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PII: S2772-8013(25)00057-0
DOI: https://doi.org/10.1016/j.clcb.2025.100189
Reference: CLCB 100189

To appear in: *Cleaner and Circular Bioeconomy*

Received date: 24 March 2025
Revised date: 5 September 2025
Accepted date: 1 October 2025

Please cite this article as: Winfred R. Athembo , John Redshaw , Simon Jeffery , Effects of Plastic-Char on Soil Functions and Crop Productivity, *Cleaner and Circular Bioeconomy* (2025), doi: https://doi.org/10.1016/j.clcb.2025.100189

**Highlights**

- Plastic-char increased both aboveground and belowground biomass.
- Plastic-char affected dissolved chemical element concentration in pore water.
- Plastic-char affected soil nutrient availability.
- Plastic-char reduced production of nitrous oxide ($N_2O$) from soil.

Word Count: 8179, including references

# Effects of Plastic-Char on Soil Functions and Crop Productivity

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**Abstract**

A significant quantity of plastic waste cannot be recycled. One way of processing this plastic is through pyrolysis, which produces feedstocks for polyolefin synthesis. This process produces a biochar like product called "plastic-char". This study aimed to investigate the impact of plastic-char produced from mixed non-recyclable plastic waste on pore water elemental concentrations, plant growth and greenhouse gas (GHG) emissions using a series of pot experiments applied at 1 t $ha^{-1}$ and 10 t $ha^{-1}$ eq. Plastic-char was found to increase plant growth of *Lolium perene* by a cumulative total of approx. 60% over four harvests, with no significant impact on germination. Increases in pore water concentrations of approximately 200% were observed for Ca, K and Mg at 10 t $ha^{-1}$. Significant increases were observed in pore water concentrations for Sb (371%) Na (519%), and Ti (724%) at 10 t $ha^{-1}$, compared to the control, with no significant changes in Al, Cd, Co or Cr. The plastic-char significantly increased the production of $CO_2$ from the soil by approximately 330% over the 10 days compared to the control, when applied at 10 t $ha^{-1}$ eq. While we do not suggest that soil application of plastic-char from mixed plastic waste should be used as a means of waste disposal, evidence presented here suggests that there may be value in plastic-char in terms of plant nutrients from the ash fraction and potential GHG reduction from the carbon rich fraction if it can be shown to be sufficiently depleted in contaminants. As such, this represents a potential means of adding value to the mixed plastic waste management stream.

**KEYWORDS**

Plastic-char, germination inhibition, greenhouse gas emissions, hydrophobicity, thermochemical recycling.

## 1 | INTRODUCTION

Plastics, composed of carbon-rich synthetic or semi-synthetic polymers, have seen a drastic rise in production and waste due to their versatile properties, with global output doubling between 2000 and 2019 (Gourmelon, 2015; UN Environment Program, 2022) and current annual plastic waste nearing 400 million tonnes—a figure expected to triple by 2060 without systemic reform (UN Environment Program, 2022). Plastic waste ranks as the third-largest contributor to municipal waste by mass, following biodegradable food and green waste, and paper and cardboard (Statista, 2023), yet its persistence in the environment poses significant environmental, economic, and societal risks (UN Environment Program, 2022), worsened by inadequate waste management (Gourmelon, 2015).

In response, recent advancements in legislation (Wen et al., 2021), research (Ragaert, Delva and Geem, 2017; Thiounn and Smith, 2020), and technology (Kumar et al., 2021) have targeted solutions such as thermochemical recycling through pyrolysis—decomposing plastic waste at high temperatures with limited oxygen—which offers a potentially sustainable method for recovering value from end-of-life plastics (Thiounn and Smith, 2020). Further to this, it is not always feasible to remove plastic from feedstocks such as agricultural biomass (Rathnayake et al., 2021). Therefore, improving our understanding of plastic-char is necessary to ensure the sustainable use of the maximum range of biochars that are likely to be produced. There is also growing interest in the role of co-pyrolysis of feedstocks mixed with plastic due to the "significant promise" of this approach as a means of waste management and resource recovery (Razzak, 2024). Hilber et al. (2024) reported that in their study of mixed feedstocks with plastic content deliberately enriched to 10% (w/w) still resulted in biochars with characteristics below limit values for the European Biochar Certificate (EBC) regarding trace element content and organic pollutants.

Plastic Energy has adopted pyrolysis with the aim to close the 'plastic loop' and contribute to creating a circular economy for plastics by reducing plastic waste that would end up in landfills or as unregulated waste. ItsTAC™ pyrolysis process produces TACOIL™ (an optimal feedstock for making clean recycled plastic) and plastic-char, a biochar like product that is carbon rich and retains the majority of the mineral fraction of the plastic feedstock.

Plastic-char has some similar characteristics to biochar, which is produced from pyrolysis of organic matter with the intention of application to soils (Lehmann and Joseph, 2015). Like plastic-char, biochars have high carbon content, alkaline pH (Xu et al., 2012) and high porosity (Jeffery et al., 2015). Owing to these similarities, plastic-char may also interact with some soil properties (Novak et al., 2009; Vanapalli et al., 2021), including crop yield (Kumar et al., 2021) and impacting soil GHG fluxes (Smith, et al., 2010; Abhishek et al., 2022).

Although there are multiple studies on pyrolysis of plastic waste (Ragaert, Delva and Geem, 2017; Thiounn and Smith, 2020), application of biochar (Baronti et al., 2010; Bargmann et al., 2013; Lehmann and Joseph, 2015; Xu et al., 2012; Jeffery et al., 2015) and application of mixed plastic-char with biochar (Kumar et al., 2021; Rathnayake et al., 2021; Vanapalli et al., 2021), there is still a paucity of studies investigating application of unmixed and unadulterated plastic-chars to soils (Al-Rumaihi et al., 2023). Nevertheless, some similar effects can be expected that are reported in other biochar types, driven by similar mechanisms such as pH and nutrient input driving yield effects (Jeffery et al., 2017), reducing germination (Solaiman et al., 2012) and interactions with GHG emissionS (e.g. Yuan et al., 2019)

This study aims to explore the impacts of plastic-char application to soil on seed germination, plant productivity, nutrient and contaminant mobility, and greenhouse gas fluxes from soils. To do so it will test the following hypotheses:

Hypothesis 1: Plastic-char affects plant growth

Hypothesis 2: Plastic-char affects plant germination

Hypothesis 3: Plastic-char affects soil GHG flux

This will help develop an evidence base to inform policy and legislation around modification, management and use of plastic-char.

## 2 | MATERIALS AND METHODS

### 2.1 | Plastic-char

Plastic-char was produced by Plastic Energy using mixed, unwashed post-consumer waste plastic, multi-layered end-of-life plastics, and plastics that cannot be mechanically recycled (comprising mainly of high-and-low density polyethylene, polypropylene and polystyrene). The plastic-char was prepared using the chemical recycling technology method described in Plastic Energy's EP4217419 patent, called its TAC™ process.

In short, end-of-life plastic materials were converted into petrochemical feedstocks and plastic-char through a multi-stage thermochemical process. Feedstock was first processed into granular or flake form, then melted using an extruder under oxygen-free conditions. The molten plastic was transferred into sealed pyrolysis chambers while maintaining temperatures close to pyrolysis range (300–320°C) to prevent cooling prior to decomposition. Each chamber was purged with nitrogen and operated at 390–410°C, with continuous agitation provided by rotating helical blades and a central auger to ensure uniform thermal breakdown.

