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Implications of surfactant application on soil hydrology, macronutrients, and organic carbon fractions: An integrative field study

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Abstract: This study investigates the effects of repeated applications of the non-ionic soil surfactant H2Flo (ICL-SF Inc., Israel) on the soil water content, hydraulic conductivity, nutrient distribution, and organic carbon fractions (OCFs) in non-hydrophobic loamy sand soils under subsurface drip irrigation. Our results indicate that H2Flo treatment reduces both saturated and unsaturated hydraulic conductivity while promoting the uniform irrigation distribution, consistent with previous findings on surfactants' effects on sandy soils. An increase in soil pH levels, organic carbon content, and extractable magnesium, calcium, and potassium was observed in treated soils, with elevated levels of potassium permanganate oxidizable organic carbon (POXC) implying accelerated decomposition rates. Notably, a positive linear relationship was found between POXC and the increased NO_3^--N content of treated soils, suggesting induced conditions of nitrification. However, the carbon fractions water-soluble organic carbon (C_{ws}) and hot water-soluble organic carbon (C_{hws}) remained quantitatively unchanged, even though they exhibited a positive linear relationship with the soil's hydraulic conductivity. The study highlights the crucial role of monitoring changes in OCFs and nutrient dynamics after surfactant application to optimize soil organic matter utilization and chemical fertilizer management.

Keywords: extractable nutrients; nitrogen sources; hot water-soluble organic carbon; hydraulic conductivity, water-soluble organic carbon

Commercial wetting agents, typically based on alkyl block polymer (ABP) or polyoxyalkylene polymer (PoAP) surfactants, enhance re-wettability and infiltration rates in water-repellent sandy soils (Cisar et al. 2000; Dekker et al. 2005; Oostindie et al. 2008) and augment soil hydration in urban lawns (Dekker et al. 2019). Surfactants, comprised of polar and nonpolar parts, are attracted to the hydrophobic surfaces of soil particles, leading to alterations in both the rate of water infiltration and water distribution within the soil profile (Mobbs et al. 2012). The performance and sustainability of these products can vary significantly, particularly concerning the balance between soil water holding and infiltration abilities (Song et al. 2014), necessitating individual product examinations.

Recently, there has been a noticeable shift in the scientific focus of surfactant research. This change

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is driven by new findings on surfactant-sourced hydrophobicity (Song et al. 2019) and a rise in both dissolved organic carbon (DOC) and particulate organic carbon (POC) in soil leachates after treatment (Song et al. 2018, 2021). Specifically, PoAP-based surfactants have been observed to create hydrophobic layers on sand after multiple applications, transforming even naturally adsorbent sands to resist water. The observed rise in POC in the leachates from these treated soils is believed to indicate surfactants displacing the native organic layers on sand particles. Interestingly, ABP-based products did not induce such a change in either inherently hydrophobic or adsorbent soils in the referenced studies. Yet, a separate study highlighted that ABP-based surfactants diminished microbial activity by effectively stripping organic coatings from the sand grains (Song et al. 2019). In alignment with this, a comprehensive study by Kintl et al. (2022) delved into the impact of various wetting agents on water stable aggregates (WSA). They found a significant decrease in WSA, linked to a reduction in soil organic carbon (SOC).

In addition to the limited understanding of how wetting agents impact soil organic carbon storage, there is also a noticeable lack of studies addressing the dynamics of nutrient availability. A study by Chang et al. (2020) evaluated the effects of surfactant applications on lawns planted with St. Augustine grass (*Stenotaphrum secundatum*). Predictably, there was an enhancement in soil moisture and the quality of the turfgrass. However, the levels of ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), extractable phosphorus (P), DOC, and total organic carbon (TOC) in the soil leachates remained unchanged. On the plant side, Chaichi et al. (2017) observed enhanced nutrient absorption in tomato plants when treated with a surfactant. In a study by Banks et al. (2015), three commercial surfactants (Activator 90, Agri-Dex, Thrust) were examined. The research showed that the plant potassium (K) uptake was reduced in clay loam soils when treated with Thrust. Conversely, in soils treated with Activator 90 and Agri-Dex, there was a significant decrease in the uptake of several macro- and micro-nutrients.

Despite the poorly understood dynamics of nutrient fixation and release in surfactant-treated soils, the application of surfactants aided in the elimination of specific organic contaminants like polycyclic aromatic hydrocarbons (PAH), enhancing their desorption and fostering their degradation, as noted by Yang et al. (2017) and Li et al. (2019).

H2Flo (ICL-SF Inc., Israel) is a commercial nonionic PoAP-based soil surfactant. The manufacturer notes that the product contains a minor organic element presented as 'root activator' molecules. This study aims to (*i*) uncover the changes in saturated (K_s) and unsaturated (K(h)) hydraulic conductivity of non-hydrophobic loamy sand soils under subsurface drip irrigation while (*ii*) exploring the induced alterations in nutrient distribution and chemically distinguished organic carbon fractions (OCFs) following applications of the wetting agent H2Flo; (*iii*) magnesium (Mg), calcium (Ca), and extractable phosphorus (P) were examined due to their agronomic significance and their possible modified distribution under surfactant applications; (*iv*) to understand potential shifts in soil nitrification rates due to expectedly altered soil and water interactions, the ratios and levels of NH_4^+-N and NO_3^--N were assessed; (*v*) to further comprehend the shifts in byproducts of organic matter degradation under different conditions of moisture, temperature, and matric potential, we examined the content and distribution of hot water-soluble organic carbon (C_{hws}), water-soluble organic carbon (C_{ws}), potassium permanganate oxidizable organic carbon (POXC), and TOC.

