20]. It becomes very necessary for operational Tokamak or other fusion devices to study and found waves and transport properties of dusty plasma. Thermal conductivity, diffusion coefficient, shear viscosity in dusty plasma and charging mechanisms of dust particles in nuclear fusion devices are also needed to investigate [21]. The dust particles are also observed in radio frequency (RF) device and direct current (DC) glow discharge tube and Z-Pinch device etc. Under the laboratory condition, the plasma crystals are observed in different devices such as in RF, DC, thermal plasma, nuclear-induced dusty plasma over wide range of plasma parameters [22].

1.5 Nuclear fusion devices

Fusion energy is a source of energy for a future generation which is almost inexhaustible. Currently, it is an undefeatable challenge for engineering and

thermophysical researchers. The basic challenge to achieve the fusion energy is “to achieve a rate of heat emitted by fusion plasma that exceeds the rate of energy injected into the plasma”. The central expectations are focused on two fusion reactor devices, one is Tokamak and the other is stellarator. Today the whole world community is working for nuclear fusion device, which is known as Tokamak. Fusion energy is investigated and comes closest to the explosion. These devices consist of a ring-type magnetic field used to confine the plasma. Tokamak plasma is confined by an electric current flowing in plasma, and in the stellarators, a magnetic field of very complicated shape used to confine plasma stationary. The Tokamak work only in the pulsed mode without auxiliary facilities and stellarators is suitable for continuous operation. The most effective magnetic field configuration is toroidal in the shape of the doughnut. The Tokamaks, stellarators and the reversed field pinch (RFP) are commonly under developing fusion nuclear devices based on toroidal confinement configuration. The Z-pinch is also nuclear fusion device in which is a strong electrical current in plasma to generate X-rays. The magnetized target fusion, referred to as a MIF (magneto-inertial fusion) system, is also currently in progress. In these nuclear devices, a magnetic field is applied to confine the plasma with the help of electromagnetic or mechanical linear implosion. A compression heating is provided with laser hot dense magnetized plasma which is created in the plasma focus (PF) devices. The PF devices belong to the family of dynamic noncylindrical Z-pinch. If in this device deuterium is used as gases then DD fusion reaction takes place [23–27].

1.6 Dusty plasma in fusion devices

The working conditions of nuclear fusion devices are such that the fuel of these devices must be heated up to heat fuel in nuclear fusion devices heat in the range of 100×10^8 K temperature, at this temperature the fuel is in the plasma state. The temperature of the plasma is very high, and materials are vaporized that contact with it, that's why plasma must be confined kept in the magnetic fields. In the Tokamak reactor fuel is use in the range of grams (g), so it is a very safe device. The solid impurities are known as “dust” were also found and investigate Scrape-Off Layer transport that is a key element of edge physics research program. For safety precautions against the dust particles, it is very significant for engineers to predict where the quantity of dust particles increases. To resolve the dust transport problem in fusion devices it is necessary for physicists to develop a fully accurate dust transport code (DTC) [28]. It is also required to calculate the plasma parameters from geometrical relations and engineering constraints of nuclear fusion Tokamak device. Plasma density (n), pressure (p), temperature (T), energy confinement time, β (normalized plasma pressure) as a function of α (minor radius of plasma) are the basic main plasma parameters. In addition, some plasma parameters such as plasma current, bootstrap fraction and kink safety factor are required for a plasma physicist in order to understand Tokamak process. The reactor demands toroidal current I to achieving high energy confinement time (very large) for ignition [3, 26]. There are several techniques used for heating plasma in Tokamak. The most common technique use to heat plasma is Ohmic heating, neutral beam injection, RF heating. The fusion plasma has such as high temperature so that they emit little visible light [29, 30].

1.7 Waves spectra in dusty plasma

To understand dynamical information and basic properties of gas, liquids, and solids, it is compulsory to study the basic two phenomena such as phase transition

and waves [31]. Dust particles in SCDPs support longitudinal (compressional) waves, also known as dust acoustic waves (DAWs) and transverse waves (shear) [12]. The propagations of longitudinal modes are faster than the transverse mode in the crystalline phase of dusty plasma. The WCDPs does not sustain the transverse wave and only sustain longitudinal waves. The compressional electrostatic waves and DAWs have low-frequency modes due to a larger mass of dust particles. In order to study the thermal motion of dust particles through MD simulation and it was found that cut off wave number is calculated for transverse mode near the solidification phase of dusty plasma [32]. The generalized hydrodynamics (GHD) model of the equation is predicted by the existence of transverse wave mode in the liquid and strong coupling regimes and dispersion properties of longitudinal modes [18]. Investigation of dusty longitudinal waves (DLWs—dust lattice waves) in two-dimensional bi-crystal in an arbitrary direction and it was found that hybrid modes have both components along with transverse and longitudinal directions. The hybrid modes become purely transverse to longitudinal waves for the angle of propagation is 0 or $\pi/2$ [33]. Background of the colloidal suspension liquid exerts large friction on the motion of charged particles than the background of dusty plasma gases. Due to low friction between charged particles in the gas phase of dusty plasma waves damped slowly. The complex (dusty) plasma the current correlation functions of complex (dusty) plasma are classified into the longitudinal current and transverse current, also known as longitudinal and transverse (shear) wave's mode. In the classical fluids, when k approaches zero then longitudinal modes known as acoustic modes. Strongly coupled plasma in the liquid phase supports shear maintained transverse mode. In SCDPs, when k approaches zero then transverse modes are also considered approach as acoustic modes [34] (**Figure 1**).

