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Research Article

Anthropogenic Factors Affecting Soil Water Repellency: Comparative Analysis of Fire Events, Microplastic Pollution, and Soil Amendment

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Soil water repellency (SWR) is a parameter that can significantly impact agricultural productivity by altering water infiltration, retention, and distribution in soils. This study compares three anthropogenic factors that increase SWR in sandy soils: fire (simulated by burning of soil in a muffle furnace), high-density polyethylene (HDPE) microplastic pollution (5% w/w), and hydrophobic biochar amendment (1% w/w). The severity of water repellency was quantified by measuring the soil-water contact angle (CA). Results demonstrate that all three treatments increased the CA of sandy soils, with HDPE microplastic addition causing the highest relative increase (10.06-fold), followed by hydrophobic biochar addition (3.89-fold), and fire event with 300 °C (4.35-fold). The mechanisms underlying these increases vary: microplastic and biochar introduce new hydrophobic surfaces to the soil matrix, while burning transforms existing organic matter into more hydrophobic compounds. These findings highlight the potential risks of these anthropogenic factors for soil hydrological properties and provide insights for future soil management strategies in agricultural systems.

Keywords: soil water repellency, contact angle, fire events, microplastics, biochar, sandy soil

1 Introduction

Soil water repellency (SWR) is a phenomenon where soils resist wetting for periods ranging from seconds to hours, days, or weeks. It reduces the affinity of soils to water, leading to decreased infiltration rates, increased runoff and erosion, preferential flow paths, and reduced agricultural productivity (Doerr et al., 2000). The severity of SWR is commonly quantified by measuring the soil-water contact angle (CA), while its persistence is often assessed using the water drop penetration time (WDPT) test (Papierowska et al., 2018).

SWR occurs naturally in many soils due to the presence of hydrophobic organic compounds derived from plant residues, soil fauna, and microbial activity. However, anthropogenic factors can significantly enhance soil hydrophobicity (DeBano, 2000). Among these factors, fire (heating), microplastic pollution, and biochar amendment have gained increasing attention for their potential to induce or enhance SWR.

Fire can alter soil properties through heat-induced changes in organic matter composition and mineral structure. During wildfires (grass) or prescribed burning, soil temperatures can exceed 300 °C at the surface, transforming hydrophilic organic compounds into hydrophobic ones (Forgeard & Frenot, 1996). These changes can persist for months after the fire event, affecting soil hydrological properties.

Microplastic pollution represents an emerging environmental concern in agricultural soils. High-density polyethylene (HDPE) is one of the most common microplastics found in agricultural environments, introduced through plastic mulch, irrigation systems, and other agricultural practices (Lincmaierová et al., 2023). The inherent hydrophobicity of HDPE particles can potentially modify soil water repellency when incorporated into the soil matrix.

Biochar, a carbon-rich product from biomass pyrolysis, is increasingly used as a soil amendment to improve soil

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properties and sequester carbon. However, depending on its feedstock and production temperature, biochar can exhibit varying degrees of hydrophobicity (Kinney et al., 2012). Hydrophobic biochar may induce or enhance SWR in otherwise wettable soils.

While these three factors can increase SWR, the magnitude of their effects and the underlying mechanisms may differ significantly. This study aims to compare the relative increase in soil water repellency, as measured by contact angle, caused by fire (burning of soil in a muffle furnace), HDPE microplastic pollution (5% w/w), and hydrophobic biochar amendment (1% w/w) in sandy soils.

2 Materials and Methods

Three separate experiments were analysed to compare the effects of fire events, microplastic pollution, and biochar soil amendment on soil water repellency. All experiments used sandy soils from sites close to each other.

In the heating experiment, sandy soil was taken from an experimental site in the village of Studienka, in the Borská nížina, a lowland in southwestern Slovakia (48° 31.733′ N, 17° 07.315′ E) (Šurda et al., 2023). The site represents arable land, and the soil was classified as Arenosol with sand content of 91.94%, silt content of 1.53%, and clay content of 3.06%. The soil organic carbon content was 0.99% (Šurda et al., 2023).