In our study at a specific loamy sand soil locality, we investigate the application of the wetting agent H2Flo, even to naturally non-hydrophobic soils. Loamy sand soil, despite being naturally non-repellent, can benefit from enhanced water residence time in the root zone, especially in regions where this soil type prevails. This approach aligns with our study's objectives, which aim to assess whether OCFs would be influenced in terms of their mobility with modified K_s and K(h) of the soils, as has been previously reported for physically distinguished carbon fractions such as particulate organic carbon or dissolved organic carbon by other studies. Through these monitoring efforts, informed decisions can be made about wetting agent applications and other management practices. This could lead to more efficient nutrient use, increased crop productivity, reduced environmental impacts, and improved soil health and resilience. The present research is anticipated to offer substantial insights into the interplay of water/nutrient adsorption by soil mineral particles when exposed to wetting agent treatments. Additionally, it explores their connections with OCFs, standing out as one of the comprehensive field studies.

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MATERIAL AND METHODS

Description of the study area and soil sampling. The research field is situated in the Benátky nad Jizerou district, Central Bohemian Region, Czech Republic, and features loamy sand soils consisting on average from 81.2% of sand, 13.3% of silt and 5.5% of clay. Positioned at an altitude of 220 m with WGS84 coordinates 50.2782878N, 14.8392344E, the region has a temperate climate marked by gentle, dry winters. The area registers a long-term average temperature of 8.4 °C and an annual rainfall of 560 mm. This site is nestled in the alluvial plains of the Jizera River, notable for its varied soil compositions, predominantly sandy in nature.

Potatoes were sowed on 1 April 2019, with drip irrigation starting on 1 May 2019. Organic fertilizer was applied in spring at a rate of 10 t/ha. Before the planting on 1 April and subsequently on 28 April, just before the canopy took shape, NPK fertilizer was used, amounting to 180 kg N/ha in total. The wetting agent, H2Flo, was dispensed three times through subsurface driplines: on 3 May, 5 June, and early July, with each application consisting of 5 L mixed into 1 000 L of water. From 11 June onward, fungicides and insecticides were used, with subsequent applications every 7–10 days. Before H2Flo applications and after the second application of H2Flo, disturbed soil samples were collected from two depth ranges, 0–15 and 15–30 cm. A detailed depiction of the study area location and sampling scheme is provided in Figure 1A, while a schematic representation of the sensor placement is provided in Figure 1B.

Soil analyses. K_s was determined using undisturbed core rings (250 cm^3) employing a KSAT device (Meter Group Inc., USA), falling head technique. These samples were collected after the initial two applications of H2Flo. The soil had no considerable structure. Four core rings were tested three times each for the control and H2Flo treated soils. For statistical assessment, the obtained K_s values (measured in cm/day at 20 °C) underwent a logarithmic transformation. The naturally wet disturbed samples were carefully mixed and sieved (8 mm) to remove any larger objects, such as stones, roots, and earthworms. The cleaned soil samples were then repacked into containers with a 5 L volume, maintaining a dry bulk density value of 1.44–1.49 g per cm^3 and an initial soil water content of 0.055 g/g. Subsequently, the Mini Disk Infiltrometer (Meter Group Inc., USA) was employed to determine K(h) in these artificially packed soil columns. Repacked soil columns on structureless soil were preferred due to the difficulty of using the infiltrometer in a potato field. Two pressure heads, namely –2 and –5 cm, were consecutively applied during each measurement. The disturbed soil samples were taken after the second application of H2Flo.

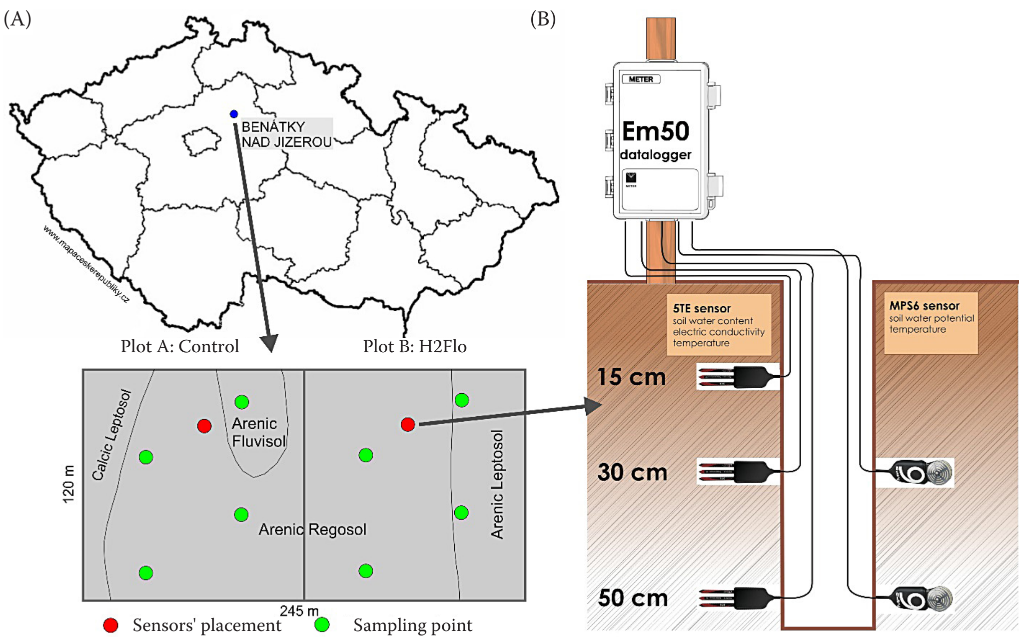

Figure 1. Study area location and sampling scheme (A) and schematic representation of the sensor installation (B)

