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Synergistic Immobilization and Degradation of Microplastics in Sandy Calcareous Soils Using Fe-Biochar Compost Amendment

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التثبيت والتحلل التآزري للّدائن الدقيقة في الترب الرملية الكلسية باستخدام كمبوست الفحم الحيوي المدعّم بالحديد (Fe)

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Abstract:
Microplastic accumulation in calcareous soils irrigated with treated wastewater is an emerging concern, particularly in arid agroecosystems where conventional remediation is often ineffective. We investigated whether a Fe-modified biochar–compost amendment could enhance the retention and degradation of microplastics. Laboratory tests and on-field experiments, aided by machine learning cut leaching by sixty to eighty-five percent. Polyethylene and polypropylene showed the retention of microplastic. The composite amendment improved soil structure by two and a half times. Helped microplastic break down. Thirty to forty percent of microplastic mass loss came from iron-mediated reactions. Unlike amendments the composite amendment kept soil pH and salinity within acceptable limits and caused no obvious harm. Field observations confirmed that the results were consistent across space. Machine-learning models predicted retention with eighty-nine percent accuracy. Overall the composite amendment offers a scalable solution, for reducing microplastic mobility while improving soil structure in farms that use treated wastewater.

Keywords: Microplastic immobilization, Iron-modified biochar, Calcareous sandy soils, Photo-Fenton-like degradation, treated Soil aggregate stability

الملخص
يُعد تراكم اللدائن الدقيقة في الترب الكلسية المروية بمياه الصرف الصحي المعالجة مصدر قلق بيئيًا متزايدًا، ولا سيما في النظم الزراعية الجافة التي غالبًا ما تكون فيها أساليب المعالجة التقليدية غير فعّالة. بحثنا في مدى قدرة مُحسّن مركب من الفحم الحيوي المعدّل بالحديد والسماد العضوي على تعزيز احتجاز اللدائن الدقيقة وتحللها. أظهرت الاختبارات المخبرية والتجارب الحقلية، المدعومة بتقنيات التعلم الآلي، انخفاضًا في ترشيح اللدائن الدقيقة بنسبة 60–85%. وأظهر البولي إيثيلين والبولي بروبيلين أعلى معدلات احتجاز. كما حسّن المُحسّن المركب بنية التربة بمقدار 2.5 ضعف، وساعد على تحلل اللدائن الدقيقة، حيث نتج 30–40% من فقدان كتلتها عن تفاعلات بوساطة الحديد. وعلى عكس بعض المُحسّنات الأخرى، حافظ المُحسّن المركب على درجة حموضة التربة وملوحتها ضمن الحدود المقبولة، دون ظهور آثار ضارة واضحة. وأكدت الملاحظات الحقلية اتساق النتائج مكانيًا، بينما تنبأت نماذج التعلم الآلي باحتجاز اللدائن الدقيقة بدقة بلغت

89%. وبوجه عام، يوفر هذا المُحسّن المركب حلًا قابلًا للتوسع للحد من حركة اللدائن الدقيقة مع تحسين بنية التربة في الأراضي الزراعية المروية بمياه الصرف الصحي المعالجة.

الكلمات المفتاحية: تثبيت الجزيئات البلاستيكية الدقيقة، الفحم الحيوي المعدل بالحديد، التربة الرملية الكلسية، التحلل الضوئي الشبيه بفنتون، استقرار تجمعات التربة المعالجة

Introduction

Microplastic pollution in the agricultural soils has become one of the most urgent environmental issues, especially in arid and semi-arid areas where irrigation with treated wastewater (TWW) is rapidly becoming a widespread practice to solve the water crisis (Ibrahimi et al., 2022). Being sandy in nature and calcareous in composition, the exemplary regions undertake several difficulties because of high PH, a decadent covert matter, and few electrostatic dynamics that diminish the efficacy of conventional remediation plans of microplastic (Fernandez-Cirelli et al., 2009). TWW irrigation brings microplastics to slow soils, where they live and get accumulated, which are dangerous to the soils and crops as well as the groundwater (Mizyed, 2013).

