Multiphysics Simulation And Analysis Of Ion-Induced Charging For Microplastic Separation

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Abstract

Microplastic contamination in sediment samples presents analytical challenges, as microplastic concentrations typically remain below 1% in environmental matrices [1]. Current analytical workflows require cost-effective and rapid pre-separation methods to concentrate microplastic particles before subsequent analysis via DSC or density separation. Traditional density separation methods become impractical for large sample masses due to increased processing time and equipment requirements. Electrostatic separation offers a promising approach due to its energy efficiency and scalability, but requires sufficient surface charge density for effective particle adhesion and separation. However, detailed understanding of charge transfer to insulating microplastic particles in dynamic environments remains incomplete [1]. This study addresses that gap by combining multiphysics simulation with targeted experiments to investigate the transient charging behavior of common plastics conveyed under a corona electrode gun.

Simulations were performed using COMSOL Multiphysics® 6.3, employing the AC/DC Module® to characterize the electric field generated by a commercial GB3 charging electrode (KIST + ESCHERICH GmbH, Germany; up to -30 kV, tungsten emitter, ABS body) above a conveyor belt. A particle tracing approach was implemented, stochastically releasing negative ions from a spatial grid. Release probabilities follow a statistical distribution calibrated to experimentally observed corona emission patterns. The Particle Tracing Module® resolved the emission and detailed trajectories of negative ions in air. These paths determine how and where charge is delivered to the conveyor and microplastic particles. A bidirectional Electric Particle Field Interaction (EPFI) coupling represented feedback between mobile space charge and the evolving electric field. The time-dependent charge accumulation on both the conveyor belt and microplastic particles (HDPE, PP, PS) was simulated, with particles transported at controlled velocities through the corona discharge zone.

Parametric studies highlighted the sensitivity of charging dynamics to factors such as belt speed and material-specific properties including dielectric constant, surface conductivity, geometry, and charge retention characteristics. Multi-needle studies showed electrode needle spacing >7 mm prevents field line interference. Results demonstrate polymer-specific charging behavior, with HDPE achieving the highest surface charge density (-27 μC/m²), followed by PP (-12 μC/m²) and PS (-7 μC/m²), all well exceeding the calculated minimum threshold of 3 μC/m² required for electrostatic adhesion forces to overcome gravitational detachment. Optimal belt velocities were identified in the range of 0.3-0.5 m/s, balancing charging time with throughput.

Experimental validation employed a corona-ion separation system replicating the simulated configuration with the identical GB3 electrode, moving belt, and microplastic reference standards fabricated via 3D printing according to Harre et al. [2]. Surface charges on particles were measured directly with a calibrated Faraday cup, while the electric field above the belt was mapped using an electrostatic field meter.

This work has clarified key requirements for system optimization, including belt materials with surface resistivities of 10^{10} to 10^{13} Ω·m, permittivity (2.3-2.7), and belt thickness (0.6-1.0 mm). Critical design parameters include maintaining electrode-belt distance of 30 mm, belt velocities of 0.3-0.5 m/s, optimizing lateral electrode position relative to belt centerline, spacing electrode needles >7 mm apart for uniform charge distribution. These findings enable optimized electrostatic microplastic separation system design.

Reference

1. L. Kurzweg et al., Application of Electrostatic Separation and Differential Scanning Calorimetry for Microplastic Analysis in River Sediments, Frontiers in Environmental Science, 10, 1032005 (2022).

2. K. Harre et al., A New Class of Reference Material: Additively Manufactured Monodisperse Number Accurate Microplastic Reference Material through Microextrusion, Research Square, Preprint, 10.21203/rs.3.rs-6411430/v1 (2025).