The main chemical characteristics of the plastic-char are reported in table 1.

Table 1: Characteristics of the Plastic-char used in this study.

| Main Characteristics of Plastic-char. | |
|---|---|
| Chemical Element* | Value |
| C % | 44.6 |
| H % | 1.8 |
| N % | 0.8 |
| S % | 0.8 |
| pH | 8.9 |

Plastic-char pH (in water) = 8.9.

### 2.2 | Plastic feedstock

The plastic feedstock consists of end-of-life, non-recyclable plastic. It comprises at least 80% plastic. The feedstock is substantially free of non-hydrocarbon plastic such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC). It preferentially comprises non-aromatic hydrocarbons only such as polyethylene (PE) and/or polypropylene (PP).

A positive control using plastic feedstock from Plastic Energy that was used to make plastic-char was chopped up in a blender to decrease particle size closer to that of the plastic-char and passed through a 2 mm sieve to homogenise. C and N plastic feedstock contents were determined using a LECO CN- 828 (Michigan, United States of America).

The pH of the plastic feedstock was measured using a Jenway 3510 pH meter by mixing a 10 ml scoop of plastic feedstock with 25 ml of deionized water in a glass bottle followed by shaking on an automatic shaker for 15 minutes. The main chemical characteristics of plastic feedstock used in this study are reported on table 2.

Table 2: Characteristics of the plastic feedstock used in this study.

| Chemical Element | Value |
|---|---|
| C %<br>N %<br>pH | 71.5<br>0.3<br>7.5 |

### 2.3 | Soil collection

The two types of soils used in the experiments were collected from Harper Adams University, located in Newport, Shropshire, UK (52.7790° N, 2.4277° W). The sites where the soils were collected from had been in an arable rotation for at least 20 years and have a temperate maritime climate. The soils were individually mixed, air dried and passed through a 4 mm sieve. Sub-samples of soil were analysed at NRM Laboratories (Berkshire, UK) for specification of topsoil analysis (table 3).

Table 3: Textural and chemical characteristics of the experimental soils.

| | Unit | Germination & Plant yield experiment | Incubation experiment |
|---|---|---|---|
| **Textural class** | | Peaty Clay | Sandy Clay Loam |
| Clay | % w/w | 49 | 27 |
| Silt | % w/w | 21 | 22 |
| Sand | % w/w | 30 | 51 |
| Organic Matter | % w/w | 31.6 | 13.1 |
| pH | | 6.4 | 6.4 |
| Carbonate | % w/w | 4.0 | 2.2 |
| **Available plant nutrient** | | | |
| Nitrogen | % w/w | 1.10 | 0.606 |
| Phosphorus | mg/l | 5.8 | 18.2 |
| Potassium | mg/l | 145.4 | 126.5 |
| Magnesium | mg/l | 187.5 | 168.3 |

| | | | |
|---|---|---|---|
| Carbon: Nitrogen Ratio | | 16.7 | 12.5 |
| Exchangeable Sodium Percentage | % | 0.4 | 0.4 |
| **Phytotoxic Contaminants** | | | |
| Total Zinc | mg/kg | 73.6 | 81.3 |
| Total Copper | mg/kg | 23.6 | 22.2 |
| Total Nickel | mg/kg | 27.5 | 19.7 |
| **Additional Analysis** | | | |
| Available Sodium | mg/l | 21.0 | 16.0 |
| Available Calcium | mg/l | 4520 | 3595 |
| Conductivity | µS/cm | 2202 | 2155 |

### 2.4 | Hydrophobicity experiment

Hydrophobicity was assessed with the sessile drop method as proposed by Shang et al. (2008) and Ponomar et al. (2022) by measuring the contact angle of a drop of test liquid over a sample surface. Glass microscope slides were cleaned with acetone, rinsed with demineralised water and left to air dry before use. A glass microscope slide was placed on a flat surface and covered with a thin layer (~2 – 3 mm) of plastic-char, which was flattened by pressing another glass microscope slide on top. A single 0.5 ml droplet of demineralized water was pipetted onto the surface of the biochar. A photo of the profile of the droplet was taken using an iPhone 11 camera with a Dual Ultra-Wide Camera f/ 2.4 aperture from approximately 10cm away from sample. The image was cropped and uploaded on the ImageJ 1.53t; Java 1.8.0_361 software. The image was converted to grayscale, and the droplet was analysed using contact angle drop analysis plug-in (Brugnara, 2006). Points along the profile of the drop edges were selected and analysis was made based on circle or ellipse of best fit to generate contact angle as shown in Figure 1. The apparent hydrophobicity angle is calculated as (Buahom, 2018):

$$180° - Theta\ (C\ or\ E) \quad (1)$$

Where Theta (θ) C is the angle obtained from the circle; Theta (θ) E is the angle obtained from the ellipse.

### 2.5 | Hygroscopicity experiment

Samples of plastic-char and plastic feedstock were dried in an oven at 105°C for 48 hours. The samples were cooled down to ambient temperatures in a desiccator and the dry weight of each sample was recorded. The samples were then placed in open room conditions and weighed until the difference between two successive weightings was less than 0.1 g (after approximately 48 hours). The final weight measured and recorded to quantify hygroscopic water sorption of atmospheric water vapor (Miao et al., 2014). The methodology adhered to BS EN 13040:2007 soil improvers and growing media moisture content measurement standard (British Standards Institution, 2008). The percentage of hygroscopic sorption of water vapour was calculated as:

$$Water\ vapor\ absorbed\ (\%) = \frac{W2 - W1}{W1} \times 100 \quad (2)$$

Where W1 is the dry weight of the sample from the oven, in g; W2 is the final weight of the sample after exposure to atmospheric humidity, in g.

### 2.6 | Germination experiment

The germination rate was assessed using AberGreen ryegrass (*Lolium perenne*) seeds in petri dishes consisting of three replicates with 5 seeds per dish with plastic-char applied at 1, 10 and 50 t $ha^{-1}$ carbon (C) equivalents. The petri dishes were setup in a randomized complete block design in the dark and kept moist throughout the experiment. The number of seeds germinated was recorded daily for 14 days.

### 2.7 | Plant yield pot experiment

A pot experiment was conducted using AberGreen ryegrass (*Lolium perenne*) in a glasshouse with artificial lighting, with 16-hour days and 8-hour nights. Pots (1.5 L; 18 cm height) were packed with homogenised peaty clay soil (table 3) that had been homogenised by passing a 4mm sieve, packed at a bulk density of 1.3 g/$cm^3$ and maintained at 60% water-filled pore space (WFPS). The five treatments consisted of plain soil (control), plastic-char (treatment) and plastic feedstock (positive control) each applied individually at rates equivalent to 1 and 10 t $ha^{-1}$ carbon (C). After mixing soils with the respective treatment, the pots were packed to a depth of 13 cm. Five seeds of AberGreen ryegrass were sown into each pot, set up in a randomized complete block experimental design under lights with five replicates.