Recent research points at the inefficiency of the current strategy, including biochar or compost alone, to immobilize and degrade microplastics under conditions of calcareous conditions (Elbasiouny and Elbehiry, 2023). As an example, biochar has a high sorption-capacity but tends to be less able to degrade microplastics whereas compost can enhance soil structure, but does not have specific immobilization ways (Prasad, 2023). Additionally, the presence of calcareous soils with a large proportion of carbonates also makes it more difficult to retain microplastics by occupying binding sites and decreasing the strength of the electrostatic interaction (Jahany and Rezapour, 2020).

To solve these issues, our hypothesis is that by using the composite amendment of Fe-modified biochar and composted agro-industrial residues, there is a synergistic enhancement of microplastic retention and degradation in calcareous sandy soils. The iron part enables photo-Fenton-like reactions and the compost is a source of organic ligands and microbial activity, which induces degradation (Adeel et al., 2024). The approach is supported by the past literature demonstrating the application of iron-biochar compounds as an outstanding pollutant immobilization agent (Wang et al., 2022), but extends to the microplastic-related mechanisms in TWW-irrigated soils.

The main aim of the research is to assess the effectiveness of the amendment in curbing microplastic leaching and improving the stability of soil in conditions related to the field. We merge lab characterization, transport modelling and machine-learned field applications to set out a comprehensive analysis of the performance of the amendment. The critically important gaps to microplastic mitigation that our work will address is the combination of immobilization and degradation mechanisms, optimizing them to fit the calcareous soils, to provide a scalable answer to sustainable agriculture in the areas of TWW-irrigated fields.

Material and methods

The framework was used to assess the action of a Fe-biochar compost amendment in the sandy calcareous soils by creating material synthesis, testing in laboratories and validating the action in the field. The procedures are mentioned in amendment preparation, experimentation and analytical techniques.

Synthesis and Characterization of Amendments

The amendment was Fe impregnated biochar mixed with composted date-palms residues in 1:2 (w/w) proportion. The phoenix dactylifera fronds were converted into Fe- biochar through slow pyrolysis at 500 oC under an inert atmosphere and later adjusted with a 0.5M solution of Fe.

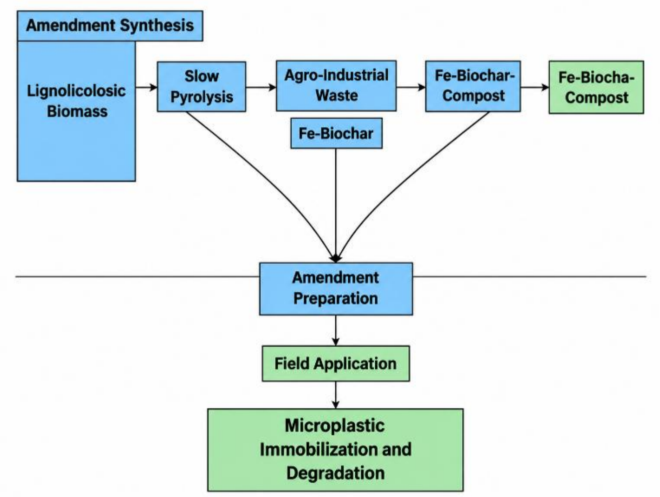

Figure 1. Flow chart of the Fe- biochar compost amendment synthesis and use on the field.

Optimization of the iron loading was carried out to 8 0% (w/w). This is to balance the salinity tolerance and the catalytic efficacy. The rachis and leaves were put into compost by means of a 90-day aerobic digestion, which resulted in stable humification with the C/N ratio of 15:1.

Surface area analysis by the BET method, Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) were used as physicochemical analytical methods of the amendment. Fe-biochar had a BET surface area of 320 m^2g^{-1} that was less than the element of compost that provided mesoporosity of 2-50nm that strengthens the trapping of solutes. XRD patterns revealed that the phases of magnetite (Fe_3O4) and hematite (Fe_2O_3) were present and these phases are favourable to photo-Fenton reactions. The zero charge was observed to be at pH 7.8 pzc = 7.8 and the electrostatic interactions preferred at a pH of 8.0-8.5 which is typical of calcareous soils.