The uniform liquid phase does not support transverse modes of waves. The reason for this is to ignore the migration of diffusion damping. For isotropy liquid, the transverse mode approaches the same Einstein frequency ω_E as a longitudinal mode, when the wavenumber k approaches to infinite. The current correlation functions of DPs are studied theoretically, numerically and experimentally.

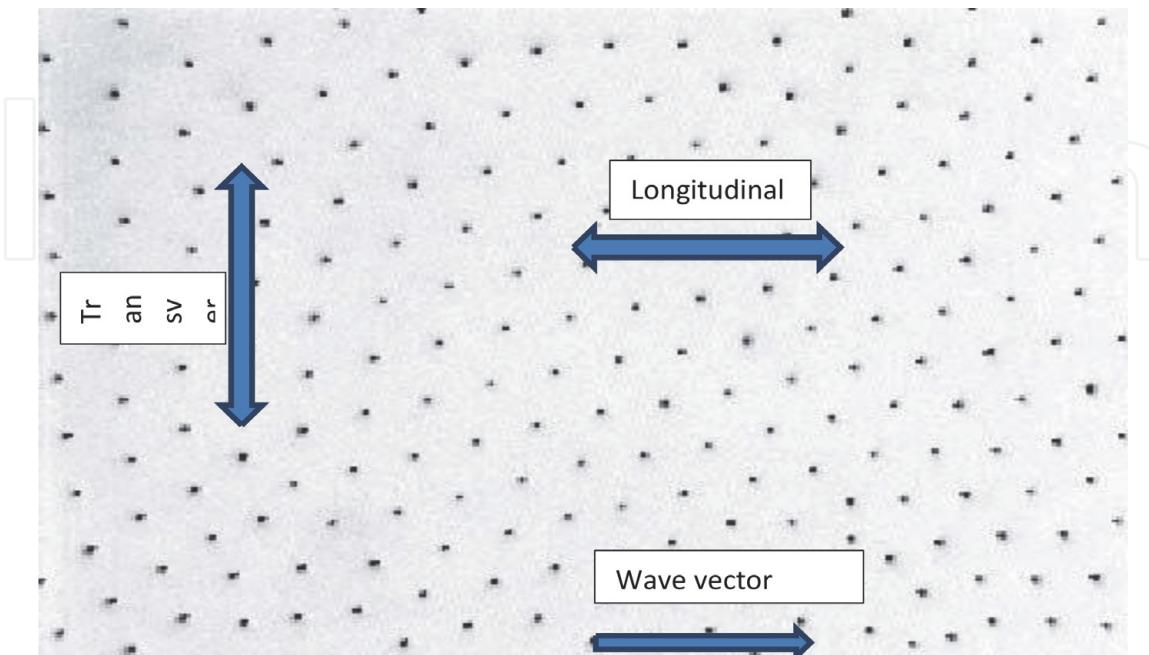


Figure 1.
 Directions of longitudinal and transverse waves in DPs relative to the direction of wave numbers vectors. The direction of the wave vector shows that direction of $C_L(k, t)$ is along the wave vector and direction of $C_T(k, t)$ is perpendicular to the wave vector (\mathbf{k}) [35].

The results are in good agreement with the theoretical prediction, in support of simulation measurements and also verified by experiments [13, 15, 23].

1.8 MD simulation and types

An MD simulation is a tool that studies the microscopic model in a macroscopic system, and this model is quantified in terms of intermolecular interaction and the molecular structure. The results are obtained with accuracy through different simulation techniques (algorithm) and compared with theoretical and experimental results. Simulations are also used to study the wave properties of complex models at the microscopic level which cannot be investigated by experiments [36]. There are several computational techniques that have advantages and also disadvantages with their respective fields. Monte Carlo (MC) and molecular dynamics (MD) simulations are influential tools for the study of transport properties of dusty plasma. Transport properties can also be calculated by Langevin dynamics (LD), MC, path integral MC (PIMC) and MD methods. The disadvantage of the MC technique is that it cannot evaluate the transport properties of dynamical systems and cannot solve and apply the equations of motion [37].

2. Mathematical model and numerical method

In this chapter the EMD Simulations are performed for a selected system, having the number of particle $N = 500$ with apply periodic boundary condition (PBCs) on the cubic box in three dimensions coordinates directions. These particles are placed in a cube volume V and interact with each other by pairwise Yukawa potential is given:

$$\phi(|\mathbf{r}|) = \frac{Q^2}{4\pi\epsilon_0} \frac{e^{-|\mathbf{r}|/\lambda_D}}{|\mathbf{r}|}, \quad (1)$$