The pots were irrigated with tap water every other day to maintain the soil at 60% water-filled pore space (WFPS). Above ground biomass production was quantified for three growth cycles (one, two and three months after plant emergence) by manually clipping plants approximately 1 cm above the soil surface. Samples were dried at 60°C for 3 days. After third harvest, below ground biomass was determined by washing out the plant roots and drying at 60°C for three days. Following weighing, the samples were combusted in a Carbolite muffle furnace at 550°C for 3 hours, with the mass left (consisting of stones, gravel and soil) subtracted from the initial dry weights.

#### 2.7.1 | Collection of pore water and preparation of analysis by ICP-MS

Soil pore waters were collected over the entire timeframe of the growth experiment from the pots of the plant yield experiment at heights of 8 and 12 cm using Rhizon Flex pore water samplers (Wageningen, The Netherlands), with pore sizes ranging from 0.12- 0.18 µm. The chemical analysis of collected samples was done in duplicate on the Perkin Elmer NexION 2000B ICP Mass Spectrometer (Shelton, United States) using the standard addition calibration method as suggested by Gaschnig, et al. (2014); Yang et al. (2018) and Aramendía et al. (2022). This equipment has an LOD in the ppq range. (Perkinelmer.com, 2025). The concentration of the following 21 chemical elements were assessed (K, Na, Ca, P, Mg, Cr, Fe, Cd, Cu, Mo, Mn, Se, Pb, Al, Ni, As, Zn, Ti, Co, B, Sb). The relative concentration of the elements was determined by applying a multiple reaction monitoring experiment on the ICP-MS equipment.

### 2.8 | Incubation experiment

To assess the effect of plastic-char on greenhouse gas emissions, an incubation experiment was set up in a Weiss Technik modular plant growth chamber, Fitotron® HGC (Heuchelheim, Germany). The growth chamber was set to a 50% humidity and 24°C for 16 hours a day and 12°C for 8 hours a night. Polypropylene pots of 1 L (20 cm height) were packed with sandy clay loam soil (table 3), which was passed through a 4 mm sieve, to a bulk density of 1.3 g/cm$^3$. Pots were maintained gravimetrically at 60% water-filled pore space (WFPS) by irrigating every other day for the duration of the experiment. The pots consisted of five treatments: control (no addition), plastic-char (treatment) and plastic feedstock (positive control) each applied individually at rates equivalent to 1 and 10 t ha$^{-1}$ C. the pots were packed to a depth of 10 cm, in a randomized complete block experimental design with five replicates.

The gases were collected at the same time when the temperature of the chamber was at 12°C. The pots had screw top lids with a septum in the middle to allow gas sampling with a syringe. Soil GHG fluxes ($CO_2$, $CH_4$ and $N_2O$) were sampled from the headspace on Days 1, 3, 8 and 10 after a closing time of 1 hour. The content of each syringe was passed through pre-evacuated 20 ml vials, with the excess gas vented to store samples at atmospheric pressure. The concentration of GHGs was determined by gas chromatography at Rothamsted Research (Hertfordshire, UK) within 6 weeks of the experiment.

Daily gas fluxes measured in parts per million (ppm) were converted to mg $CO_2$-C hr$^{-1}$ m$^{-2}$, mg $CH_4$-C hr$^{-1}$ m$^{-2}$ or mg $N_2O$-N hr$^{-1}$ m$^{-2}$ as follows:

$$\frac{(\frac{ppm}{hr} * headspace\ volume * atomic\ weight\ of\ gas)}{R \times T(K) \times area(m^2) \times 1000} \quad (3)$$

Where R is the Ideal Gas Constant, 0.0821 L.atm/mol.K; T is temperature at time of gas collection, K.

The daily gas flux value was then converted to cumulative fluxes assuming linearity of flux rate between each measurement.

### 2.9 | Statistics and software

Data preparation and presentation was performed using Microsoft Excel Software and statistical analyses were performed using R software. The results of the germination experiment were analysed using analysis of variance (ANOVA) using linear mixed model fit by RELM via Satterthwaite's degrees of freedom method (Kuznetsova, Brockhoff and Christensen, 2017) for treatment applied and rate of germination. The 10 t ha$^{-1}$ plastic-char application rate was used as the reference level for the analysis. Data was tested for normality using a Q-Q plot. A mixed model analysis was also done with a day of germination as a random effect and treatment applied included as a fixed effect.

Above and below ground biomass were analysed using ANCOVA using the lmer package for treatment applied against above ground and below ground biomass separately. Number of seeds germinated was included as covariate.

For the ICP-MS results, due to a non-normal distribution a Kruskal-Wallis rank, a sum test was performed to determine significance. This was followed by a one-way ANOVA of treatment against chemical element concentration using post-hoc Tukey HSD which was computed to perform multiple comparisons between the mean of groups.

For the cumulative greenhouse gas fluxes, analysis was performed using ANOVA linear mixed model fit by RELM criterion of convergence with day of gas collection included as a random variable.

## 3 | RESULTS

### 3.1 | Hydrophobicity

The contact angle of demineralised water on the surface of the plastic-char was 116.3° (by measurement of using a circle of best fit) or 132.3° (by measurement of using an ellipse of best fit) as shown in Figure 1. As both contact angles exceed 90°, the plastic-char is hydrophobic (Ahmad et al., 2018).

Figure 1: Image used for contact angle analysis of plastic-char. Analysis was performed using ImageJ with contact angle drop analysis plug-in.

### 3.2 | Hygroscopicity

The mass gained by both plastic-char and plastic feedstock after exposure to atmospheric water vapour was equated to the material's hygroscopic capacity. The average water vapour absorbed

was 2.8% and 1.0% for plastic-char and plastic feedstock respectively. Both materials were considered to have a low hygroscopic water content with the plastic-char being slightly more hygroscopic than the not pyrolyzed feedstock.

### 3.3 | Germination responses

The rate of germination for each treatment is as shown in Figure 2. Different plastic-char applications rates did not inhibit the overall germination of *Lolium perenne* with the lowest rate of germination being 92% for 1 and 10 t $ha^{-1}$ plastic-char application. There was a delay in germination for the 50 t $ha^{-1}$ plastic-char application with first germination being recorded on day eight but by day 14 the average number of seeds in all treatments germinated was not significantly different with all grains forming cotyledons and radicles in all treatments.