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The TOC content was determined using the method developed by Nelson and Sommers (1996) based on rapid dichromate oxidation. The electrical conductivity (EC) and pH of the soils were determined in a 1 : 2.5 dH_2O solution (Rayment & Higgenson 1992). Extractable concentrations of Ca, K, Mg, and P were ascertained using the Mehlich III solution method (Mehlich 1984). Concentrations of NH_4^+-N and NO_3^--N were gauged post 0.01 mol/L $CaCl_2$ extraction, as prescribed by ISO 14255:1998. The C_{ws} and C_{hws} levels were identified using a modified Körschens method (Körschens 1980). The POXC measurement followed the method detailed by Weil et al. (2003), which relies on the discernible colourimetric variation at a 540 nm wavelength in 0.2 M $KMnO_4$ soil extracts. Changes in POXC were investigated since it is viewed as a gauge for the readily decomposable carbon reservoir, comprising a mix of both water-repellent and water-attracting compounds, which arise from the preliminary breakdown of soil organic matter (SOM) (Bongiorno et al. 2019). This indicator of labile carbon pool may highlight the altered degradation dynamics after surfactant applications. C_{ws} refers to the fraction of TOC that can dissolve in water at room temperature. These could include simple sugars, amino acids, and certain other organic compounds, which are often readily available for microbial activity and can contribute significantly to soil fertility and nutrient cycling. Conversely, C_{hws} contains a greater variety of complex organic compounds (Uchida et al. 2012). These include microbial biomass carbon, root exudates, amino acids, and carbon linked to soil enzymes (since many enzymes are denatured at high temperatures), which allows C_{hws} analysis to cover significantly more carbon than C_{ws} analysis can. The relevant soil analyses were carried out with three replicates revealing the properties of four sampling points per treatment.

The non-hydrophobic nature of the experimental soil was determined using the standard soil survey test method for water-repellency (Roberts & Carbon 1971; King 1981). Deionized water was dropped onto the surface of both control and treated soils and was observed to be absorbed in under 1 second.

Monitoring the soil water content. The sensors 5TE by METER Group Inc. (USA/Germany) which uses capacitance and thermistor technology to monitor soil's volumetric water content (VWC), bulk EC, and temperature, were used to monitor the relevant parameters. It provides high precision with ±3% VWC accuracy in typical soils and a temperature accuracy of ±1 °C.

The MPS-6 matric potential sensors, from the same manufacturer, were used to monitor the soil water potential. It operates well in drier systems where tensiometer cavitation would be a problem. The MPS-6 covers a range from –10 to –10 000 kPa.

The EM50 data loggers, also by METER Group Inc., were used to collect data from sensors. This five-channel device reads sensors with analogue or digital outputs and is designed for long-term, low-power usage. The monitoring period for data collection using these loggers extended from April 16th to August 15th, 2019. Sensor positions throughout the soil profile are shown in Figure 1B.

Statistical analyses. Statistical evaluations and visualizations were conducted using STATISTICA software (Ver. 13, Statsoft, USA). The normality of the data were checked before variance analysis, per each parameter for the same soil depth and treatment by Shapiro-Wilk test ($P < 0.05$). Differences between treatments and soil depths were assessed using *t*-test based on groups of control and H2Flo treated soils or soils of 0–15 and 15–30 cm. Pearson's correlation coefficient were used to explain linear relationships between parameters.

Given the nature of saturated hydraulic conductivity data for soils, it is common to observe a wide range of values with an erratic distribution, which commonly directs researchers to log-transform of the data as in the current study. In that context, K_s results were evaluated with both *t*-test and the *F*-test and non-parametric Kruskal-Wallis test.

RESULTS AND DISCUSSION

Distribution of soil water content in the root zone. Repeated applications of the H2Flo provided more uniform distribution of soil VWC in the root zone compared to the control soils as observed by 5TE sensor measurements during the monitoring period (Figure 2A, B). Irrigation events are noticeable till the first half of July, when the rainy period occurred and at the end of July the irrigation was terminated. The water content values were in accordance with the observed matric potential differences by MPS-6 sensors (Figure 2C). The influence on soil VWC was more pronounced at 30 and 50 cm depths, along with the 15 cm depth after the second application of H2Flo in June. These findings are consistent with the well-defined improvements that can be provided

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by wetting agent applications in non-hydrophobic soils. Wetting agents, known for their strong affinity for soil surfaces, are adsorbed onto even non-hydrophobic soil particles. Concurrently, this process can enhance water penetration into the soil, regulating the redistribution of water within the soil profile. The application of these agents is well documented for the management of water repellency in thatch and surface layers in sandy soils and for the enhancement of soil hydration (Oostindie et al. 2008; Dekker et al. 2019). Recently, wetting agents have been widely used to homogenize water distribution at the root zone, too (Ou & Latin 2018). In accordance, significant increases in soil water contents after treatment with surfactants have been documented by many researchers (Oostindie et al. 2005; Moore et al. 2010).