Q is the charge, on dust particles, ϵ_0 is permittivity of free space, λ_D is the Debye length which accounts for the screening of the interaction by other plasma species. The dimensionless plasma parameters have fully characterized the system under study. One is Coulomb coupling parameter and defines as $\Gamma = Q^2/4\pi\epsilon_0\alpha_{ws}k_B T$ (already defined in Section 1.1), where α is the Wigner-Seitz radius and is define as $\alpha_{ws} = (3/4n\pi)^{1/3}$ with n is the dust particle density, T is the temperature of the system and k_B is Boltzmann constant. The screening parameter is and defines as $\kappa \equiv \alpha_{ws}/\lambda_D$. In an EMD technique, Newton's motion equation is, $m(d^2\mathbf{r}/dt^2) = \mathbf{F}_i = \sum_j \mathbf{F}_{ij}$, integrated numerically for N Yukawa particles with mass m positioned at \mathbf{r}_i , velocity \mathbf{v}_i and acceleration \mathbf{a}_i in the volume (V) of simulation box of particle i ($i = 1, 2, 3 \dots N$) is exerted a force on other particle j and it is given as $\mathbf{F}_i = \sum_j \mathbf{F}_{ij}$ and $i \neq j$. The EMD is performed in the microcanonical ensemble (NVT) for constant volume and temperature [38]. In this chapter, the EMD has been used to investigate the time-dependent current correlation functions [$C_L(k, t)$ and $C_T(k, t)$]. The dimension of the simulation box is L_x, L_y, L_z . The periodic boundary condition is used to minimize the surface size effect and applied to the simulation box. The main calculation is performed for $N = 500$ particles at $\kappa = 4.5$ and 5.5 , plasma coupling parameters Γ (temperature of the Yukawa system) varies from 1 to 100 and wavenumbers $k = 0, 1, 2$, and 3 . The simulation time step is taken as $\Delta t = 0.001$ to allow computing the important data for sufficient 425,000 simulation run. EMD method is reported of the current correlation of SCDPs over sufficient domain of

plasma parameters of Debye screening ($4.4 \leq \kappa \leq 5.5$) and Coulomb coupling ($1 \leq \Gamma \leq 100$).

2.1 Current correlation functions

The SCDPs support both longitudinal and transverse waves. The experimental importance of time-dependent correlation function is that the spectroscopic technique an example of this technique is neutron scattering. Investigate microscopic dynamical quantities through the MD approach and then comparison by Fourier analysis of the simulation result. The local density gives information about the atom's distribution. There is also possible to analyze the motion of atoms. The Fourier component of Particle current or momentum current for a single atomic particle in MD unit is given as.

$$\pi(r, t) = \sum_j v_j \delta(r - r_j(t)) \quad (2)$$

where v_j and r_j are the velocity and position of a j th particle, by using the Fourier transformation of particle current becomes as for a given wavenumber vector (\mathbf{k}).

$$\pi(k, t) = \sum_j v_j e^{-ik \cdot r_j(t)} \quad (3)$$

The correlation function of the current vector component is defined as

$$C_{\alpha\beta}(k, t) = \frac{k^2}{N_m} (\pi_\alpha(k, t) \pi_\beta(-k, 0)) \quad (4)$$

For the isotropic fluid under consideration of symmetry above equation can be expressed in term of longitudinal current correlation and transverse current correlation in the relative direction of k , where k is the wave vector and equal to multiple of integers $k = 2\pi/L$ and L is the size of the simulation box. Wave vector \mathbf{k} becomes equal to $\mathbf{k} = 2\pi/L$ (k_0, k_1, k_2, k_3), $k_j \in \mathbb{Z}, j = 0, 1, 2, 3; L$ is the length of simulation box and $V = L^3$.

$$k = |\mathbf{k}| = \frac{2\pi}{L} |(x, y, z)| \quad (5)$$

Here x, y , and z are integers.

$$C_{\alpha\beta}(k, t) = \frac{k_\alpha k_\beta}{k^2} C_L(k, t) + \left(\delta_{\alpha\beta} - \frac{k_{\alpha\beta}}{k^2} \right) C_T(k, t) \quad (6)$$

By putting $\mathbf{k} = k \mathbf{z}$ the time-dependent longitudinal current correlation becomes as.

$$C_L(k, t) = \frac{k^2}{N_m} \left\langle \sum_i v_i e^{-ik \cdot z_i(t)} (k, t) \sum_j v_j e^{-ik \cdot z_j(t)} (k, t) \right\rangle_j \quad (7)$$

Where N_m represents the number of particles, v_i and v_j are the velocity of the i th and j th particles, $\langle \dots \rangle$ gives the statistical average of particle current. Longitudinal current correlation function explains the direction of the waves along the wave vector (wavenumber) and a transverse direction perpendicular to k .

$$C_T(k, t) = \frac{k^2}{2N_m} \langle \pi_x(k, t)\pi_x(-k, 0) + \pi_y(k, t)\pi_y(-k, t) \rangle \quad (8)$$

The longitudinal current correlation also related to the dynamical structure factor.

$$S(k, \omega) = \frac{1}{\omega^2} C_L(k, \omega) \quad (9)$$

In Eq. (9), the dynamical structure factor and longitudinal current correlation contain the same physical information of the systems. Transverse current and longitudinal current also explain the wave spectra in 3D SCDPs. In our EMD simulation model, the current correlation function is the only function of wavenumber and time (k, t). Through this mathematical model of current correlation, we checked out variation in frequency and peak amplitude of transverse and longitudinal waves in SCDPs for at Γ, κ, N , and k [13, 18, 31, 34].

