



Introduction

Microplastics (MPs): Plastic particles <5 mm, either primary or secondary

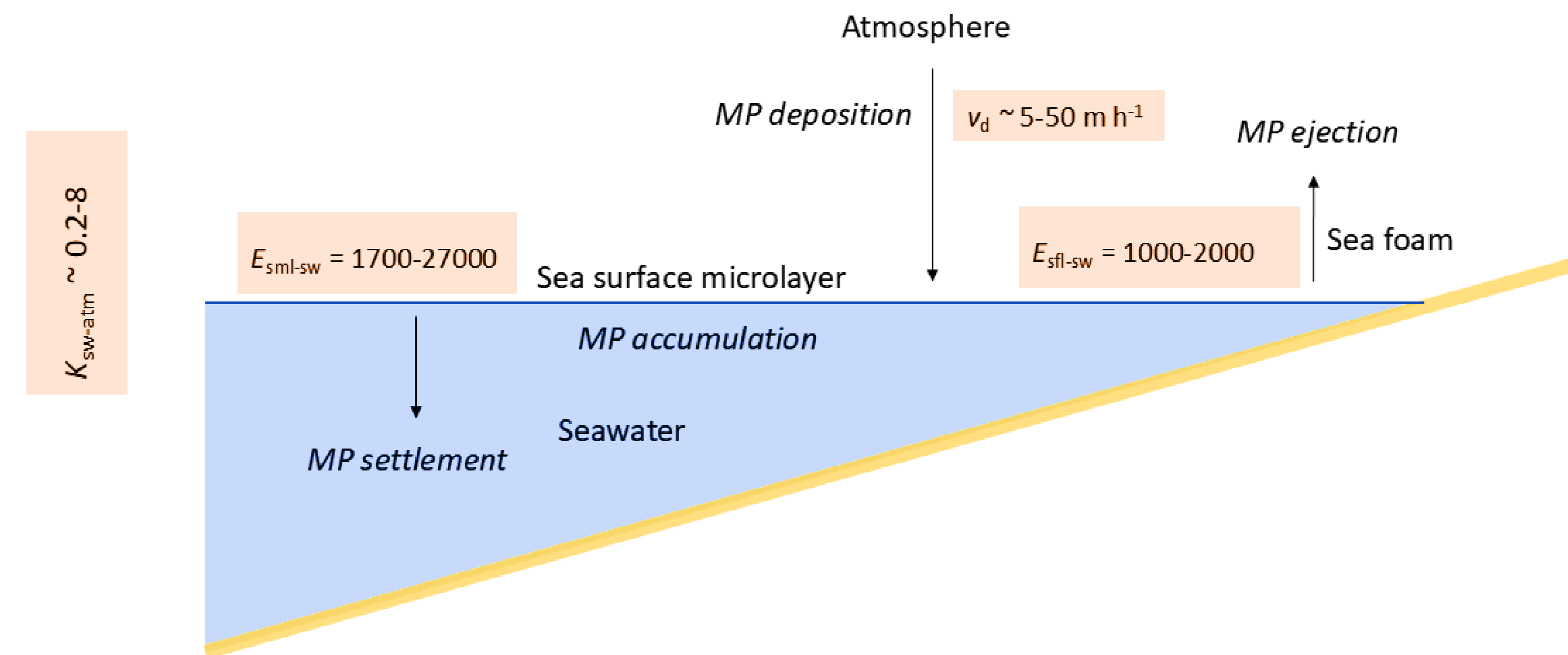
Widespread contamination: Increased plastic production and use + poor waste management

Environmental impacts: Ability to adsorb and transport chemical and microbial pollutants; threat to wildlife