The microplastic experiment used sandy soil taken from an experimental site in the village of Borský Mikuláš, in the Borská nížina, a lowland in southwestern Slovakia (48° 37′ 01″ N, 17° 12′ 54″ E) (Lincmaierová et al., 2023). The site represents arable land, and the soil was classified as Fluvic Umbrisol with a sandy texture (89.8% sand, 6.7% silt, and 3.5% clay), organic carbon content of 0.99%, and $pH_{(H_2O)}$ of 7.29 (Lincmaierová et al., 2023).

The biochar experiment used sandy soil collected from Plavecký Štvrtok area, in the Záhorská nížina, a lowland in western Slovakia (N 48° 21′ 58.33″; E 16° 59′ 49.23″) (Šurda et al., 2025). The site represents abandoned arable land, and soil was classified as Arenosol with 91% sand, 7.5% silt, and 1.5% clay. The soil had a $pH_{(H_2O)}$ of 6.84 and contained 0.04% of organic carbon (Šurda et al., 2025).

The soil organic carbon content was determined by oxidation with $K_2Cr_2O_7$-H_2SO_4 and the titration of non-reduced dichromate according to ISO 10694 (International Organization for Standardization, 1995b), and the carbonate content was determined from the volume of CO_2 produced during the decomposition of carbonates with approximately 10% hydrochloric acid, according to ISO 10693 (International Organization for Standardization, 1995a). The granulometric distribution was determined by sieving and sedimentation, as specified in ISO 11277 (International Organization for Standardization, 2009).

2.1 Heating Experiment

For the heating experiment, approximately 60 g of soil was placed in ceramic dishes and heated in a muffle furnace (LAC, s.r.o., Židlochovice, Czech Republic; Type: LE 15/11) for 20 minutes at temperatures ranging from 50 to 900 °C, with a focus on 300 °C for this comparative study. After heating, the samples were cooled to ambient temperature before further analysis (Šurda et al., 2023).

2.2 Microplastic Experiment

HDPE microplastic was obtained by milling and sieving commercial plastic to achieve a powder with a particle size of <400 μm. The HDPE had a bulk density of 0.35 $g.cm^{-3}$, a contact angle of 135.17°, and a water drop penetration time of 10,200 seconds, indicating extreme hydrophobicity. The sandy soil was homogenized by a hammer mill, sieved (2.5 mm mesh size), and mixed with HDPE microplastic at a concentration of 5% (weight of microplastic/total weight). The soil-microplastic mixture was allowed to settle under laboratory conditions for 14 days, during which three wetting-drying cycles were conducted (Lincmaierová et al., 2023).

2.3 Biochar Experiment

The hydrophobic biochar produced from Swedish biomass willow variety (*Salix schwerinii* L. × *S. viminalis* L. var. Tordis) at 520 °C was used. Biochar had a carbon content of 83.1%, a contact angle of 128.30°, and a water drop penetration time of 12,613.8 seconds. Biochar was ground with a hammer mill and sieved to obtain a fraction with particle diameters ranging from 125 μm to 2 mm. The sandy soil was mixed with biochar at a concentration of 1% (w/w) (Šurda et al., 2025).

2.4 Measurement of Soil Water Repellency

The severity of SWR was assessed by measuring the static contact angle (CA), using the sessile drop method. A water drop was placed on the soil surface, and the CA was evaluated using an OCA 11 optical goniometer (DataPhysics Instruments GmbH, Filderstadt, Germany). The procedure described by Bachmann et al. (2000) was used to prepare the samples. It involved covering a glass slide with double-sided adhesive tape and pressing soil particles onto the tape for several seconds. The slide was shaken carefully to remove any unglued soil particles, and then a 5 μL drop of deionized water was placed on the sample surface using a 0.91 mm syringe needle. After

1 s when mechanical disruption of the surface was complete after drop placement, CA was evaluated by analysing the shape of the drop (ellipsoid approximation) and fitting tangents on both sides of the drop using dpiMAX software (DataPhysics Instruments GmbH, Filderstadt, Germany). The CA of each drop was determined as the average of the CA values on the left and right sides of the drop (Šurda et al., 2023; Lincmaierová et al., 2023; Šurda et al., 2025).