3. Results and discussions

In this section, we describe the consequences of extensive MD simulations methodology work, carried out to explore the current correlation functions (compressional and shear waves) of 3D Yukawa liquid via the EMD simulation technique. $C_L(k, t)$ (Eq. 7) and $C_T(k, t)$ (Eq. 8) is simulated at an extensive combinational range of parameters (Γ, κ, N and k). The $C_L(k, t)$ and $C_T(k, t)$ which are normalized by plasma frequency (ω_p) has been extensively used for prior studies of SCDPs but while here we are investigating its correspondence with time (t). The information waves spectra for nuclear fusion device conditions is generated from simulation goes, that prediction which is true for frequency spectra, current correlation function [$C_L(k, t), C_T(k, t)$] simulation are executed for higher screening strength of spherical charged dust particles ($\kappa = 4.5$ and 5.5) and Coulomb coupling parameters (inverse of plasma temperature) parallel closely same experimental plasma state (κ, Γ). This was executed to facilitate comparison with presented simulation results and available data of recent and earlier.

In this section, we present our EMD simulation results and their discussion of wave spectra from the current correlation function in the longitudinal and transverse wave's modes. The specific attention in this chapter is given to $C_L(k, t)$ and $C_T(k, t)$ for a different combination of plasma parameters which are investigate the behavior of transverse and longitudinal waves in 3D SCDPs. Explanation qualitatively features of the longitudinal (compressional or sound) waves in 3D complex (dusty) plasma shown in **Figures 2 and 3**. Here our EMD outcomes we compute the $C_L(k, t)$ for $\kappa = 4.5$ and 5.5 for a number of particles ($N = 500$) and in the direction of wave vector numbers ($k = 0, 1, 2$ and 3). We determined properties of longitudinal waves in SCDPs at a different combination of plasma parameters (κ, Γ), the results have plotted the magnitude of $C_L(k, t)$ against simulation time (t). In our EMD simulations result, the effect about plasma temperature is observed on the magnitude, wavelength, frequency, and damping phenomena of waves in SCDPs. **Figure 2** consists four panels which covering from non-ideal to the liquid and then liquefy state of dusty plasma. The panel (a) of both **Figures 2 and 3** represent the results of longitudinal wave spectra in the non-ideal state of dusty plasma at $\kappa = 4.5, 5.5$ respectively. It is observed from first panel of these two figures that collective modes of wave spectra are highly damped due to high temperature of dust particles confirmed good agreement with earlier published worked by Nunomura due to

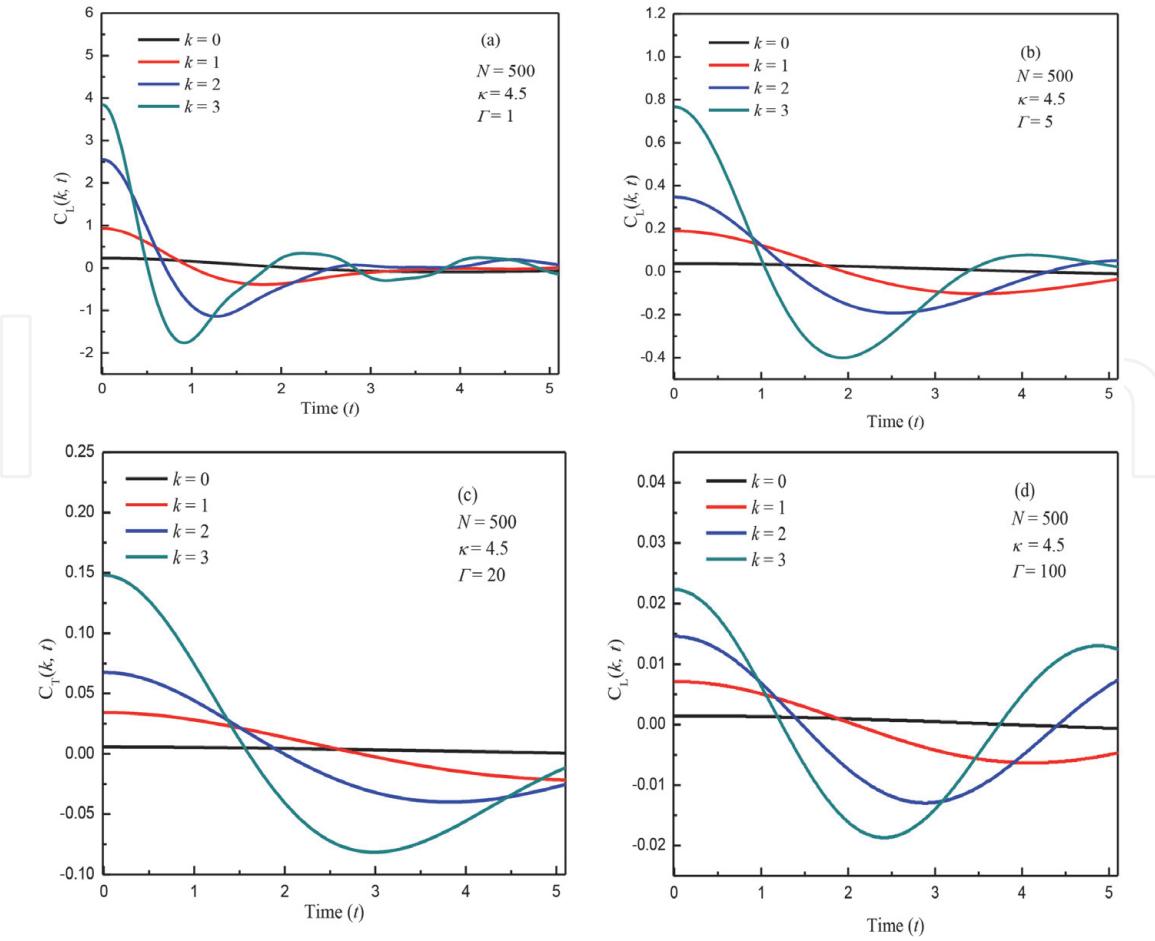


Figure 2.
 EMD simulations results of wave spectra of the longitudinal mode against the simulations time (t) for $\kappa = 4.5$ covering from non-ideal to liquid states ((a) $\Gamma = 1$, (b) $\Gamma = 5$, (c) $\Gamma = 20$ (d) $\Gamma = 100$) of 3D SCDPs and $N = 500$ for higher wave number ($k = 0, 1, 2$ and 3).