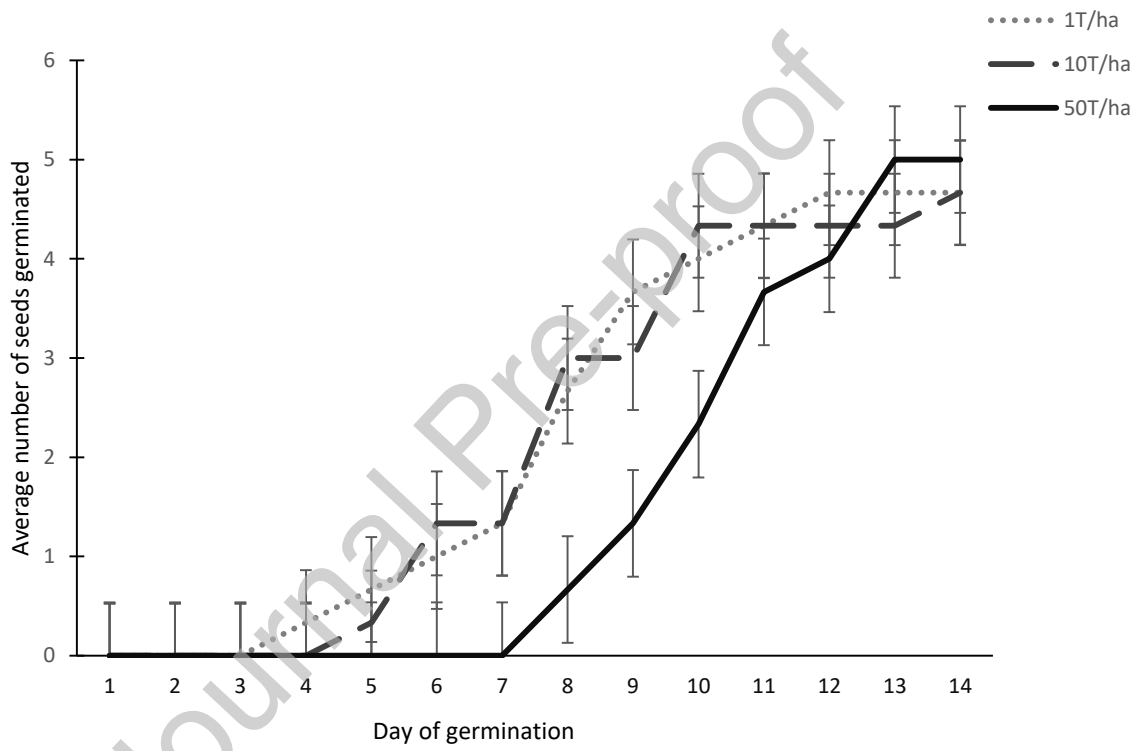


Figure 2: Average rate of germination under different plastic-char application rates. Lines represent germination (n = 3), error bars show standard errors.

### 3.4 | Effects of different treatment application rate on above and below ground biomass.

The average cumulative above ground and below ground biomass for each treatment is as shown in Figure 3. There was a significant increase in above ground biomass for all treatments compared to the control (1 t $ha^{-1}$ biochar = 236%; 1 t $ha^{-1}$ plastic = 56%; 10 t ha-1 biochar = 279%; 10 t $ha^{-1}$ plastic = 35%; $p<0.001$). There was a significant increase on below ground biomass of 140% and 181% for 1 t $ha^{-1}$ and 10 t $ha^{-1}$ biochar respectively ($p = 0.054$). Both 1 and 10 t $ha^{-1}$ of plastic-char application had a higher increase in yield than 1 and 10 t $ha^{-1}$ plastic feedstock application.

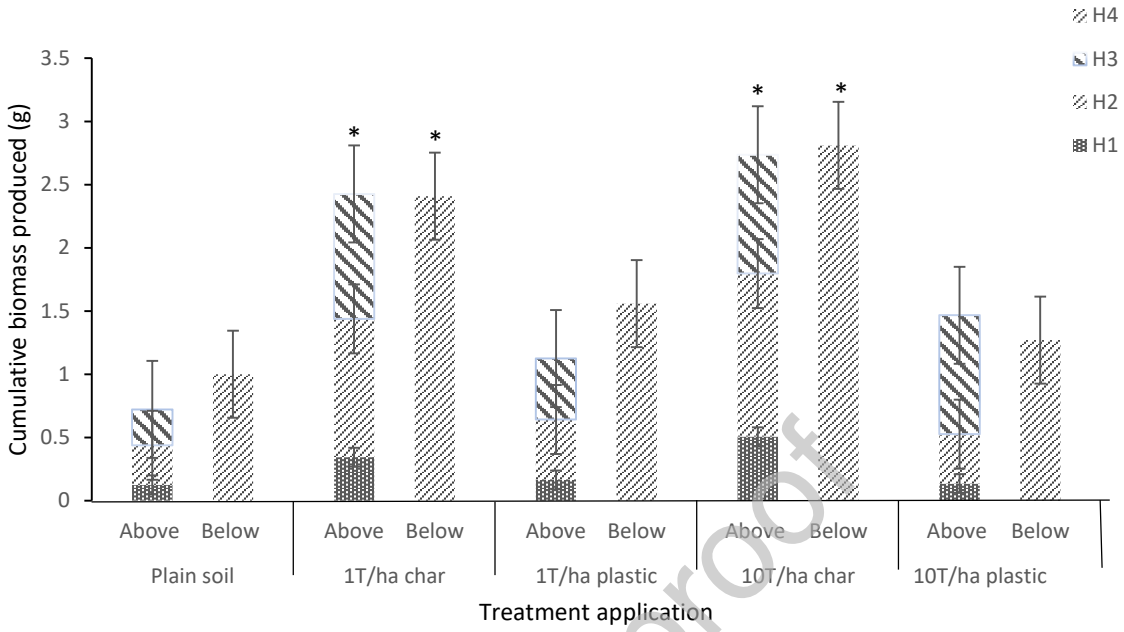


Figure 3: Average cumulative mass for above ground harvests in harvest 1 (H1), harvest 2 (H2) and harvest 3 (H3) and below ground biomass at the end of the planting season (H4). Bars represent average harvests (n=5), error bars show standard errors. * indicates significant differences to the control (P=0.05).

### 3.5 | Effect of treatment application on macronutrient availability in pore water

The macro-nutrient concentration in pore water collected from the plastic-char and plastic feedstock treatments are shown in Figure 4. Concentration for Ca, K and Mg were higher in treatments of plastic-char at 1 and 10 t $ha^{-1}$ compared to treatments of plastic feedstock at the same rates. Plastic-char at 10 t $ha^{-1}$ had the highest concentration of Ca, K and Mg at 325% 321% and 322% increases respectively ($p<0.001$). Plastic feedstock at 10 t $ha^{-1}$ significantly increased porewater P to 120% compared to all the other treatments ($p<0.001$).

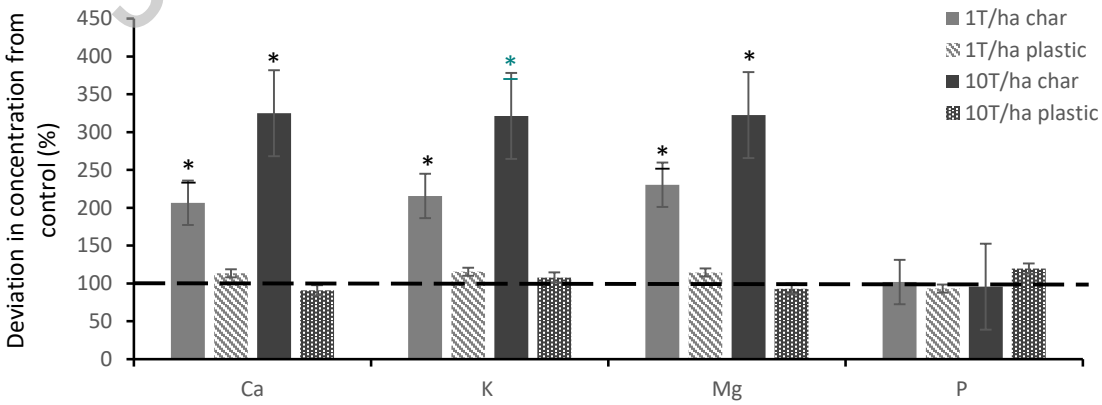

Figure 4: Macro-nutrient concentration available in the pore water collected from the different treatments. The values show percentage deviation from control treatment (plain soil). The black broken line at the 100% value represents the concentration of nutrients in the control. Bars represent mean elemental concentration (n =10), error bars show standard errors. * indicates significant differences to the control (P=0.05)