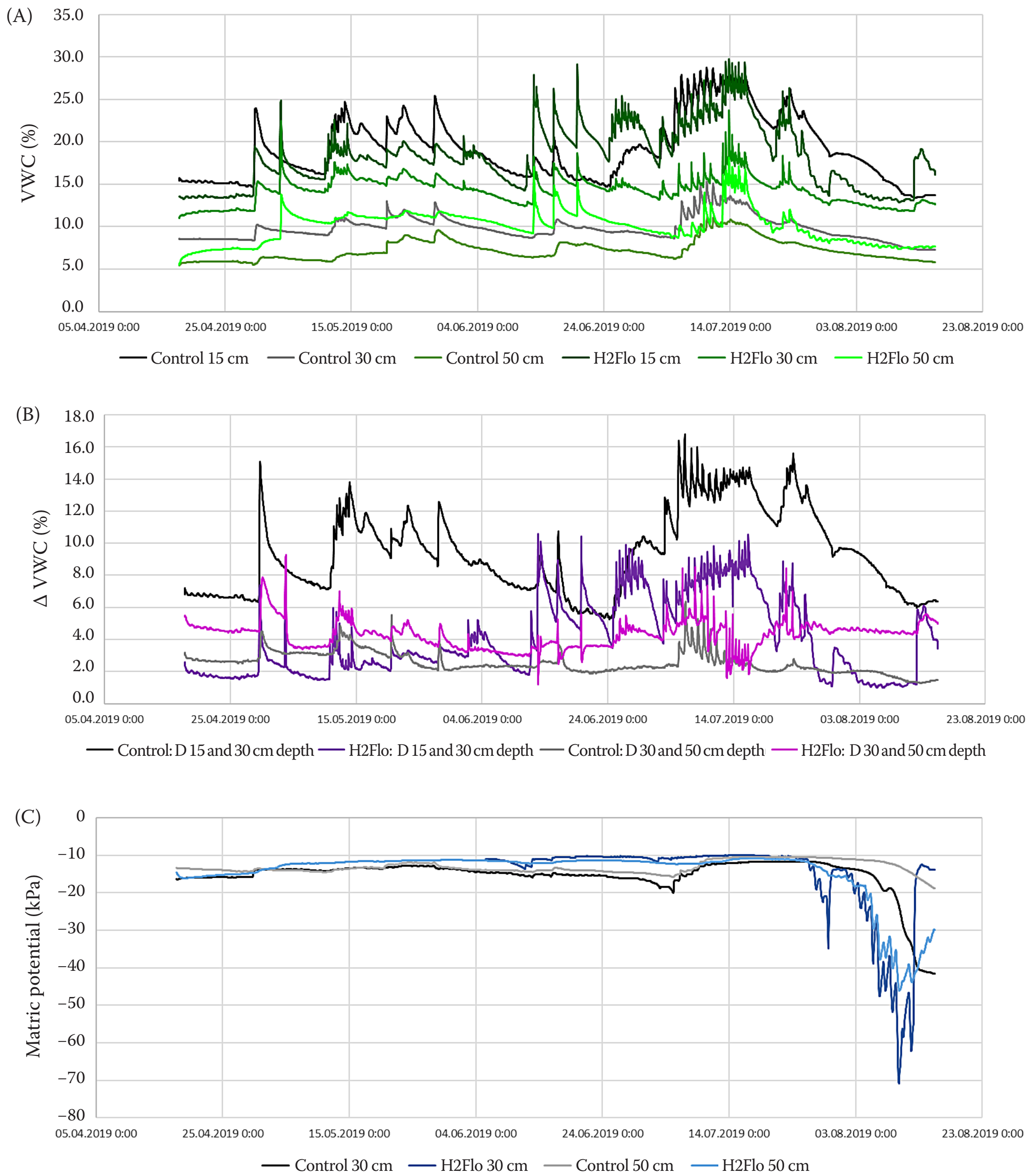

Figure 2. Visualization of the impact of non-ionic soil surfactant H2Flo treatment on soil volumetric water content (VWC) and matric potential: comparison of VWC between untreated control soils and H2Flo treated soils (A); variation in soil water content at different depths for both the control and H2Flo treated soils (B); difference in matric potential values between control and H2Flo treated soils (C)

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Table 1. Statistical evaluation of soil physicochemical properties based on treatments

	Before application of H2Flo				After 2nd application of H2Flo			
Depth (cm)	0–15		15–30		0–15		15–30	
Treatment	H2Flo	control	H2Flo	control	H2Flo	control	H2Flo	control
pH	5.0875	5.2225	5.3325	5.4975	5.215**	4.6675	5.3875*	5.045
EC (µS/cm)	266.25*	149.4	224**	80.525	384.75	492.75*	266.5	301.5
TOC (g/kg)	5.9	7.7	5.9	7.1	10	10	9.6	8.1
SOM[a] (%)	1.02	1.33	1.02	1.23	1.73	1.73	1.66	1.4

H2Flo – non-ionic soil surfactant treated soil; EC – electrical conductivity; TOC – total organic carbon; SOM – soil organic matter; [a]Van Bemmelen transformation of TOC with the factor of 1.724; *t*-test applied for the soils of the same depth and the same treatment; *,***P* < 0.05, 0.01

Figure S1 in Electronic Supplementary Material (ESM) presents the lower temperature through the profile of treated soils, as a result of increased VWC values, particularly after the second application of the product, as demonstrated in Figure 2A.

Physicochemical characteristics of the soil. The differences in pH, electrical conductivity, and TOC in soil profile were evaluated by ANOVA before the application of H2Flo to eliminate any potential misunderstanding about possible spatial natural variability. The only significant difference was observed in the electrical conductivity of the soils, which did not affect the salinity interpretation class (Table 1).