Figures used in the abstract

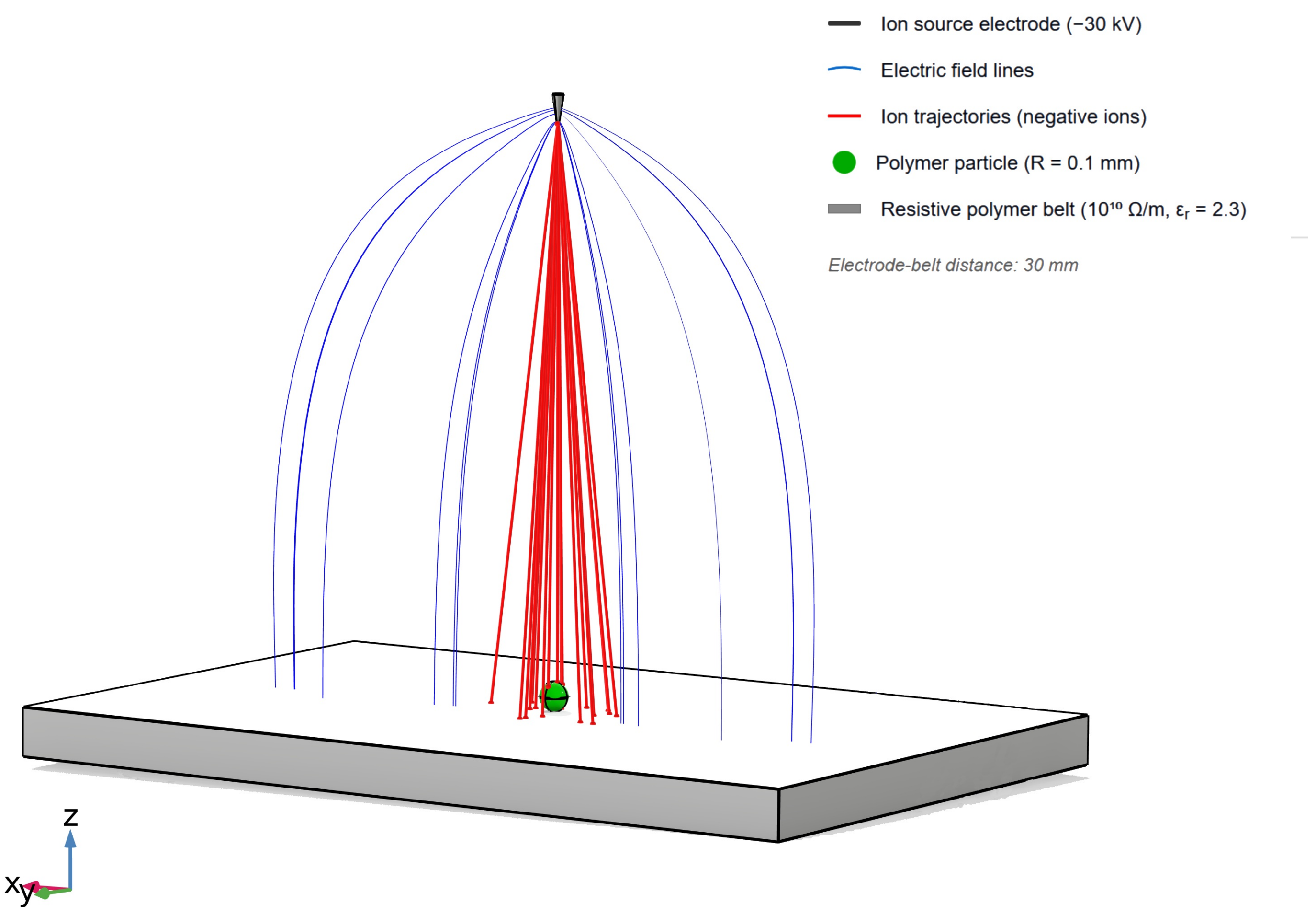

Figure 1 : Simulation setup in COMSOL Multiphysics® 6.3, showing negative ion emission from a tungsten needle electrode held at -30 kV, directed toward a polymer flake resting on a resistive conveyor belt. Electric field lines illustrate field focusing, while simula