### 3.6 | Effect of treatment application on micronutrient availability in pore water

The micro-nutrient concentration in pore water collected from the plastic-char and plastic feedstock treatments are shown in Figure 5. Significant treatment effects were observed in concentrations of B, Mn, Mo and Zn ($p<0.001$). Concentrations for B, Cu, Mn and Zn had a percentage decrease for plastic-char treatments of 1 and 10 t $ha^{-1}$ from the control and the respective plastic feedstock. Conversely, concentrations for Cu, Mn, Ni and Zn were highest in 10 t $ha^{-1}$ plastic feedstock treatments at 131%, 169%, 129% and 217% increases respectively.

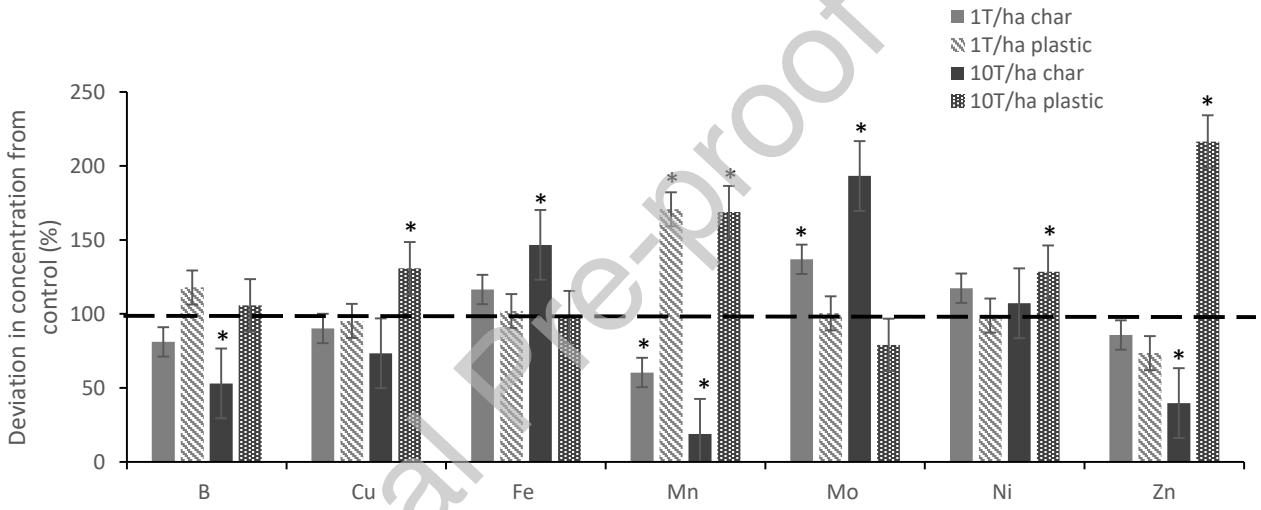


Figure 5: Micro-nutrient concentration available in the pore water collected from the different treatments. The values show percentage deviation from control treatment (plain soil). The black broken line at the 100% value represents the concentration of nutrients in the control. Bars represent mean elemental concentration (n =10), error bars show standard errors. * indicates significant differences to the control (P=0.05)

### 3.7 | Effect of treatment application on potential contaminant availability in pore water

The elemental concentration in pore water collected under the plastic-char and plastic feedstock treatments are as shown in Figure 6. The concentration of micronutrients were significantly affected by plastic-char application ($p<0.001$). The highest significance was identified across concentrations of Na and Ti with p-values of <0.001 with the highest increase observed in treatments of 10 t $ha^{-1}$ plastic-char having 519% and 724% respectively more Na and Ti respectively. Conversely, concentrations for Al, Cd, Co and Cr had a percentage decrease for plastic-char treatments of 1 and 10 t $ha^{-1}$ from the control and the respective plastic feedstock. However, it should be noted that, while the increase in Sb and Ti is significant compared to controls, the concentration of these elements in the pore water was still very low (maximum 7 ppb Sb and 51 ppb for Ti).

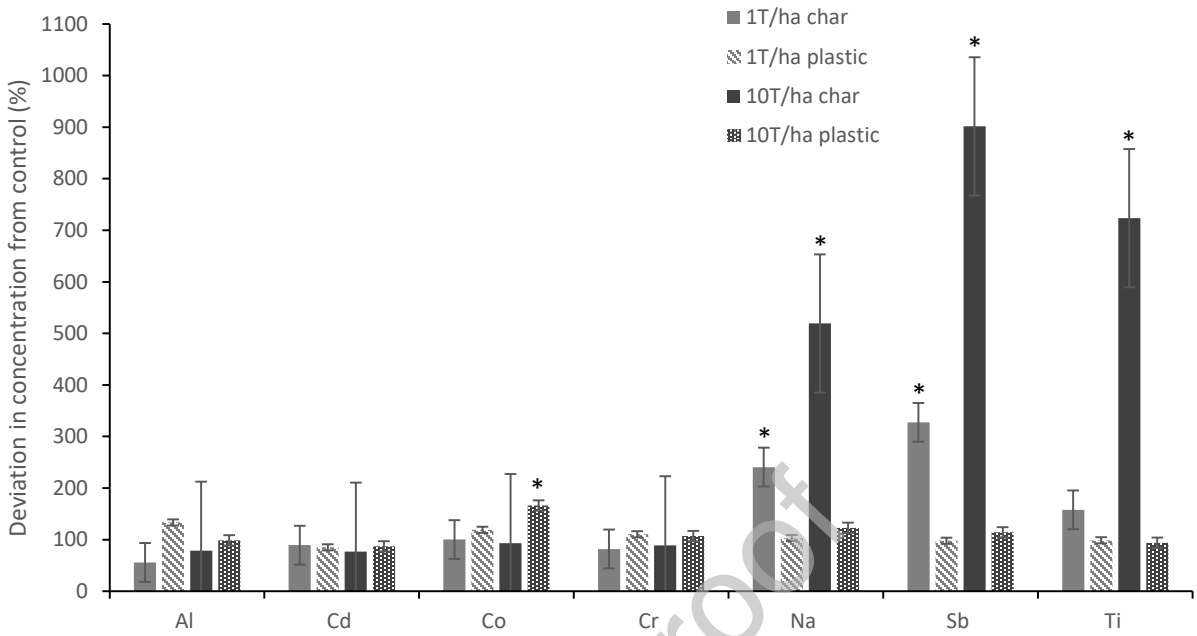


Figure 6: Dissolved element concentration available in the pore water collected from the different treatments. The values show percentage deviation from control treatment (plain soil). The black broken line at the 100% value represents the concentration of nutrients in the control. Bars represent mean elemental concentration (n =10), error bars show standard errors. * indicates significant differences to the control (P=0.05).