collisions between particles [29] and Shahzad et al., for low screening strength [2]. The modes of these waves in amplitudes of longitudinal waves increased at higher wavenumber ($k = 3$) and also at lower wavenumber has low peak amplitude mode clearly seems from results plotted in **Figures 2 and 3**. The damping of waves at a higher temperature would attribute this to viscous/collision and Landau damping. The effects of Γ on the propagation of waves in SCDPs are observed from four panels of **Figure 2**. The frequency modes are increases and amplitude decreases of $C_L(k, t)$ with increasing Γ . With increasing Γ the thermal effect decreases in the magnitude and the correlation effect clearly seems. **Figures 2 and 3** show the wave's spectra of longitudinal mode at different values of coupling which covering the non-ideal phase dusty plasma and also liquefy state. It is observed that the damping effect in wave's mode decrease with decreasing the plasma temperature. Here higher damping at $\Gamma = 1$ and at $\Gamma = 5$ comparatively low damped and then oscillate very at a low magnitude for $\Gamma = 5$. If we further increase the coupling values the damping decrease and longitudinal waves propagate in form of sinusoidal. At $\Gamma = 20$ and 100 waves in longitudinal modes properly propagate and with the passage of time, the magnitude of waves decreases we can observe **Figures 2 and 3 (d)** at $\Gamma = 100$ in the liquid liquefy phase.

There is a slight effect of screening strength (κ) on longitudinal wave's mode in plasma with respect to damping and propagation phenomena. The frequency and amplitude of waves in SCDPs are high at lower values of κ when we increase screening strength at the same N , k and Γ amplitude and wavelength are gradual decreases with respect of κ . The magnitude of $C_L(k, t)$ 0.2332, 0.0379, 0.0057 and