3 Results and Discussion

The initial CA values varied across the three experiments due to soil properties and organic matter content differences. The soil in the heating experiment had an initial CA value of 9.99°, indicating wettable soil (Šurda et al., 2023). The control soil in the microplastic experiment had a CA of approximately 7.98°, which also indicated wettable soil (Lincmaierová et al., 2023). The control soil in the biochar experiment was wettable with a CA of around 15.44° (Šurda et al., 2025).

Heating the soil to 300 °C increased the CA to 43.43° (Šurda et al., 2023). The addition of HDPE microplastic (5% w/w) increased the CA from 7.98° to 80.31° (Lincmaierová et al., 2023). The addition of hydrophobic biochars (1% w/w) increased the CA from 15.44° to 60.06° (Šurda et al., 2025). Fig. 1 presents the increase in CA across the three treatments.

The results clearly show that microplastic addition caused the highest relative increase in CA (10.06-fold), followed by burning (4.35-fold) and by hydrophobic biochar addition (3.89-fold). This suggests that microplastic pollution has the most significant impact on SWR among the three factors studied, which can be explained by the higher concentration and CA values of the HDPE particles than the biochar particles. The mechanisms underlying the increase in SWR differ among the heating and amendment treatments. The heating-induced increase in SWR is primarily attributed to the transformation of soil organic matter. At temperatures below 300 °C, non-destructive distillation of volatile organic substances occurs, leading to the formation of hydrophobic compounds on soil particle surfaces (Hosking, 1938). As noted by Šurda et al. (2023), CA started to decrease at temperatures above 300 °C, suggesting that further heating leads to complete combustion of organic matter and a reduction in SWR. Moreover, heating can lead to redistribution of hydrophobic organic compounds. As the temperature rises, these compounds can melt, flow, and coat mineral particles, increasing the overall soil hydrophobicity (DeBano et al., 1976). Additionally, some hydrophobic compounds may migrate downward due to the temperature gradient, creating water-repellent layers below the surface (Novák et al., 2009).

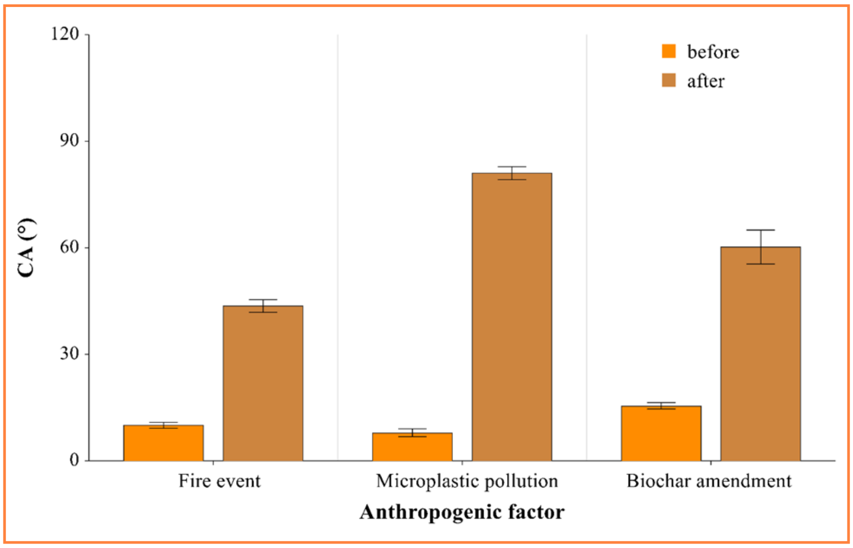

Figure 1 Increase in contact angle (CA) after fire event (heating to 300 °C), microplastic (HDPE) pollution (5% w/w), and addition of hydrophobic biochar (1% w/w) to sandy soils