### 3.8 | Effect of treatment application on cumulative greenhouse gas fluxes

#### 3.8.1 | Cumulative $N_2O$ fluxes

The cumulative $N_2O$ fluxes were highly variable as shown in Figure 7. Generally, the fluxes for 1 and 10 t $ha^{-1}$ plastic-char showed a cumulative reduction up to Day 8 where it stabilized for the 10 t $ha^{-1}$ plastic-char treatment and started increasing for 1 t $ha^{-1}$ plastic-char treatment. The cumulative $N_2O$ fluxes for the 1 and 10 t $ha^{-1}$ plastic feedstock treatment were higher than that of the control over the period of 10 days. Statistical analysis suggests that there was no significant difference in cumulative flux ($p = 0.85$).

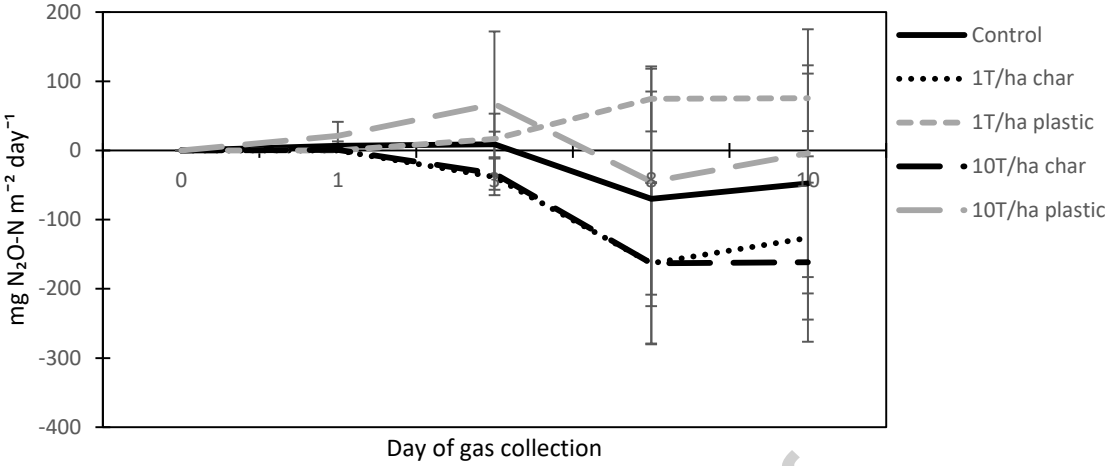


Figure 7: Cumulative $N_2O$ fluxes control and different treatments of 1 and 10 t $ha^{-1}$ plastic-char and plastic feedstock. Lines represent average fluxes (n = 5), error bars show standard errors of the mean.

### 3.8.2 | Cumulative $CO_2$ fluxes

The cumulative CO2 fluxes are as shown in Figure 8. There was a general increase in cumulative gas flux for all treatments including the control. The highest increase is observed in the 10 t $ha^{-1}$ plastic-char treatment (245%; $p < 0.001$). The cumulative gas flux obtained by day 10 was 27724 mg $CO_2$-C $m^2$ $day^{-1}$ for the 10 t $ha^{-1}$ plastic-char treatment application.

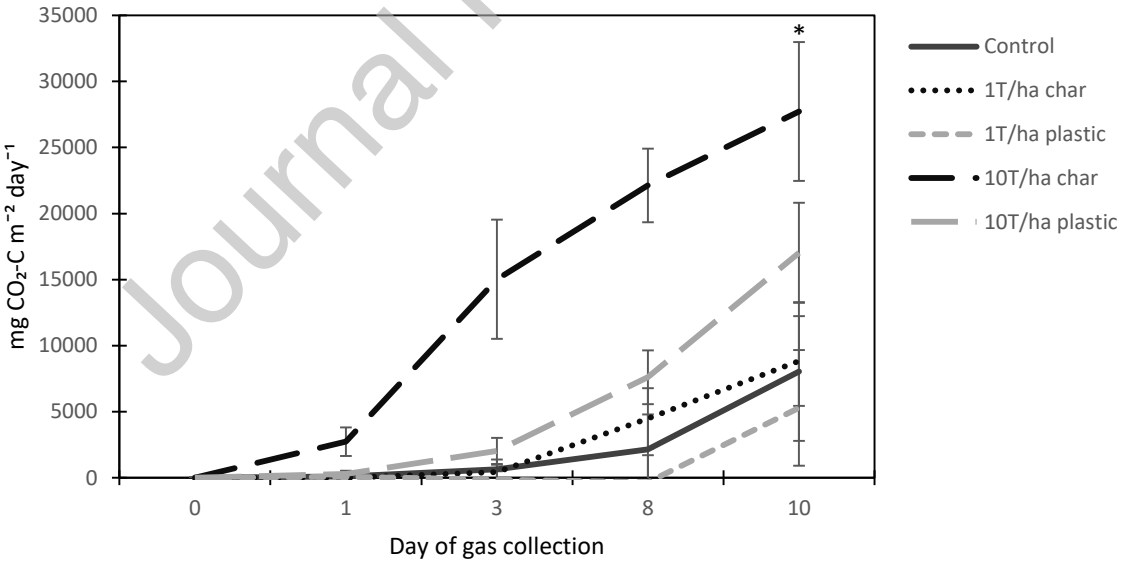


Figure 8: Cumulative $CO_2$ fluxes over the timeframe of the experiment against control and different treatments of 1 and 10 t $ha^{-1}$ plastic-char and plastic feedstock. Lines represent average fluxes (n = 4), error bars show standard errors of the mean. * indicates significant differences to the control (P=0.05)

### 3.8.3 | Cumulative $CH_4$ fluxes

The cumulative $CH_4$ gas fluxes are as shown in Figure 9. There was a general decrease in cumulative gas flux level over the 10-day period with the highest reduction observed from the 10 t $ha^{-1}$ plastic feedstock treatment application, however there was no statistical significance of cumulative gas flux across the different treatments ($p = 0.37$). The cumulative gas flux obtained by day 10 is -3.6 mg $CH_4$-C $m^2$ $day^{-1}$ for the 10 t $ha^{-1}$ plastic feedstock treatment application.

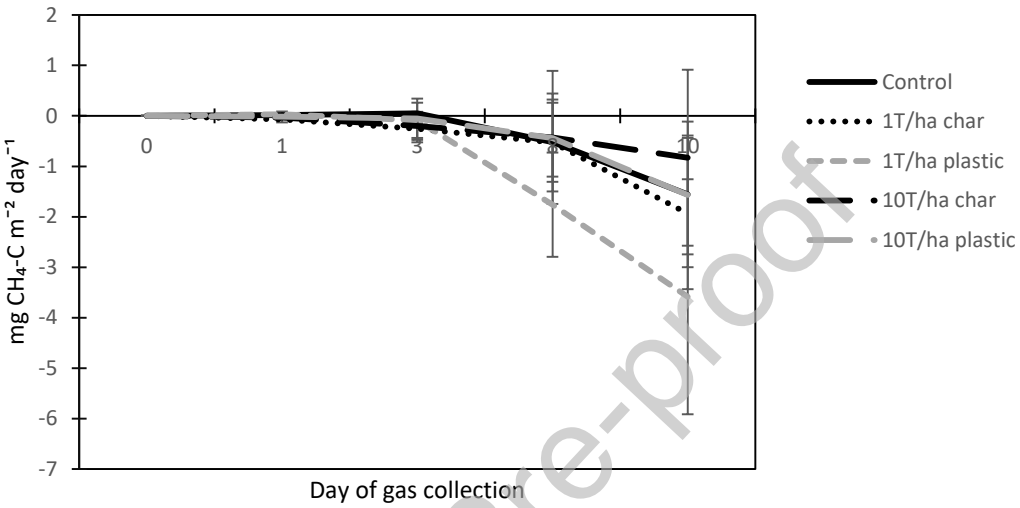


Figure 9: Cumulative $CH_4$ fluxes over the timeframe of the experiment against control and different treatments of 1 and 10 t $ha^{-1}$ plastic-char and plastic feedstock. Lines represent average fluxes ($n = 4$), error bars show standard errors of the mean.