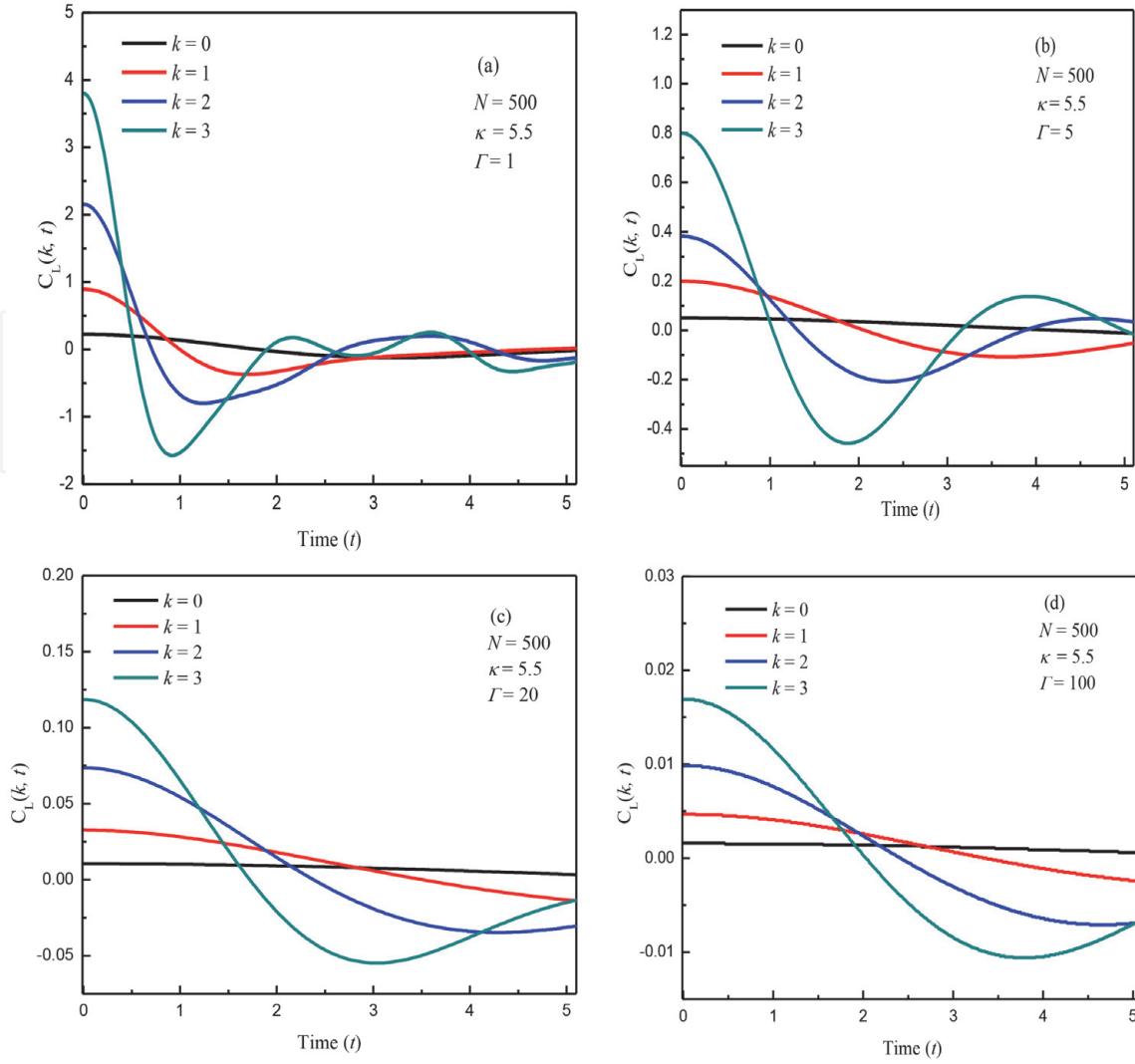


Figure 3.

EMD simulations results of wave spectra of the longitudinal mode against the simulations time (t) for $\kappa = 5.5$ covering from non-ideal to liquid states ((a) $\Gamma = 1$, (b) $\Gamma = 5$, (c) $\Gamma = 20$ (d) $\Gamma = 100$) of 3D SCDPs and $N = 500$ for higher wave number ($k = 0, 1, 2$ and 3).

0.0014 for $\Gamma = 1, 5, 20$ and 100 respectively at $\kappa = 4.5$ and $k = 0$. When we increase value of screening $\kappa = 4.5$ to $= 5.5$ then the magnitude of $C_L(k, t)$ at $k = 0$ increase 0.2244, 0.0508, 0.0105 and 0.0016. In this chapter, we have simulated at an $N = 500$ for the same combination of parameters (N, κ, Γ).

In this part, we have investigate $C_T(k, t)$ through EMD simulations for 3D SCDPs coulomb system in the classical ensemble (NVT) for $N = 500$ particles. The charged particles are interacting with each other via Yukawa pair potential. We have analyzed the behavior of the wave's spectra in the transverse (shear wave) direction in SCDPs, using Eq. (8), by EMD simulations technique. It is found that our results is calculated for $C_T(k, t)$ are in a good agreement using the EMD algorithm over an extensive range of plasma parameters and selecting a number of particles. We have ensured that the presented results of $C_T(k, t)$ are in satisfactory agreement with prior known simulation, theoretical and numerical results. In our MD simulation result, the effect of plasma temperature is observed on amplitude, wavelength, frequency, and propagation of waves in SCDPs.

Figures 4 and 5 demonstrate the Simulation results which are obtained for $C_T(k, t)$ of SCDPs plasma using EMD simulations at $k = 0, 1, 2$ and 3 , $\Gamma = 1, 5, 20$ and 50 for $\kappa = 4.5$ and 5.5 . The given simulation results of $C_T(k, t)$ spectra are compared with increasing and decreasing sequences of κ, Γ , and k . It is observed that the magnitude of transverse current waves has increases behavior with increasing wave numbers.