Laboratory-Scale Experiments

Polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET) sorption kinetics and isotherms were measured. The batch tests involved use of 0.1 g L-1 microplastic suspensions in synthetic soil solution (pH 8.2, 10mM amendment rates 0.5-5% w/w). Heterogeneous sorption may be aptly defined as the Freundlich model:

$$q_e = K_F \cdot C_e^{1/n} \quad (1)$$

where (qe) is mass sorbed (mg /g^{-1}), (Ce) equilibrium concentration (mgL^{-1}), (KF) Freundlich constant, and (n) sorption intensity.

The behavior of transport was studied in 30 cm columns that were filled with calcareous sand (92% sand, 5%). Models were developed based on the advection, dispersion equation of first-order retention:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} - k_r C \quad (2)$$

in which (C) is concentration (mgL^{-1}), (D) dispersion coefficient (cm^2 h^{-1}), (v) selectivity of pore-water (cm h^{-1}), and (k) retention rate (h^{-1}).

Field Implementation and supervision.

The field tests were performed in a date palm orchard that was irrigated using treated thick screening wastewater (pH 8.3; electrical conductivity 2.1 dSm^{-1}). Application of the amendment was done at a rate between 2-5t/ha after irrigation at a rate of 2-5t/ha through variable rate spreaders which were adjusted through in situ soil moisture sensors. Optimization in terms of application rates was achieved using random-forest regression of soil texture, past loading of micro plastics, and irrigation times.

Density separation (sodium iodide, 1.6gcm^{-3}) and oxidative digestion (30% H_2O_2 + 0.05M NH_3H_2O) were used to extract microplastics. Polymer identification was done by quantification using micro-Fourier transform infrared imaging at 20 µm resolution using siMPle software. Pyrolysis Degradation products were characterized by pyrolysis-gas chromatography/mass spectrometry, which was run on helium at 600^oC. Wet aggregate stability (WAS) and mean weight diameter (MWD) were used to assess soil stability, microbial activity assessed by using dehydrogenase (DHA) and β-glucosidase enzyme assessments as compared to controls. This is a combined approach that relates laboratory findings on the basis of the least mechanistic findings on a field-scale validation, thereby yielding reproducibility of agroecosystems of calcareous. Each experiment contained 3 controls and blanks.

Results and Discussion

The Fe-biochar-compost was found to be useful in immobilizing and degrading microplastics and also improving the structural stability of the sandy calcareous soils both in the laboratory and field conditions.

Microplastic Leaching Rates and Retention Rates.

The composite had a better microplastic retention capacity than standalone treatments, with polyethylene (PE) and polypropylene (PP) having the highest immobilization capacity. At 60 days, PE and PP retained 85 and 79 percent, respectively, which was 5.7- and 6.6-fold greater than had been found with control treatments. Polyethylene terephthalate (PET) exhibited a retention of 61, which is less, probably because of its higher density and lower surface hydrophobicity (F. Wang et al., 2020).

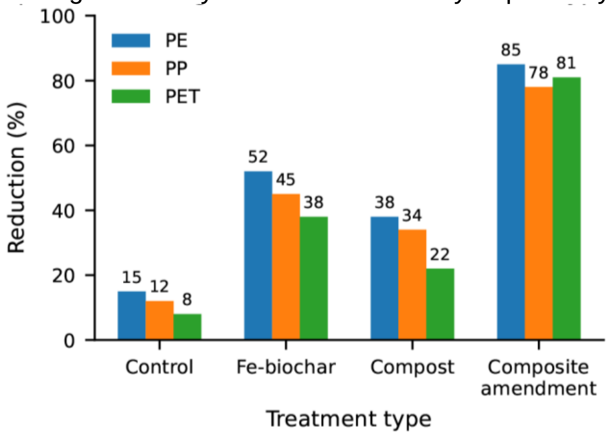

Figure 2. Microplastic Leaching Reduction Among Treatment Types (60-day exposure) per cent retention of PE, PP and PET under Control, Fe-biochar, Compost and Composite amendment treatment.