## 4 | DISCUSSION

Of the three hypotheses presented in the introduction, hypothesis 1 (plastic-char affects plant growth) and hypothesis 3 (plastic-char affects soil GHG flux ) were accepted, but for hypothesis 3 only in terms of $CO_2$ as no significant effect was observed for $N_2O$ or $CH_4$.

Hypothesis 2 (plastic-char affects plant germination) was rejected, as no significant impact on germination was observed within the context of this experiment.

Data presented here suggests that, as well as pyrolysis providing feedstocks for polyolefin synthesis, the resulting char contains plant available macro and micronutrients, including K, Mg, Ca, Mn, and Mo. This aligns with other analyses that have found characterized significant quantities of plant nutrients from biochar ash (e.g. Chen et al., 2022; Puri et al., 2024). However, separating these from other potential contaminants such as Sb remains an issue. Research is progressing in separating ash components (Puri et al., 2024) but further research is required to allow maximization of the added value of pyrolysis approaches to plastic waste stream management.

### 4.1 | Characteristics of plastic-char and potential effects on soil hydrological properties

The addition of soil amendments such as plastic-char may influence the porosity, water tension, hydraulic conductivity and cation exchange capacity (CEC) of soils (Zong, Chen and Lu, 2014). Vanapalli et al. (2021) suggested that mixed plastic eucalyptus char increased the water retention capability of soil by up to 20% due to its porous surface and associated pore continuity. Contrasting results by Jeffery et al. (2015) suggested that, even though a biochar may be highly porous, its hydrophobic characteristic can prevent it from having any significant effect on water retention. The hydrophobicity characteristic (Das and Sarmah, 2015) showed that plastic-char is strongly hydrophobic, meaning that little to no water would be expected to infiltrate its pores (Jeffery et al., 2015). Therefore, when mixed with soil, these materials may likely not or only very weakly interact with soil moisture under ambient conditions and are likely to remain hydrophobic for extended periods. However, an experimental analysis quantifying the water holding capacity impacts of application of plastic-chars to a range of soil types is needed to be able to test the interactions between plastic-chars and soil water-holding capacity.

While hydrophobicity prevents water infiltration, prolonged exposure of hydrophobic materials to water may increase their water affinity. Das and Sarmah (2015) reported that extended exposure of hydrophobic biochars to water reduced their degree of water repellence and eventually increased water infiltration. Therefore, prolonged exposure to soil moisture may reduce the hydrophobicity of the plastic-char and change its interactions with soil hydrological characteristics. Furthermore, the hydrophobic nature of biochars can be harnessed to improve poor physical conditions of clayey soils by increasing water repellence of the soil and decreasing rate of wetting and water retention (Zong, Chen and Lu, 2014).

### 4.2 | Effect of plastic-char application to rate of germination and plant yield

Rates of 1, 10 and 50 t $ha^{-1}$ of biochar C were chosen based on commonly applied rates (i.e. 1 and 10 t $ha^{-1}$) and the "maximum sustainable" biochar application rate of 50 t $ha^{-1}$ as defined by Woolfe et al. (2010). The results suggest that application of plastic-char to soil at rates up to 50 t $ha^{-1}$ had generally no inhibition on overall germination of *Lolium perenne* seeds within the high organic matter soils used in this study. The lowest rate of germination was 92%, which exceeds the 90% rate that is considered "very good" (Steil, 2023).. An experiment using biochar on perennial ryegrass showed similar results, with negative effects on germination only observed at above 60 t $ha^{-1}$ (Baronti et al., 2010). It is therefore likely that this plastic-char applied to soils at rates lower than 50 t $ha^{-1}$ would have negligible, if any, inhibition to germination.

For the plant yield experiment, a positive control was included even though plastic waste is not typically used as a soil amendment. This was to compare the effects of plastic waste pollution in agricultural soils and allow differentiation of char properties from feedstock effects (Jeffery et al., 2015). Above and below ground biomass increased in all treatments. This result is similar to observation by Kumar et al. (2021) where plant height and leaf number were highest with the addition of mixed plastic-char: soil at a ratio of 4:100. Baronti et al. (2010) also reported an increase in above and below ground biomass of rye grass at a biochar application rate of 60 t $ha^{-1}$. The increased biomass may be attributable to increased soil fertility by reducing leaching losses of N and increasing soil organic matter (Vanapalli et al., 2021). Finally, this result aligns with work reported by Rathnayake et al. (2021) who also found no phytotoxic effect of the biochars used in their study, irrespective of the concentration of plastic contamination of their feedstock. However, it remains to be seen if different plastic-chars produced from different types of plastic, with different pyrolysis co-products and under different conditions, would have different

characteristics and effects (Al-Rumaihi et al., 2023; Razzak, 2023). More research is needed across the wide range of plastic-chars to gain insights into the ubiquity of this finding.

Plastic-chars have high pH. This characteristic may have contributed to a liming effect on soils and consequently reduce nutrient antagonism thus enabling plants to take up essential nutrients for growth (Kumar et al., 2021). Another factor for improved plant yield may be improved microbial activity by creating conducive habitat as biochars reduce the exchangeable acidity of soils as suggested by Novak et al. (2009). The data reported here suggests that plastic-char incorporated into soils may have the potential to increase productivity, although characterising the mixed plastic-char to be aware of potential contamination issues would be required for most soils. Nevertheless, as part of soil remediation, where soils are already contaminated, addition of plastic-char may represent a means of increasing plant productivity and so aiding ecosystem restoration as long as the material does not itself cause contamination issue. Further research is required to conduct long-term studies on effect of plastic-chars on soil and wider ecosystems. Comprehensive risk assessments should always be required when considering plastic-char applications.

### 4.3 | Soil Nutrients

Soil pore water was collected to investigate elements that may solubilise from the plastic-char and be available for plant uptake. Some of these elements are essential plant nutrients which may have contributed to the observed increased crop productivity. Conversely, others have contamination potential. Similar to biochars, plastic-char addition caused significant increases in the concentration of plant macronutrients in the pore water samples, including K, Ca, and Mg. However, there was a decrease in soil available P, which may have been due to the pH impact of the plastic-char addition combined with the low P content of the plastic-char and its feedstock. This is contrary to the findings of Kumar et al. (2021) who reported a significant increase in P concentration due to the increase in pH and CEC following mixed plastic-char addition to the soil. This effect is likely to be a soil specific effect due to the dominance of soil pH as a mechanism for P availability. Which of these effects dominates is likely to be dependent on soil type and feedstock used. Micronutrient concentrations in plastic-char treatments were lower than those in the plastic feedstock except for Fe and Mo. Observed concentrations for Mn and Zn were similar to biochar results reported by Novak et al. (2009) on sandy, acidic and low organic carbon content soils.