Soil reaction was significantly influenced by the surfactant treatment at both soil depths, resulting in slightly elevated pH values. Boomgaard et al. (1987) provided an explanation on the adsorption of non-ionic surfactants. Surfactants are amphiphilic molecules, meaning they have both hydrophilic (water-attracting) and lipophilic (fat-attracting) parts. The primary mechanism for adsorption when the surfactant concentration is low involves hydrogen bonding. This occurs between the non-ionic surfactant chain and the hydroxyl groups located on the mineral surface. As a result of this hydrogen bonding, non-ionic surfactants adsorb in the form of individual units or monomers, leading to a reduced concentration of hydrogen ions and an increase in soil pH.

The difference in electrical conductivity between the soil depths was lower in the treated soils compared to the control soils. This may be connected with a more even distribution of the soluble salts throughout the soil profile as a result of observed changes in VWC throughout the soil profile. The untreated soils exhibited significantly higher EC values at 0–15 cm depth. Contrary to the untreated soils, TOC values were in a similar range for both soil depths in the treated soils, resulting in significantly higher TOC content in the subsoil.

Given the coarse texture of the experimental soils and the region's typical highly acidic pH values, nutrient availability dynamics are of utmost importance in our study.

Extractable macronutrients. In the H2Flo treated topsoils, concentrations of extractable Ca, K, and Mg were markedly elevated (as shown in Figure 3). While Ca and Mg concentrations also increased in the treated soils between 15–30 cm depth, K concentrations did not exhibit significant differences at this depth. Notably, the only discernible variation in nutrient concentrations across depths in control soils

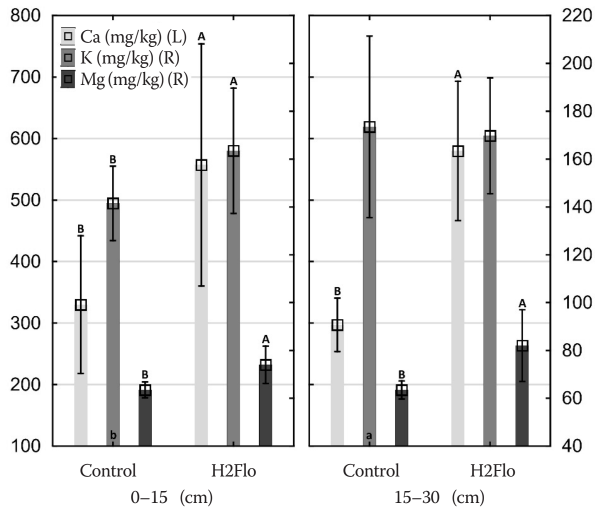

Figure 3. Alterations in extractable Ca, K and Mg levels relative to treatment and soil depth

L – left *y*-axis; R – right *y*-axis; H2Flo – non-ionic soil surfactant treated soil; statistically significant differences between treatments at the same sampling depth are denoted by capital letters, while differences between sampling depths are indicated (*P* < 0.05)

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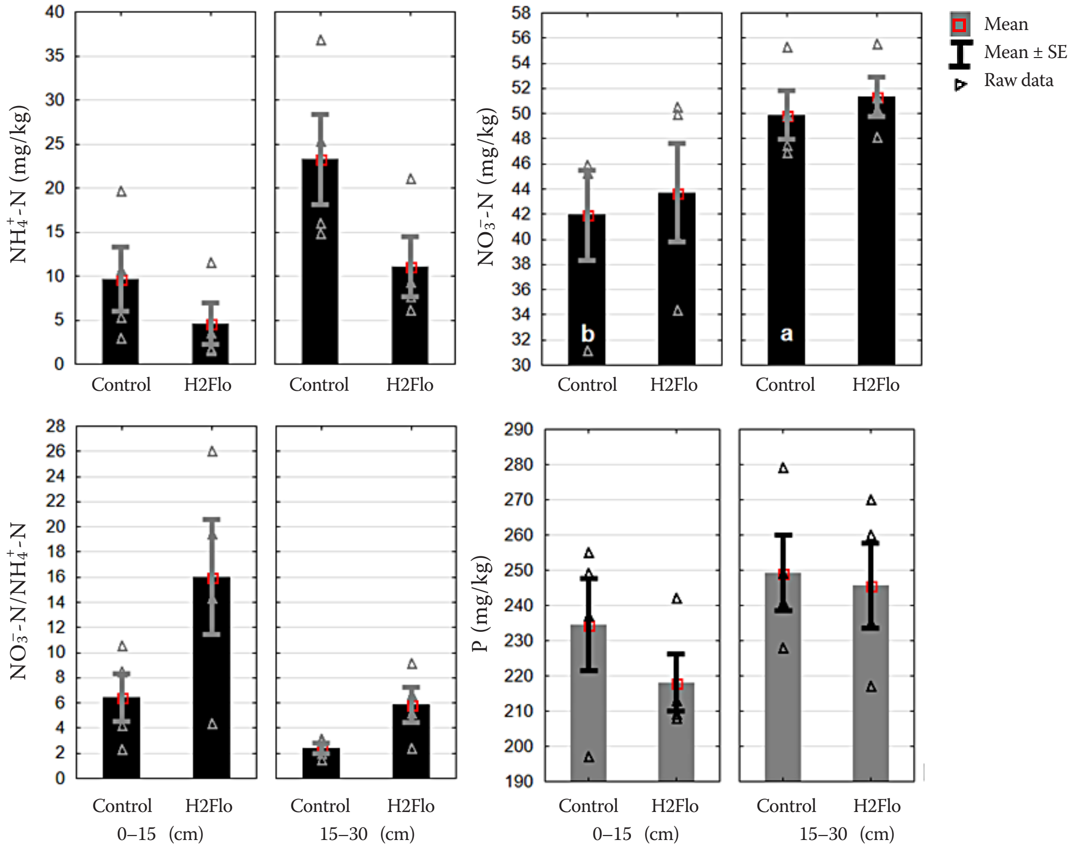