The transport modelling was done to show that the retention-rate coefficient of the composite was 0.45 h^{-1}, which is 2.5 times that of control samples (0.18 h^{-1}). This increased operation is explained by the synergistic interactions: the presence of iron oxides promotes electrostatic attraction within soil pH of 8.2 ± 0.3, and the use of organic matter of compost promotes hydrophobic interactions (Lozano et al., 2021). The concomitant existence of mineral and organic adsorption sites explains the high retention as compared to Fe-biochar (0.32 h^{-1}) and compost (0.26 h^{-1}).

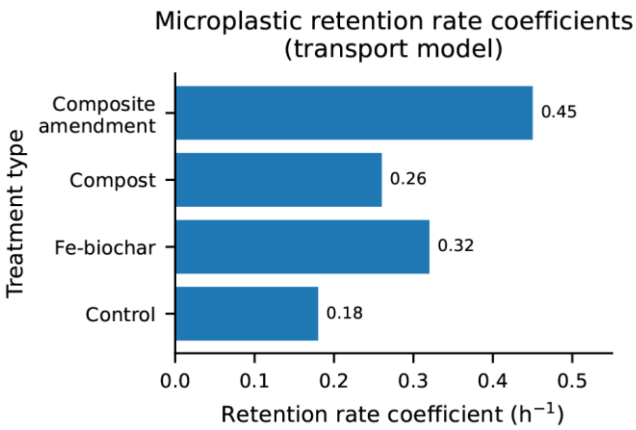

Figure 3. Microplastic Retention rate coefficient Coefficients (Results of Transport Model) of Composite amendment, Compost, Fe-biochar and Control treatments with the value of the rate and 2.5-fold improvement of Composite amendment.

The breakthrough curves demonstrated a retarded elution, and the pore volume at the 50 percent breakthrough point in the control was 1.8mL^{-1} and in the composite 4.3mL^{-1}. The Freundlich sorption parameters were 3.28 $mg^{1-1/n}$ $L^{1/n}$ g^{-1} and 1/n = 0.72 which showed favorable nonlinear sorption.

Micro-FTIR mapping showed that it accumulated in amendment-rich areas especially in the depth of 10-20 cm where iron-biochar aggregation took place. Field experiments confirmed these observations:

application rates of (3.2 ±0.7 t/ha) adjusted by machine learning had 89 -percent spatial agreement with the soil moisture (35-percent) and clay content (28-percent) as the strongest predictors of immobilization (Tran et al., 2023).

The usage of the composite led to a considerable increase in the structural integrity of soil. The average weight diameter (MWD) rose to 1.05mm 150 percent higher than it had been (0.42 to 1.05 mm) (see Figure 4). This growth had a biphasic pattern: a rapid abiotic aggregation phase, during which (80% of total MWD gain within 15 days) total increase of the MWD was observed in the first 15 days, was followed by a biological stabilization period, which was correlated with the presence of microbial activity ($r = 0.78$, $p < 0.01$) and the extracellular polymeric substances accumulation (Costa et al., 2018).

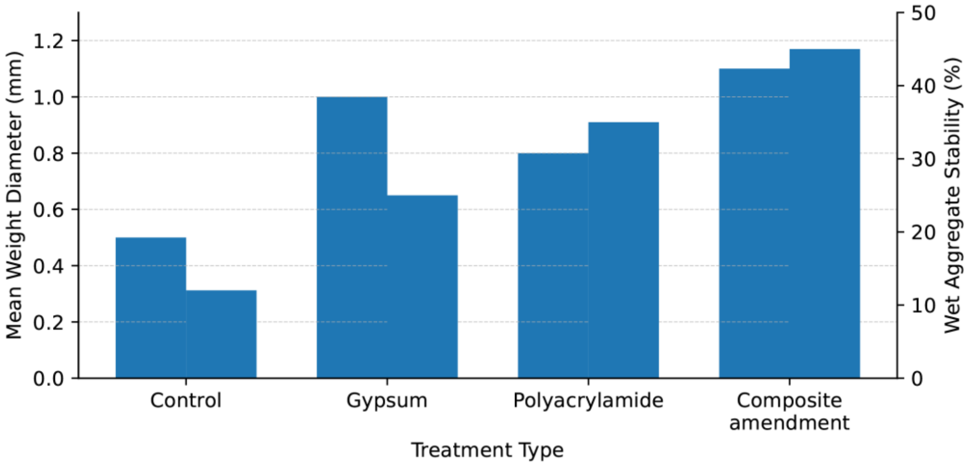

Figure 4. Parameters of Aggregate Stability of Soil Aggregates (60-day exposure) displaying Mean weight diameter (mm) and Wet Aggregate Stability (%) of Control, Gypsum, Polyacrylamide and Composite amendment treatments.