Key coastal sources: Urban runoff, sewage, industrial and maritime activities

Atmospheric transfer processes: Deposition, wave breaking and bubble bursting

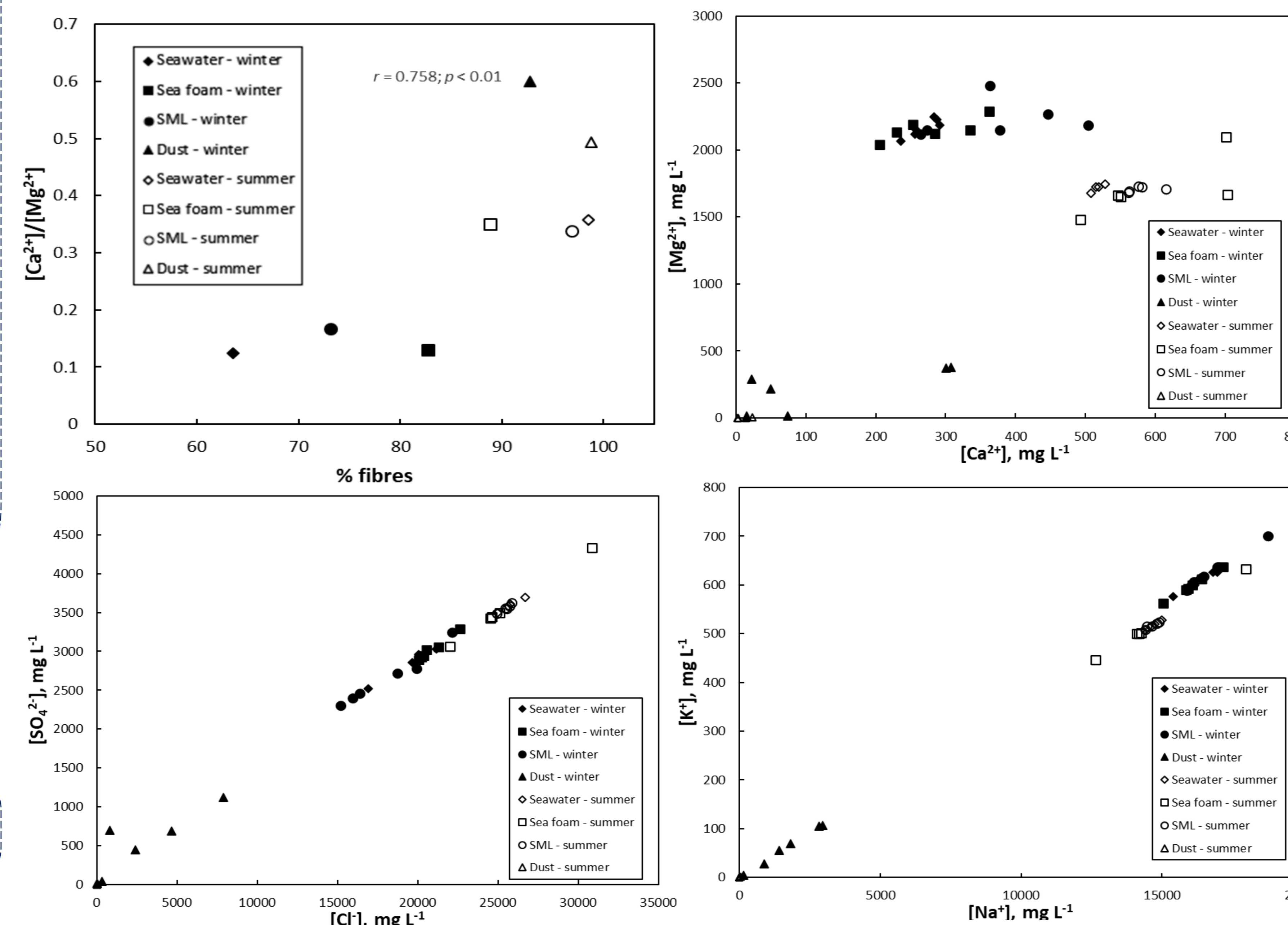
Aim of this study: Investigate seasonal dynamics of MPs + geochemical signatures and fluxes between atmosphere, SML, sea foam, and seawater.