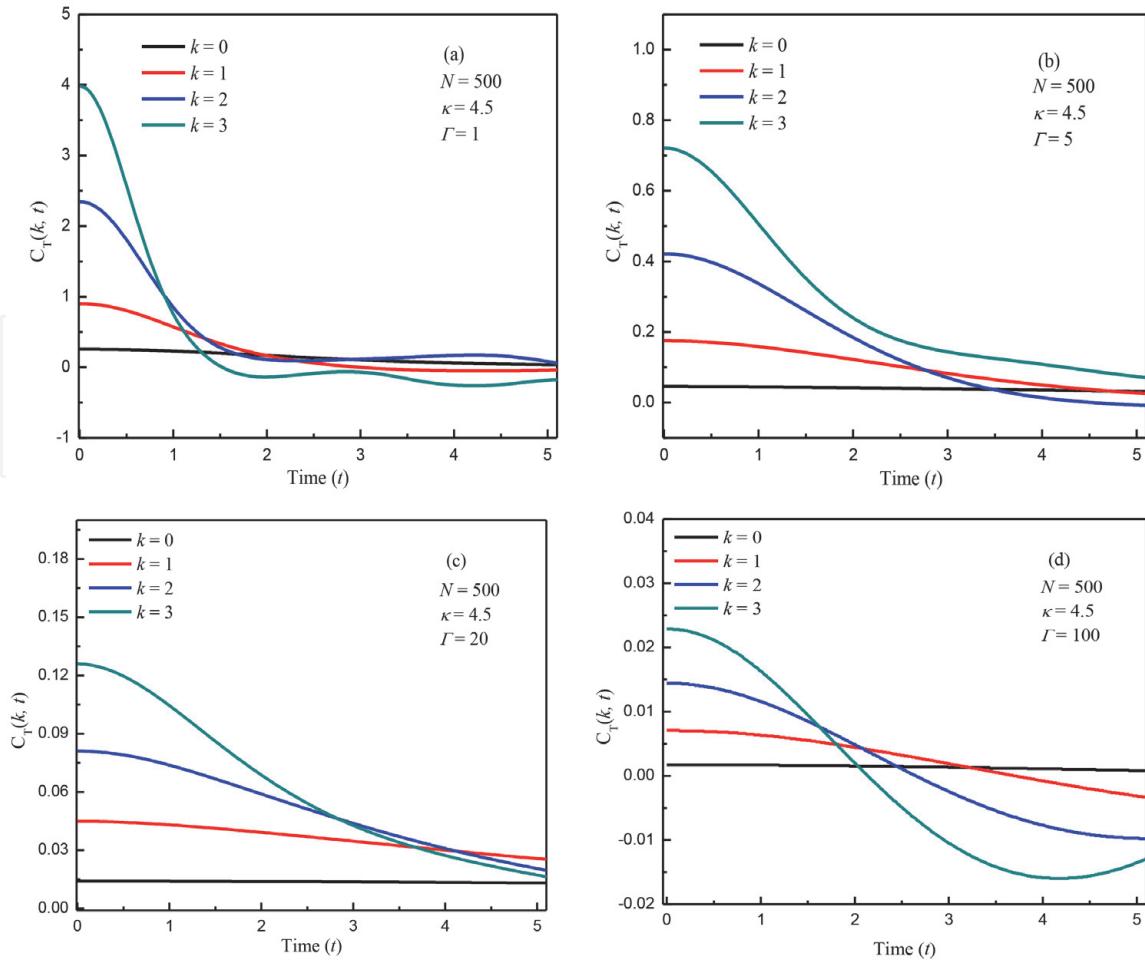
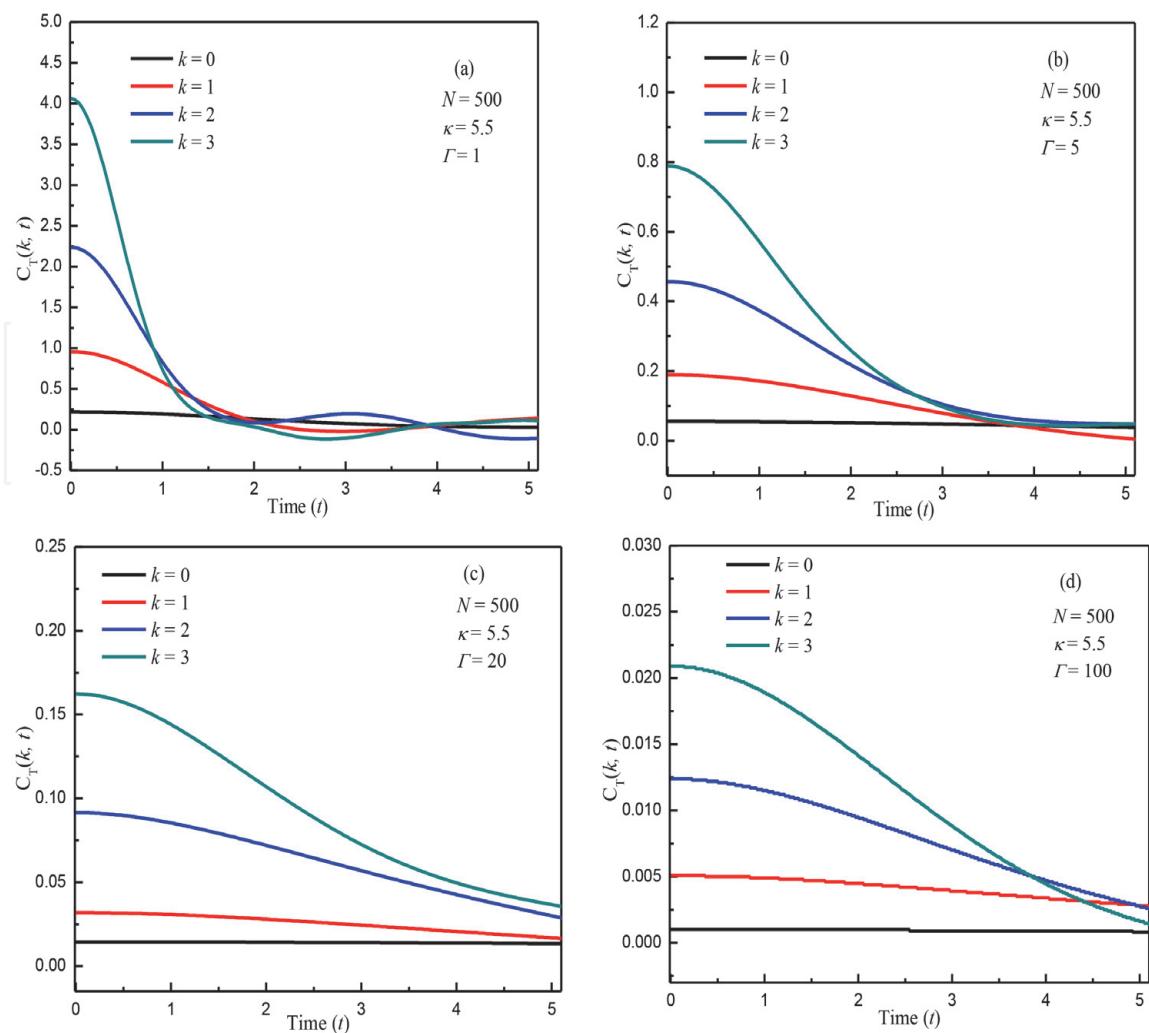


Figure 4.
 EMD simulations results of wave spectra of the transverse mode against the simulations time (t) for $\kappa = 4.5$ covering from non-ideal to liquid states ((a) $\Gamma = 1$, (b) $\Gamma = 5$, (c) $\Gamma = 20$ (d) $\Gamma = 100$) of 3D SCDPs and $N = 500$ for higher wave number ($k = 0, 1, 2$ and 3).