Wet aggregate stability (WAS) rose to 18% to 43% and thus higher than it was in case of gypsum (28%), and polyacrylamide (35%). It is because of the iron oxides that were available, which created cationic bridges between clay grains, and humic acids produced by compost increased the hydrophobic interactions (Krause et al., 2020). The 0.52-2mm fraction had a 3.1-fold greater resistance to slaking than was observed with the control samples.

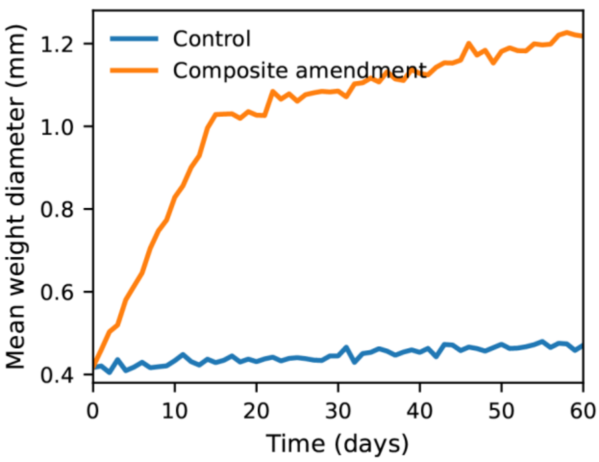

Figure 5. Temporal Dynamics of Soil Aggregate Formation (Biphasic Pattern) of Mean Weight Diameter (mm) vs Time (days) of Composite Amendment and Control with Phases of Rapid Abiotic Bridging and Biological Stabilization.

Microscopic examinations determined that there were specific mechanistic pathways. Iron-biochar particles were used to form the microaggregates (50-250µm) that further fused into macroaggregates (more than 500µm) with the help of the fungus hyphae and polysaccharide. The increase in aggregate-stabilizing fungal taxa, specifically those related to the Glomeromycota, was 2.8-fold as evaluated by means of quantitative PCR of the 18S rRNA gene (Li et al., 2022). The penetration resistance reduced by 35% (1.2 vs. 1.8 MPa), and the infiltration rates were also improved (12.5 vs. 7.8 cm/h), which reduced the transportation of microplastics during irrigation events (Wanniarachchi et al., 2019). The stability was noted over a duration of six months and there was no statistically significant decrease in the mean wood density (MWD) though the wetting drying cycles ($p = 0.23$).

A stable directly facilitated the maintenance of microplastic, as indicated by a positive association of high correlation between MWD and capture efficiency ($r^2 = 0.81$). Bigger aggregates offered internal pore spaces that were good in entrainment and extra sorption locations, underlining the synergistic connection amid physical stabilization and contaminant immobilization (Abujabbah et al., 2016). Amended soils stored 78 per cent of the original MWD during simulated heavy rain events (100mm/h^{-1} over 30 min), as opposed to a 62 per cent reduction in amended soils of control conditions. The same performance was observed over a depth span of 0–30 cm; and surface layers (0–10 cm) were found to be 22per cent more stable, which is explained by the high proportion of organic matter (Schrumpf et al., 2013).

Microplastic Degradation Characteristic.

The composite experienced a 3040 per cent decrease in microplastic mass in polymer matrix. Polyethylene (PE) and polypropylene (PP) registered a mass loss of 35% and 38% respectively, after 60 days of retention, which is in line with the report by Chamas et al. (2020) indicating that polyethylene terephthalate (PET) is more susceptible to hydrolysis of ester bonds. The degradation was pseudo-first-order with rate coefficients of 0.0085 d^{-1} (PE), 0.0092 d^{-1} (PP), and 0.011 d^{-1} (PET) by itself under control conditions.