Biogeochemical links & fractionation:

•The percentage of MPs as fibres correlates with the Ca^{2+}/Mg^{2+} ratio, suggesting that calcium-related biogeochemical processes (precipitation, flocculation, organic bridging) influence MP fractionation by shape and size.

•Size and polymer type appear to control transport and fate (e.g., polyester common in seawater but scarce in the lower atmosphere; rubbers more abundant in air).



Sources & inputs: Main sources include wastewater/urban runoff, tyre wear, marine and urban paints, ship discharges, and direct atmospheric deposition. These inputs deliver MPs directly to underlying seawater and to the sea surface microlayer (SML).

SML (key role):

•SML concentrations (areal): $\approx 202 \text{ m}^{-2}$ (winter) and $\approx 151 \text{ m}^{-2}$ (summer).
•SML is highly enriched relative to bulk water: $E_{sml-sw} \approx 2.5 \times 10^3$ (winter) and $\approx 1.8 \times 10^3$ (summer), the SML acts as a concentrated reservoir and an interface for exchange.

Pathways & fluxes (outputs):

• **Foam/bubble ejection** → atmosphere:

Enrichment in sea foam relative to seawater $E_{sf-sw} \approx 1000$ (winter) and ≈ 390 (summer); for the finest fraction values are higher (≈ 2000 and 780). Foam-mediated ejection is an important transfer route from SML/water to air.

• **Atmospheric suspension** → deposition:

Depositional fluxes and suspended concentrations in the lower atmosphere were higher in winter. Settling velocities estimated from measured suspension and deposition: $vd \approx 27.9 \text{ m}\cdot\text{h}^{-1}$ (winter) and $\approx 46.6 \text{ m}\cdot\text{h}^{-1}$ (summer); size-dependent values for fine particles were lower (≈ 5.5 and $21.7 \text{ m}\cdot\text{h}^{-1}$).

Water–air partitioning:

•Partition constant $K_{sw-atm} = [MP]_{sw} / [MP]_{atm}$: ≈ 2.44 (winter) and ≈ 7.87 (summer), overall preference for the aqueous phase, stronger in summer.

•For the finest particles ($<100 \mu\text{m}$), $K_{sw-atm} \approx 0.17$ (winter) and 0.31 (summer), indicating a relative preference for the atmospheric phase.

One-line takeaway:

The SML concentrates MPs ($E_{sml-sw} \sim 10^3$) and mediates transfers between seawater and atmosphere: foam-mediated ejection and atmospheric deposition create size- and shape-dependent fluxes that vary seasonally.

Materials and Methods

Sampling site: Coastal zone of Bushehr, Persian Gulf, Iran, shallow ($<5 \text{ m}$), rocky-gravelly substrate, semi-diurnal tides ($\sim 80 \text{ cm}$), salinity $>40 \text{ ppt}$.

Sampling was conducted in winter and summer 2024 under different weather conditions: stormy, moderate, and calm days.

Sample types & collection: Seawater, sea foam, sea surface microlayer (SML), airborne particles, and deposited dust were collected using pre-cleaned glassware and metallic components. Seawater and foam were sampled in 500 mL bottles and sieved ($38 \mu\text{m}$). SML was sampled with a glass cylinder and sieve. Airborne MPs were captured on $1 \mu\text{m}$ glass fibre filters using vacuum pumps, and dust was trapped in water-filled collectors.

MP identification: MPs were isolated via vacuum filtration ($2 \mu\text{m}$), counted, and classified by size, shape, and color under a digital microscope (up to $200\times$). A subset ($n=95$) was analyzed by micro-Raman spectroscopy (785 nm) for polymer type.

Major ions & statistics: Major seawater ions were measured by ion chromatography. MP concentrations were normalized per volume or area. Statistical analyses (correlations, t-tests) were conducted in Minitab v19 ($\alpha=0.05$).

Results and Discussion

Overall: Total MPs counted, Winter: 935 particles; Summer: 444 particles. Fibres dominated all compartments.