Figure 4. Variations in nitrogen sources, nitrogen source ratios, and extractable P in relation to treatment and sampling depth H2Flo – non-ionic soil surfactant treated soil; statistically significant differences between sampling depths are indicated using lowercase letters within the corresponding columns ($P < 0.05$)

pertained to K content, which manifested substantially higher concentrations at 15–30 cm ($P < 0.05$) relative to the topsoil.

In a recent specialized investigation (Ogunmokun & Wallach 2021), varying doses of a non-ionic surfactant blend (Aquatrols) were administered to grapefruit crops in sandy loam soils supplemented with treated wastewater. As anticipated, both soil moisture levels and the degree of saturation increased. Interestingly, the study reported that the surfactant treatments led to significantly diminished levels of extractable K and exchangeable Ca + Mg at soil depths of 0–20 and 20–40 cm. These reductions were corroborated by the observed decrease in soil electrical conductivity. It is noteworthy that higher crop yields were observed in the treated soils compared to the untreated soils, possibly indicating enhanced nutrient uptake by the plants. This contrasting outcome aligns with the observations of Banks et al. (2015), emphasizing the product-specific ramifications of wetting agents on the availability of soil nutrients.

The rise in the concentrations of extractable nutrients in the current study might be linked to the shift in pH towards a more neutral soil reaction. Notably, the treated soils exhibited a significant rise in pH at both depth intervals, potentially enhancing nutrient availability. Given that EC values were found to decline post-treatment, the elevated pH could be a contributing factor to the noted increase in nutrient concentrations.

Nitrogen sources and extractable phosphorus. Following H2Flo applications, a significant reduction in NH_4^+-N was observed at both soil depths, while NO_3^--N showed a proportionate ascent, as depicted in Figure 4. This points towards an environment favourable for nitrification. Consequently, the most pronounced distinction between treatments manifested in the comparative ratios of these forms of N, with a *P*-value of 0.057 in the *t*-test . Chang et al.'s (2020) findings concerning N sources aligned with the subtle significance of our observations. Contrastingly, Ogunmokun and Wallach (2021) documented a decline in total N across both depths.

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In one of the exceptional studies regarding the influence of non-ionic surfactants on the NH_4^+-N and NO_3^--N content of potato-grown sandy loam soils, Arriaga et al. (2009) reported decreased content for both of these nutrients. A significant reduction (30.1%) was observed in soil NO_3^--N concentration 20 days after the final N fertilization when a surfactant was applied, regardless of the N application rates. There was also a trend towards a decrease in soil NH_4^+-N following the surfactant application, though this reduction was less pronounced (19.7%, with a P-value of 0.12).

No significant differences were observed between treatments or depths regarding extractable P concentrations, although they were marginally reduced in the treated soils, as illustrated in Figure 4. These observations align with those reported by Ogunmokun and Wallach (2021) and Chang et al. (2020). It should be emphasized that study of Chang et al. (2020) was confined solely to topsoil examination. Figure S2 in ESM provides insight into the enhanced vegetative growth via crop coverage, enhanced vegetation index (EVI) and normalized difference vegetation index (NDVI) of treated and control soils.

Organic carbon fractions. Repeated applications of H2Flo led to a significant increase in POXC content of topsoils, while the C_{hws} and C_{ws} contents of both top and subsoils remained unchanged (Figure 5). The POXC and C_{hws}, being initial products of SOM degradation, have been identified to have strong associations with the WSA, water holding capacity, and bulk density of soils, as described by Bongiorno et al. (2019). Additionally, these components correlate with extractable forms of N, P, and sulfur (S) as highlighted by Verma et al. (2010). Blair et al. (2006) further noted that K(h) and the average weight diameter of aggregates were linked to POXC changes through inverse and direct relationships, respectively.

The concurrent rise of POXC at both soil depths suggests that the change could primarily stem from distinctly altered degradation conditions—heightened moisture, reduced temperature, and matric potential. The H2Flo treatment's organic input, derived from the product's organic root activator molecules, might play a minor role. Regrettably, specifics regarding the quantity or character of these organic compounds remain elusive. When factoring in the treatment dosage of 5 L of H2Flo per hectare, it is clear that the H2Flo's cumulative contribution cannot solely account for the observed elevation. Additionally, a marked rise in TOC content in the treated subsoils (Table 1) possibly underscores that the POXC fraction might have had a dominant influence on the witnessed growth. This could be attributed to the induced degradation conditions and a more uniform distribution of nutrients and water.