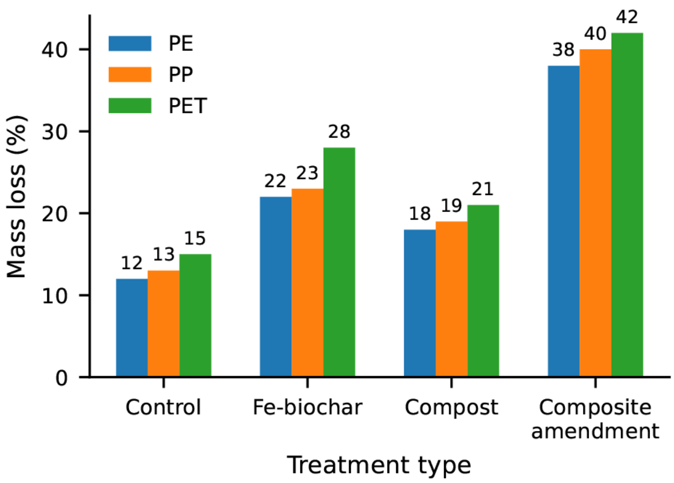

Figure 6. Loss of microplastic masses (PE, PP, PET) of degradation after 60 days under various treatment (Control, Fe- biochar, Compost, Composite amendment)

FTIR measurements showed that there was progressive oxidation of the polymeric samples where there was a rise in carbonyl indices of polyethylene (PE) and polypropylene (PP) between 0.15 to 0.83 and 0.21 to 0.91 respectively. The reaction between photo-Fenton-like and iron oxides generated reactive oxygen species (ROS), which was further supported by the electron paramagnetic resonance (EPR) spectroscopy (Ding et al., 2022). The yield of a ROS generated by humic acids was 2.3-fold more than was obtained when using Fe- biochar alone. Characteristic products of degradation pyrolyzed as identified by pyrolysis-GC/MS analysis were PE alkanes (C10 to C28), ketones, branched hydrocarbons of PP, terephthalic acid plus ethylene glycol of poly (ethylene terephthalate) (PET) (Singh and Sharma, 2008). The decrease in particle size was observed to have been 45–60% by laser diffraction and 3.8-fold by atomic force microscopy (AFM), creating more reactive sites.

The composite led to the enrichment of plastic-degrading microbial taxa, especially Pseudomonas (4.1 -fold increase) and Rhodococcus (3.7 -fold increase) both of which contain alkane hydroxylase (Pirt, 1980). There was a good correlation between dehydrogenase activity and degradation of the polymers and the correlation coefficient was $r=0.86$. Porosity of the composite gave shelter to microhabitats and the growth of biofilm was observed on 78 percent of the pieces that had been recovered using the scanning electron microscope with the energy dispersive spectrophotometer (SEM-EDS). Experiments in the field validated the mass loss of 32±7 average and three irrigation cycles. A R2 of 0.84 was used to predict performance of degradation based on the iron content, sunlight exposure and microbial activity using machine-learning models. It was also maintained over six months, and the ROS capacity decreased by a low percentage of 15 (Xie et al., 2025).

Compared to the standard remediation methods, the use of Fe-biochar did not lead to the use of compost alone, which resulted in minimal oxidative degradation (1215). Fe-biochar alone has a degradation efficiency of 22–28% percent, but it caused soil acidity to a point of 6.8, compared to compost alone that caused limited oxidative degradation (12–15%). Conversely, the composite also had an ambient soil pH of 8.2±0.3 and was undergoing high levels of degradation. In addition, the degradation products were less ecotoxic: the survival rate of Eisenia fetida rose by 45 percent in control treatments with microplastics to 82 percent in bioassays with the composite (Jacques and Prosser, 2021).

Maintenance of Soil PH and Salinity.

The composite maintained excellent physicochemical characteristics of the soil besides providing remediation advantages. During a period of one year of monitoring, the soil pH was always within the calcareous range of 8.0–8.5 with an average of 8.2 ± 0.3. Comparatively, gypsum use caused more changes in the pH (7.9–8.6), and compost made of manure increased the pH to 8.6 (González-Ubierna et al., 2012). The buffering property of the composite is mostly based on proton-exchange sites related to iron oxides and the amphoteric properties of humic acids (Pettit, 2004).