We have observed from further EMD simulations calculation that magnitudes of this wave have decreasing behavior for a high number of particles. The absence of any structure of strongly coupled plasma in the liquid phase the shear waves are not propagated through it. Wave's in SCDPs are highly damped at high plasma temperature or low values of coulomb coupling. In **Figure 4** plotted four penal of shear waves which covering from non-ideal to liquid state of dusty plasma.

The panel (a) of both **Figures 4** and **5** represent the results of $C_T(k, t)$ spectra in the non-ideal state of dusty plasma. It is observed from these figures that collective modes of wave spectra are highly damped at higher plasma temperature and damping of transverse waves reduce with corresponding to decrease the plasma temperature. In the non-ideal state of dusty plasma, the transverse current wave's mode is highly damped as compare to longitudinal modes especially at higher wave's number in our case. $C_T(k, t)$ spectra having increasing behavior in the magnitude for wave vector. The damping of waves at a higher temperature would attribute this to viscous/ collision and Landau damping that confirmed from earlier published work of [2, 29]. The effects of Γ on the propagation of waves in SCDPs are observed from four panels of **Figure 2**. The frequency modes are increases and amplitude decreases of $C_L(k, t)$ with increasing Γ . With increasing Γ the thermal effect decreases in the magnitude and the correlation effect clearly seems. Values of $C_T(k, t)$ at different parameters as for $k = 0(1)$, $C_T = 0.2558(0.9016)$, $0.0454(0.1749)$, $0.0141(0.0449)$, $0.0017(0.0071)$, and for the case $k = 2(3)$ as $C_T = 2.3453(3.9837)$, $0.4218(0.7214)$, $0.0810(0.1260)$, $0.0144(0.0229)$, at $\Gamma = 1, 5, 20, 100$ respectively for $\kappa = 4.5$. With the comparison of **Figures 4** and **5**, we have observed that there is a slight difference

**Figure 5.**

EMD simulations results of wave spectra of the transverse mode against the simulations time (t) for $\kappa = 5.5$ covering from non-ideal to liquid states ((a) $\Gamma = 1$, (b) $\Gamma = 5$, (c) $\Gamma = 20$ (d) $\Gamma = 100$) of 3D SCDPs and $N = 500$ for higher wave number ($k = 0, 1, 2$ and 3).

occurs when we increase the screening of dust charged particles. The propagation and damping behavior of waves in transverse direction remain nearly same with increasing screening. For particular wave's number (k), magnitudes of transverse waves have increasing behavior with increasing screening strength.

4. Summary

The EMD simulations are used to investigate the $C_L(k, t)$, and $C_T(k, t)$ for 3D SCDPs over an extensive range of plasma parameters κ , Γ , and k (wavenumber), N (number of particles in simulation box) and k . The first involvement of the presented simulation is that it delivers an understanding of propagation and damping phenomena of waves in SCDPs. In general, the amplitude, frequency of waves is analyzed. The presented simulation specifies that the waves are highly damped at high temperature $\Gamma = 1$, frequently propagates at intermediate and high value of $\Gamma = 20\text{--}100$. This investigation shows that the values of frequency and amplitude depend on κ , Γ , N , and k . It has been shown that the presented EMD method and earlier EMD techniques have comparable performance over the wide range of plasma points, both yielding reasonable results for correlation parameters. New simulations give more reliable and excellent data for the $C_L(k, t)$, and $C_T(k, t)$ for a wider range of κ and Γ are (4.5, 5.5) and (1, 100). The existing simulations

deliver more reliable data for existence for waves in SCDPs. In the absence of structure in dusty plasma, the shear wave does not support. The sound wave frequently propagates at medium and higher values of Γ in SCDPs. It is suggested that the presented EMD technique based on Ewald summation described here can be used to explore other ionic and dipolar materials. It is very interesting what other types of interaction potentials support correction parameters of strongly coupled plasma and how its strengths depend on the range of new interaction potentials.

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Abbreviation and symbol

EMD	equilibrium molecular dynamic
κ	screening strength
Γ	Coulomb coupling
k	wavenumber (wave vector)
N	number of particles
DP	dusty plasma
SCDPs	strongly coupled dusty plasmas
3D	three dimensional
$C_L(k, t)$	longitudinal current wave
$C_T(k, t)$	transverse current wave
CDPs	complex dusty plasmas
WCDPs	weakly coupled dusty plasmas
NLS	noctilucent clouds
RFP	reverse field pinch
MFT	magnetized target fusion
PF	plasma focus
MIF	magneto-inertial fusion
K_B	Boltzmann constant
n	plasma density
p	plasma pressure
T	plasma temperature
β	normalized plasma pressure
α	the minor radius of the plasma
I	plasma toroidal current
DAW	dust acoustic wave
PBCs	periodic boundary condition
RF	radiofrequency
DC	discharge current
DTC	dust transport code
MD	molecular dynamic



Author details

Aamir Shahzad^{1,2*}, Muhammad Asif Shakoori² and Mao-Gang He²

1 Molecular Modeling and Simulation Laboratory, Department of Physics,
Government College University Faisalabad (GCUF), Faisalabad, Pakistan

2 Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education
(MOE), Xi'an Jiaotong University, Xi'an, P.R. China

*Address all correspondence to: aamirshahzad_8@hotmail.com;
aamir.awan@gcuf.edu.pk

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