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# Synergistic feedbacks between steel slag and phytoplankton enhance ocean carbon dioxide removal

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Rising atmospheric $CO_2$ levels have created an urgent need for carbon dioxide removal (CDR) to meet global climate targets. Ocean-based enhanced weathering, dispersing alkaline materials over the ocean to accelerate natural mineral weathering and increase seawater alkalinity, represents a promising CDR approach. Steel slag, an industrial by-product generated in hundreds of millions of tons annually, is particularly attractive due to its rapid dissolution rate, high alkalinity yield, and alignment with circular economy principles. While increasing studies have examined phytoplankton responses to elevated alkalinity, the direct interactions between mineral particles and marine phytoplankton remain poorly characterised. Here, we examine these interactions using steel slag and two marine phytoplankton species: a diatom and a dinoflagellate. Our results show that steel slag both increases seawater alkalinity and supplies trace metals that stimulate phytoplankton growth. Under nutrient depleted conditions, steel slag at concentrations of 10 to 1000 mg/L enhanced growth rates and photosynthetic performance. We further identify synergistic feedback in which phytoplankton actively acquire nutrients from mineral particles, thereby accelerating steel slag dissolution. Additionally, we find that steel slag may increase marine organic aggregate density through ballasting and inhibit heterotrophic bacterial activity, potentially improving biological carbon pump efficiency, particularly in trace metal limited open oceans. Numerical simulations of steel slag dispersal in trace metal limited, macronutrient rich regions indicate that climate variability can strongly influence the transport and residence of slag constituents, potentially localising their effects. While our results are encouraging, we also observe that steel slag may trigger blooms of harmful algal species, underscoring the need for careful ecological risk assessment. Our findings reveal that steel slag interacts with marine phytoplankton to enhance the ocean carbon sink through both geochemical and biological pathways, supporting its potential use for ocean CDR provided that deployment strategies account for biological feedback and climate driven transport dynamics.