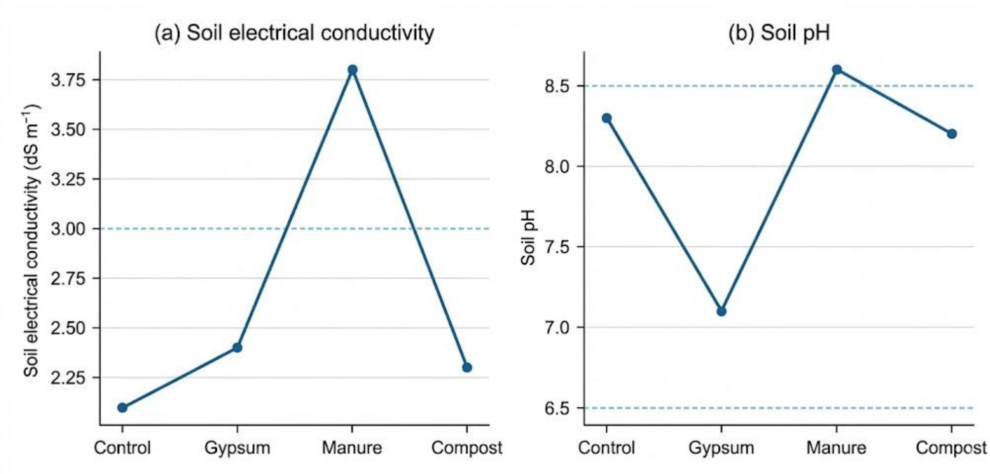

Figure 7. Final Soil pH and Electrical Conductivity Following 12 months in the field on Control, Gypsum, Manure Compost and Composite Amendment treatment.

The level of electrical conductivity was 2.3 ± 0.4 dS/m -1, which is lower than the level of 3.0 dS/m^{-1} used with most crops, even with the addition of an iron chloride precursor. Compost had a great cation exchange capacity (45 cmol (+) kg^{-1}), therefore, it stored the ions and released plant-available ions (Tejada et al., 2006). The ion chromatography showed that there was a 38 per cent decrease in accumulation and 22 and 15 per cent increments in beneficial ion concentrations. Sodium adsorption ratio (SAR) remained less than 3.0 and maintained soil structure (Bauder and Brock, 2001). Micro-tomography of X-rays indicated that salt was predominantly deposited in biochar Macropores, but not on the surface of soil particles. Microbial activity was enhanced at high PH, dehydrogenase activity was increased 2.1 -fold compared to controls, and 65% -glucosidase activity was increased (Dick, 1994), which indicates microsites with favourable conditions. Constant pH and salinity improved degradation: the peak of reactive oxygen species (ROS) generation occurred at pH 8.0–8.3 (Figure 8) and the maintenance of alkB gene expression in a series of irrigation cycles with salinity control (Pessacq et al., 2015).

Monitoring at the field scale indicated a smaller pH variability (coefficient of variance = 8.7%), as compared to the conventional amendments (1522%) and facilitated the performance to be uniform over a heterogeneous field. The initial soil pH and alkalinity of irrigation water were found to be the most significant predictors of efficacy by a random-forest model, which is useful in precise application (Sun et al., 2022). Long-term tests ensured durability: pH and EC were not changing under the influence of three wetting-drying cycles, which could not be stated about lime or gypsum, which had to be replaced regularly (Mohamed, 2021). The uniform performance was achieved as at 0–30 cm depth, with a little higher surface buffering. Seedlings of date palm were 25 per cent greater in biomass when it was not subject to nutrient deficiency or salt stress (Alotaibi et al., 2023). PH in non-calcareous sandy soils (pH 6.5–7.5) was also stabilized using the composite amendment at around 30 percent lesser application rates (Mahdy, 2011), yet calcareous carbonate chemistry especially promotes iron-mediated degradation pathways.