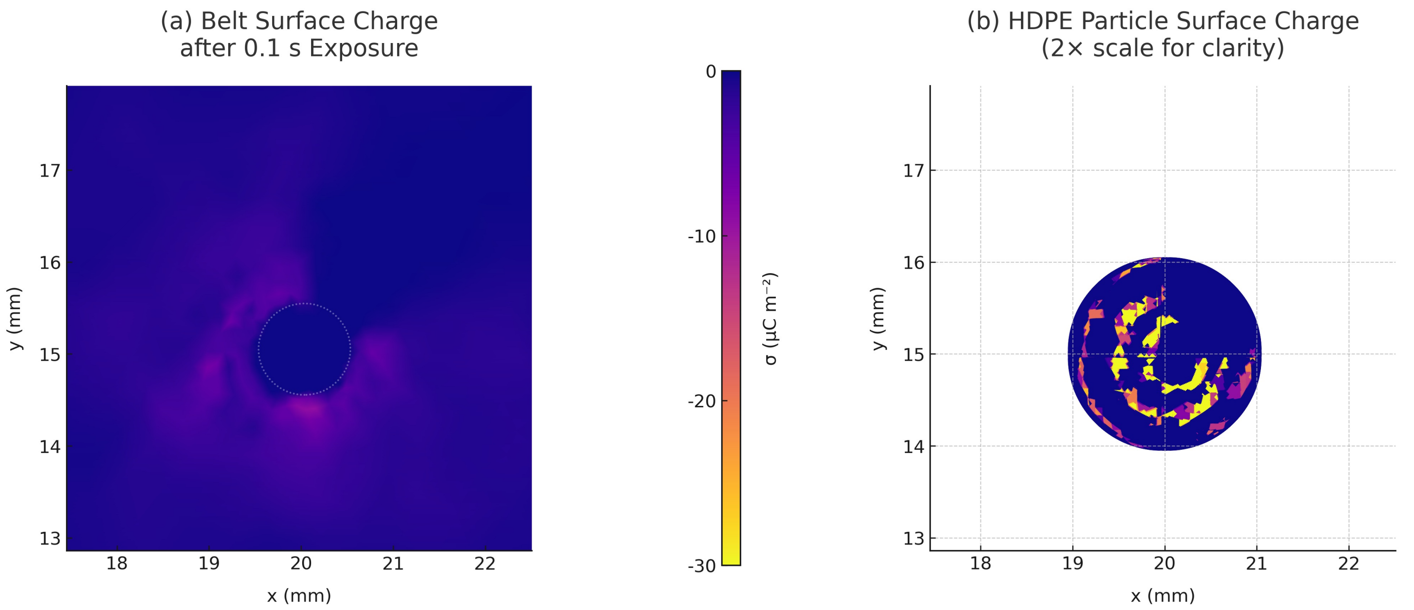

Figure 2 : Two-dimensional maps of surface charge density, σ (μC m^{-2}), after 0.1 s of negative corona exposure (-30 kV, 0.04 mA): (a) on the resistive belt surface and (b) on an HDPE flake (r = 0.1 mm, shown at 2× scale for clarity). Both panels are centered on the

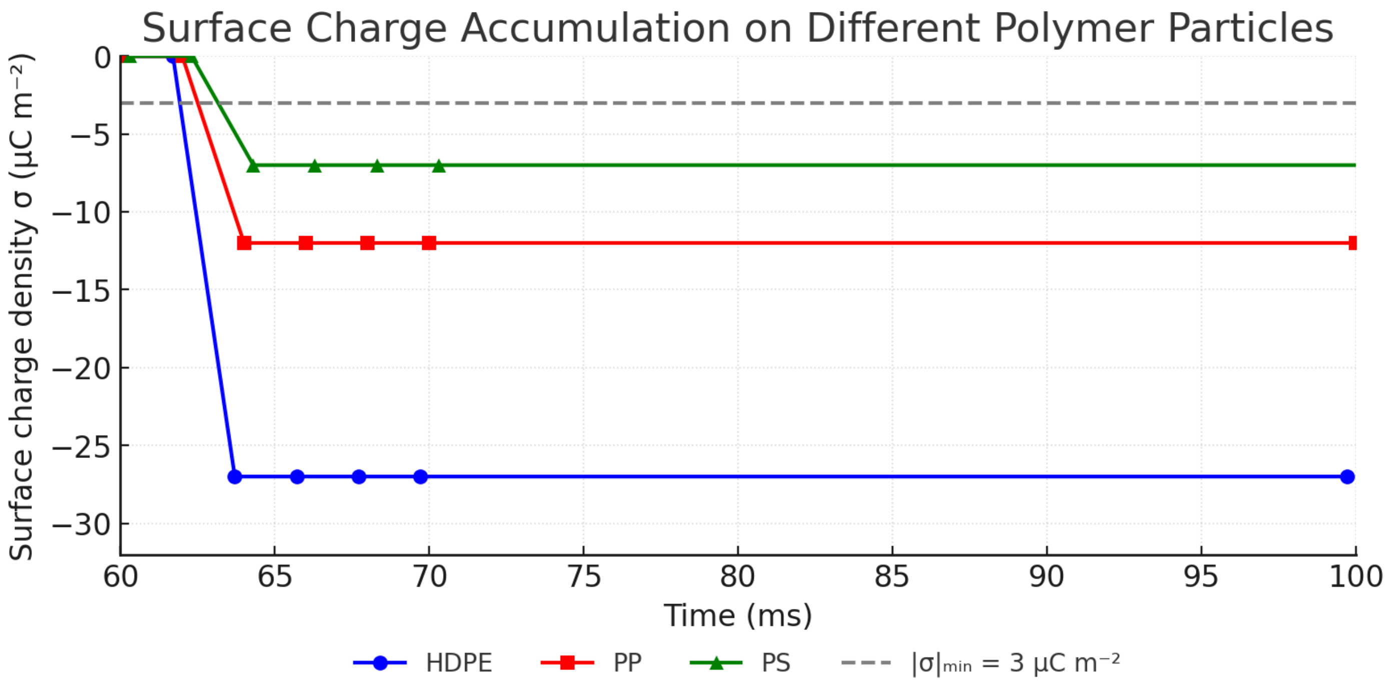

Figure 3 : Transient surface charge density, σ (μC m^{-2}), accumulated on HDPE, PP, and PS microplastic particles during 0.1 s exposure to a -30 kV corona discharge. Each curve displays a two-step deposition process: a rapid initial increase in negative surface charge