HDPE particles are inherently hydrophobic, with a CA of approximately 135.17° (Lincmaierová et al., 2023). When mixed with soil, they create a composite material with increased hydrophobicity. The particles can adhere to soil particles due to their hydrophobic nature, creating a layer with subcritical SWR at the soil-air interface. As water molecules encounter this layer, they experience an increased contact angle, resulting in inhibited infiltration. The formation of microplastic clusters within the soil matrix can further exacerbate hydrophobicity by creating microscale air pockets that hinder water flow. In sandy soils, the absence of fine particles limits the potential for capillary action and wettability enhancement, making them particularly susceptible to microplastic-induced SWR (Lincmaierová et al., 2023). This mechanism is supported by the finding that HDPE treatment also reduced hydraulic conductivity (from 0.34 mm·s^{-1} to 0.22 mm·s^{-1}) and water sorptivity (from 2.86 mm·s$^{-1/2}$ to 1.51 mm·s$^{-1/2}$) in the microplastic experiment (Lincmaierová et al., 2023).

Hydrophobic biochar particles, particularly those produced at higher temperatures (pyrolysis temperature of used biochar was 520 °C), have a highly aromatic structure with fewer hydrophilic functional groups. When added to soil, they introduce hydrophobic surfaces that increase the overall SWR (Šurda et al., 2025). The biochar particles can also interact with soil organic matter, potentially enhancing this effect. The hydrophobicity of biochar is mainly determined by its feedstock type and pyrolysis temperature. Biochars produced at temperatures between 300 °C and 600 °C tend to be more hydrophobic due to the presence of aliphatic and aromatic compounds on their surfaces (Wang et al., 2015). Interestingly, despite the high intrinsic hydrophobicity of biochar (CA of 128.30°), the biochar-amended soils showed only slight water repellency (40° ≤CA <90°) according to Papierowska et al. (2018) classification. This suggests that at the low application rate used (1% w/w), the hydrophobic biochar particles did not form a continuous network in the soil, limiting their overall impact on SWR.

However, the finding that microplastics have a more pronounced effect on soil water repellency is significant in light of growing concerns about microplastic pollution of agricultural soils. The results suggest that even small amounts of microplastic contamination could significantly alter soil hydrological properties, with potential implications for water infiltration, runoff, and crop growth.

4 Conclusions

This study compared the effects of fire (simulated by heating to 300 °C), HDPE microplastic pollution (5% w/w), and hydrophobic biochar amendment (1% w/w) on soil water repellency in sandy soils. The results indicate that all three anthropogenic factors can significantly increase soil water repellency, with HDPE microplastic having the most dramatic effect (10.06-fold increase in CA), followed by burning (4.35-fold increase) and hydrophobic biochar addition (3.89-fold increase).

The mechanisms inducing these increases vary, with microplastic and biochar introducing new hydrophobic surfaces to the soil matrix, while heating transforms existing organic matter into more hydrophobic compounds. These findings have important implications for soil management in agriculture, as increased water repellency can lead to reduced water infiltration, increased runoff and erosion, preferential flow paths, and potentially reduced crop yields.

From an agricultural perspective, the results highlight the need to consider the potential impacts of these factors on soil hydrological properties. In particular, the strong effect of microplastics suggests that plastic pollution control should be a priority in agricultural systems. Similarly, while biochar has been promoted as a soil amendment for carbon sequestration and soil improvement, its potential to induce water repellency should be considered, especially when using hydrophobic biochars produced at higher pyrolysis temperatures.

Future research should focus on investigating the combined effects of these factors on soil water repellency, their long-term persistence in soils, and developing strategies to mitigate their impacts in agricultural systems.

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