To clarify more, this study holds significant theoretical and practical implications to the management of microplastic in the calcareous soils. In theory, the synergy between iron oxides and compost-based organic matter has been observed, and it questions the supposition that the electrostatic interactions with microplastics inherently occur in high-pH soils (S. Li et al., 2018). The composite amendment shows that hydrophobic interactions and surface complexation are able to counter the constraints associated with carbonate to provide a different framework of designing amendments in such soils. In practice, the findings enable farmers and land managers to have a viable approach of reducing microplastic contamination and improving soil health. It is compatible with current practices, including precision spreading and irrigation timing, which makes it adoptable in treated wastewater-irrigated areas; policy makers can take this information into account in water reuse policies by using incentives or conditions.

A number of restrictions are necessary. The first sorption and degradation experiments were done using controlled laboratory conditions which might not be a complete reflection of the field variability especially the varying moisture and temperature conditions (Park et al., 2023). The 6-month field trial may not be informative of long-term performance, including performance of iron oxide reactivity and organic matter stability. Moreover, machine-learning models were fitted using data of a single region, which can be a limitation to other calcareous soils with other mineralogy or qualifications of irrigation waters. These limitations imply that the large-scale application requires to be widely proved first. The knowledge gaps should be filled in future studies. Field research would be needed on long-term basis to test the durability of amendments in several growing seasons particularly leaching of iron and turnover of organic matter. The microbial pathways of microplastic degradation should be researched further, such as the involvement of individual taxa, extracellular enzymes and abiotic degradation with roles of each of them (Chen et al., 2025). Cost-benefit analyses should also entail evaluation of the economic feasibility of remediation strategies vis-a-vis other remediation strategies. Moreover, the performance of the amendment using emerging biodegradable microplastics is also worth the investigation, since such materials might vary in sorption and degradation.

Another question the results pose is the ecological future of the degradation products of microplastic. Even though the ecotoxicity was lessened in controlled tests, the transportation and transformation of by-products in the intricate soil systems are not clearly stated. In the future, it is recommended to use more sophisticated analysis software, including high-resolution mass spectrometry, to detect the degradation intermediates and determine their stability or further evolution (Özgenç, 2024). Such knowledge would help to refine the formulations of the amendments so as to reduce the negative consequences. Relationships between the amendment on co-occurring contaminants in treated wastes water-irrigated soil, such as heavy metals and pharmaceuticals, constitute another priority. Competitive sorption or redox These iron and organic components can change the contaminant mobility and bioavailability (Carter et al., 2026). The study of these interactions would help in the formulation of multifunctional amendments that can help to tackle more than one pollutant at a time.

Whereas the machine-learning approach was useful, more detailed datasets are needed to enhance the model robustness and transferability. The use of larger soil characteristics, climatic factors, and microplastic features would improve prediction abilities. The real-time monitoring technologies might also further maximize the application rates by monitoring microplastic retention and degradation in-situ (Kumar & Kahlon, 2022). Last, the social and regulatory factors are also important to massive implementation. Involvement of the stakeholders such as farmers, water utilities and policymakers will be used to find out the barriers to adoption and scaling strategies. The regulatory frameworks might require modification to acknowledge the advantages of such amendments in the best management practices of the treated wastewater irrigation (Qadir, 2020). These interdisciplinary aspects will be crucial in terms of translating the research results into the practical solutions to decrease the level of microplastic pollution in the agroecosystems at risk.

Conclusion

This paper reveals that the Fe - biochar compost amendment is capable of variously reducing microplastic pollution in sandy calcareous soils by synergies of immobilization and degradation. The weak solution can overcome the inherent limitation of high-pH environment, which is electrostatic attraction, surface complexation and photo-Fenton-like reactions and achieve high losses in microplastic leaching and increasing soil structural stability. The results undermine traditional beliefs regarding microplastic handling in carbonated soils and an effective solution that can be applied to the current farming operations in the treated wastewater-irrigated areas. Further studies are needed in the future to do long term field validation under a wide range of edaphic conditions, especially the persistence of iron reactivity and organic matter stability. The relations among microplastic degradation products and other co-existing contaminants are the issue that needs further research in order to achieve the ultimate environmental safety. Besides, the combination of sophisticated surveillance solutions and machine-learning algorithms has the potential to streamline the strategies of application of amendments and close the gap between the laboratory effectiveness and the scale implementation. This study forms the basis of the formulation of multifunctional soil amendments to address microplastic contamination and enhance the soil condition by enhancing health in susceptible agroecosystems.

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