Some of the elements present in the plastic-char and plastic feedstock with contamination potential investigated here include Cd, Co, Cr, Na, Sb and Ti. All of these increased significantly compared to the control with no addition (Figure 6). Of these, only Na and Sb showed increased pore water concentrations in the biochar treatments, although their concentrations remained very low (~200 ppm for Na at 10 t $ha^{-1}$ plastic-char application). Salinisation is soil specific due to local chemistry effects and is usually measured in dS/m. However, this concentration, if generated throughout the soil would be expected to be classed as “moderately saline” (Leinauer et al., 2012). This means that some plants may experience negative growth effects and caution should be taken to avoid raising Na concentrations to this level. The level of ~7 ppb for Sb (at 10 t $ha^{-1}$ plastic char application) is well within the regulatory limits for soil (i.e. 10,000 ppb; FAO, 2004). This suggests that not all contaminants showed increased mobility following pyrolysis. Nevertheless, the increased presence of these in the pore water shows the contamination potential of the plastic-char upon soil application. Whether this can be reduced by washing with water or

other solvents is a necessary line of research before plastic-char application to soil can be considered. However, in already contaminated soils, plastic-char may have potential to be used as a sorbent material for removal of some compounds including As and Pb (Singh et al., 2020). Therefore, it may have potential as a sorbent material in soil remediation, particularly if the concentration loads of these other contaminants can be reduced. More research on the sorption index, saturation, retention capacity and management of used plastic-char is needed.

### 4.4 | Soil greenhouse gas emissions

#### 4.4.1 | $N_2O$ fluxes

Plastic-char caused an apparent visual reduction in the amount of cumulative nitrous oxide ($N_2O$) fluxes. On the contrary, the plastic feedstock shows an increase in the amount of cumulative $N_2O$ produced, with there being a greater increase with increased application rate. However, the data was highly variable, and this result was not statistically significant. The results for the variation of $N_2O$ fluxes are contradictory to the findings of Huang et al. (2004) who suggested that soil cumulative $N_2O$ emissions were negatively correlated with the C:N ratio of amendment. However, cumulative $N_2O$ fluxes are often variable as N is used in many different metabolic and biochemical pathways (Aulakh et al., 1991). These results suggest that plastic-char may help reduce $N_2O$ emissions, which may be beneficial as part of other soil remediation processes.

#### 4.4.2 | $CO_2$ fluxes

The highest cumulative $CO_2$ flux was observed at 10 t $ha^{-1}$. The main flux of $CO_2$ fluxes occurred in the first 2 days (Figure 8). This is similar to the observation of Aulakh et al. (1991) who recorded highest $CO_2$ fluxes within the first 8 days of adding amendment to their soils. Incorporating the plastic-char may have increased soil C which caused short-term mineralization (Smith et al., 2010). Continuous production of $CO_2$ gas was expected, hence a steady increase in the cumulative flux should be observed for all treatments including the control. As no reduction in soil $CO_2$ emissions was observed for the plastic-char, this suggests that the respiration of the soil microbiota was not inhibited by the addition of the plastic-char over the timeframe of this experiment.

#### 4.4.3 | $CH_4$ fluxes

There was a visual decrease in cumulative methane ($CH_4$) flux emissions for all treatments and the control. This may have been expected as $CH_4$ is consumed in aerobic soils when methanotrophs oxidise $CH_4$ to $CO_2$ (Rosace et al., 2020). However, this result was not statistically significant. Contrarily, Royer et al. (2018) suggested that plastic waste may contribute to increased $CH_4$ emissions due to the decomposition of plasticizers, but this effect was not observed over the timeframe of this experiment.

Long-term experiments on biochar as a soil amendment to mitigate greenhouses gases have suggested that they may become resistant to decomposition and act as a carbon storage pool (Smith et al, 2010). This may also be the case for plastic-char as it is expected to be a stable compound under environmental conditions. To gather more insight regarding plastic-char and mitigating greenhouse emissions, research for extended periods across different soil types should be conducted.

## 5 | CONCLUSION

In conclusion thermochemical recycling by pyrolysis provides a possible solution for better plastic waste management as it generates products which can be used as sustainable alternatives and create a circular economy for the plastic industry. Results presented here suggest that plastic-char application to soils may increase plant growth but with possible consequence for the soil active carbon balance, as demonstrated by the increase in $CO_2$ emissions. The input of plant nutrients such as K and Ca and Mg may facilitate replenishing depleted soils, improving soil functions and for carbon management but care is required to ensure that it does not contribute to soil contamination. It is possible that plastic-chars produced from different plastic feedstocks could present different contamination issue.

The types of soil used here were peat and organo-mineral soil. Research should focus on plastic-char production systems to eliminate contaminants and enhance standardization of plastic-char for soil use, different plastic-char characteristics and type of soil for application. It is necessary to test the applicability of these results across a range of soil types, including as part of long-term field trials. Detailed contaminant speciation and bioavailability studies will be required for the range of plastic-chars that may be produced. Plastic-char application to soil may have benefits as part of soil remediation programs. Investigating the impact of plastic-chars on soil microbial communities is likely to provide insights into mechanisms underlying observed effects. If key plant nutrients such as K, Ca and Mg are able to be stripped from the plastic-char, it may also present a means of adding value to the plastic waste recycling process and encourage further investment into this area, further helping to address the issue of plastic waste pollution. However, this will require the development of robust safety standards and a thorough understanding of life cycle assessments of plastic-char production and application.

**ACKNOWLEDGEMENT**

This work was financially supported by Plastic Energy through a research agreement with Harper Adams University.

**AUTHOR CONTRIBUTION**

**Winfred Athembo:** Conceptualization; writing- original draft; writing- review and editing; analysis; methodology; visualisation.

**John Redshaw;** funding acquisition; review and editing.

**Simon Jeffery:** Conceptualization; funding acquisition; supervision; writing- review and editing.

**CONFLICT OF INTEREST**

The project was funded by Plastic Energy in the form of an MRes scholarship. **Winfred R. Athembo** and **Simon Jeffery** do not have any further conflicts of interest to declare. **John Redshaw** is an employee of Plastic Energy.

**DATA AVALAILABILITY STATEMENT**

Data available on request from authors.

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# Declaration of Interest

To Whom it May Concern,

This work was funded by Plastic Energy, in the form of an MRes scholarship, which Winfred R Athembo successfully applied for following a competitive open recruitment.

John Redshaw is an employee of Plastic Energy. He has provided information for inclusion in the manuscript, as well as critically reviewing the manuscript. However, he, nor Plastic Energy, have claimed any rights to be able to decide what data is included or excluded from the manuscript.

Simon Jeffery has no interest to declare other than receiving and managing the scholarship, which then funded Winfred to undertake this research.

I can confirm that I have had full control of what is included in the manuscript and that no cherry picking of the data has taken place. Nor have Plastic Energy tried to change any of the results or messages of the manuscript.