In the control soils, there was a pronounced negative association between POXC and NH_4^+-N (r = –0.983, P = 0.017). Conversely, in the treated soils at depths between 15–30 cm, POXC displayed a marked positive relationship with the NO_3^--N/NH_4^+-N ratio (r = 0.993, P = 0.007). The induced decomposition of SOM after repeated application of wetting agents is a phenomenon that has been particularly noted in previous remediation studies on polycyclic aromatic hydrocarbons such as phenanthrene (Yu et al. 2007) and

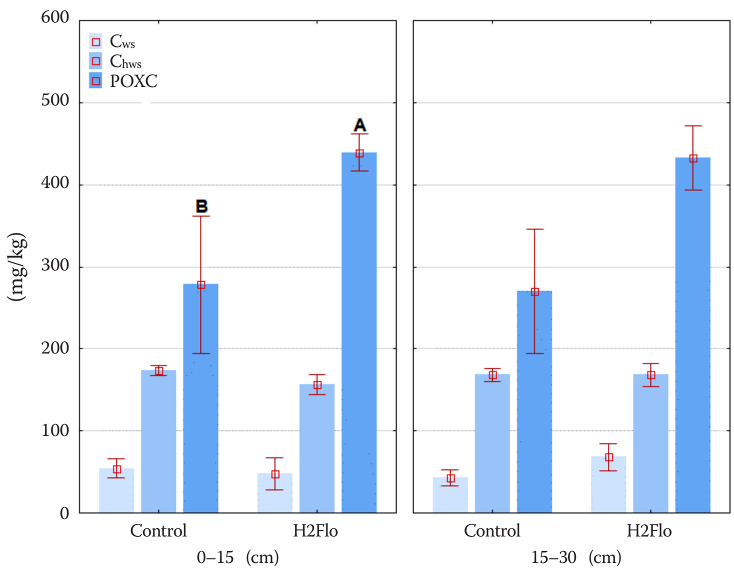

Figure 5. Variations in organic carbon fractions in relation to treatment and sampling depth H2Flo – non-ionic soil surfactant treated soil; C_{ws} – water-soluble organic carbon; C_{hws} – hot water-soluble organic carbon; POXC – potassium permanganate oxidizable organic carbon; statistically significant differences between treatments at the same sampling depth are denoted by capital letters (P < 0.05)

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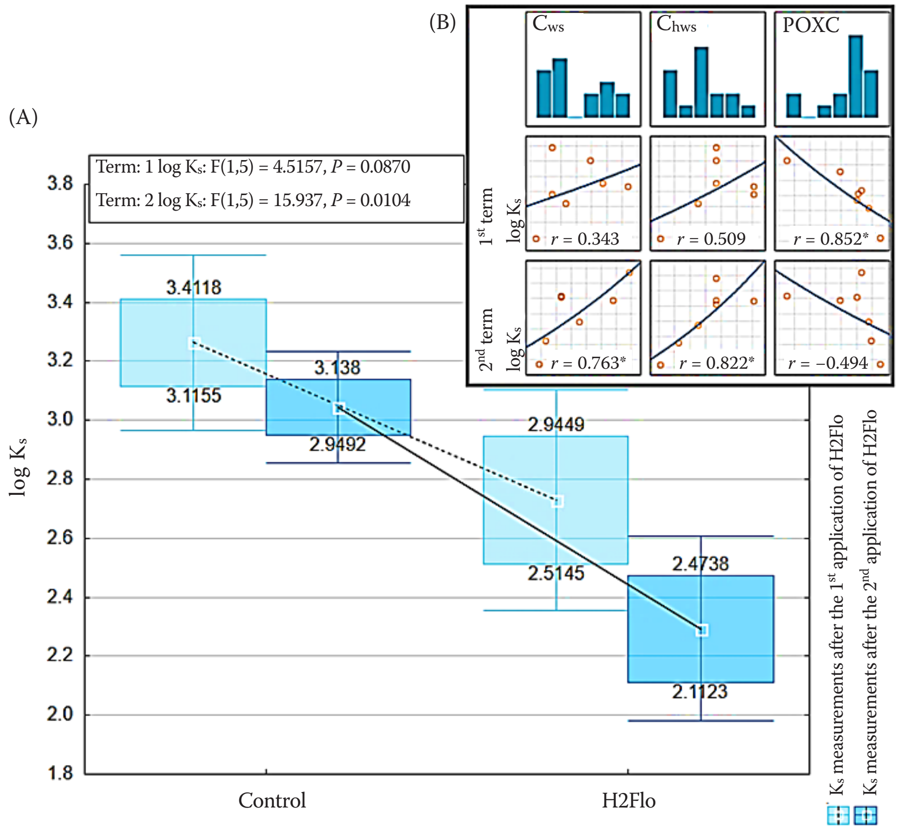

Figure 6. Alterations of saturated hydraulic conductivity (K_s) (log base 10 of cm/day outcomes) of topsoils in response to treatments (A); Pearson correlation coefficients of K_s and OCF in the scatterplots (B)

H2Flo – non-ionic soil surfactant treated soil; C_{ws} – water-soluble organic carbon; C_{hws} – hot water-soluble organic carbon; POXC – potassium permanganate oxidizable organic carbon; **P* < 0.05

tributyltin (Mathurasa et al. 2012). Later, Banks et al. (2014) revealed increased microbial activity after non-ionic surfactant applications, with minimal differentiation in microbial community members.

In the H2Flo treated soils, there was a distinct positive association between C_{hws} concentrations and Mg levels ($r = 0.773$, $P = 0.025$). Such relationships between OCF and extractable cations were absent in the control soils. C_{hws} contains various functional groups (like carboxyl and phenolic groups) (Uchida et al. 2012), that can form chelates with metal cations including Mg^{2+}. These chelates can increase the solubility of Mg in soil, making it more readily available for plant uptake.

Soil hydraulic conductivity. H2Flo applications led to a reduction in K_s rates, with the decline being more pronounced after the second application (Figure 6A; $P = 0.01$ in *t*-test and *F*-test, $P = 0.03$ in Kruskal-Wallis test). While both treated and control soils exhibited a reduction in rates over time, the variance between the average K_s rates during the sampling intervals was not significant.

In most cases, the decrease is due to: (1) the disintegration of soil aggregates, resulting from the surfactant adhering to minerals and/or the effect of a high sodium adsorption ratio (SAR), which results in pore blockage due to displaced particles (Mingorance et al. 2007; Liu et al. 2022); and (2) the blockage of pores caused by the precipitation of surfactant when divalent cations like Ca^{2+} and Mg^{2+} are present in the soil (Çelik et al. 1978; Stellner & Scamehorn 1986). Additionally, the clay content of the soil is influential in terms of the expansion of minerals and fine particle mobilization (Peng et al. 2017). These changes typically occur after multiple applications rather than when the non-ionic surfactants are initially applied. This is because the initial applications usually result in increased K_s values, particularly in hydrophobic soils.

Considering the increased POXC and nitrification activity, bioclogging could also be a possible factor behind decreased K_s rates. Research has shown that

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bioclogging can result in a decrease in K_s (Hallett & Young 1999). When bacteria colonize soils, they cover the pore walls with biofilms, comprising cells tightly entwined in a network of exopolymer glycocalyx. This causes a reduction in pore space available for water flow and the exopolymer might also lead to alterations in soil swelling properties and dispersion of colloidal particles (Peng et al. 2017).

Some implications are drawn from relatively old studies since the current scientific approach typically deals with K(h) in their experimental designs. The observed decline in K_s values from our study aligns with results from the K(h) tests conducted in laboratory settings using soils from the same region, both treated and untreated (Figure 7). Similar outcomes have been highlighted in various studies over the past two decades, particularly in non-hydrophobic soils (Mobbs et al. 2012; Bashir et al. 2020). Notably, Bashir et al. (2020) associated reduced hydraulic conductivity with a slowed vertical movement and increased lateral dispersion of water and surfactant. When examining potential interplays between K_s and OCFs, existing literature does not offer a direct comparative scenario. This might be due to many studies focusing on K(h) in tandem with DOC or POC, rather than specifically on K_s. Nevertheless, our data points to moderate to robust, yet divergent correlative links between OCFs and K_s, as illustrated in Figure 6B. Specifically, water-soluble fractions revealed a positive association with K_s, whereas POXC displayed an inverse relationship with K_s. Even though the K_s were in positive relationship with C_{ws} and C_{hws}, and negative relationship with POXC, it should be noted that the treated soils were not found to present hydrophobic properties in water droplet test, after applications of H2Flo.

CONCLUSION

Upon repeated application, the non-ionic surfactant H2Flo facilitates uniform distribution of irrigation water throughout loamy sand soil and leads to a reduction in both saturated and unsaturated hydraulic conductivity. This is consistent with the well-documented impacts of non-ionic surfactants on sandy soils.

In the treated soils, pH levels and the distribution of organic carbon content were observed to increase, notably within subsoils. The levels of POXC also rose in the treated soils, a marker for augmented active carbon content, suggesting an accelerated rate of decomposition influenced by changes in water content and distribution. A significant positive correlation was found between POXC and NO_3^--N content, and a negative correlation with NH_4^+-N content, indicative of increased nitrification. NO_3^--N of the treated soils, in this context, was considerably higher compared to the control soils.

Though the carbon fractions C_{ws} and C_{hws} remained quantitatively unchanged post-H2Flo application, they showed positive linear relationships with the soil's hydraulic conductivity and extractable Mg content found in treated soils. Treated soils additionally demonstrated increased levels of extractable Ca and K, likely a consequence of the elevated pH and the increase in organic exchange complexes stemming from higher POXC values. Interestingly, potassium leaching was less pronounced in H2Flo treated soils.

This study elucidates the effects of H2Flo applications, highlighting alterations in SOM degradation products and nitrification dynamics, as well as modifications in the soil's extractable macronutrients. Particularly, the observed changes in OCFs and in the rate of NH_4^+-N to NO_3^--N underscore the importance of meticulous monitoring of these

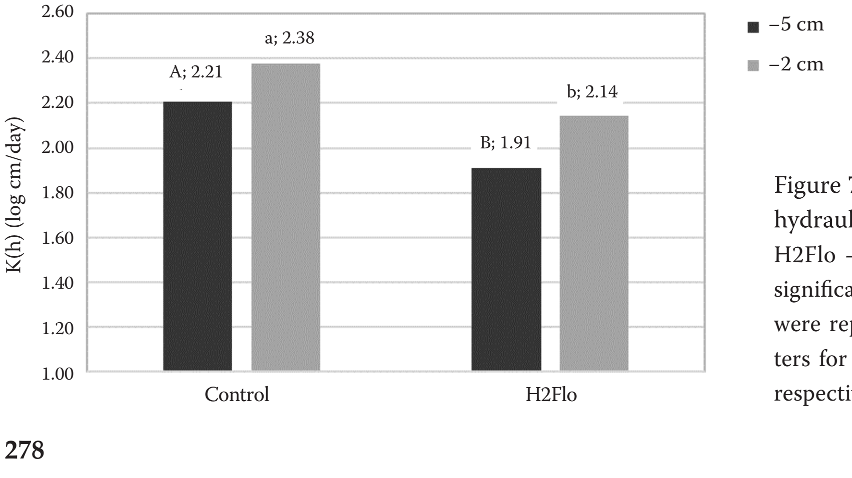

Figure 7. Comparison of average unsaturated hydraulic conductivity K(h)
H2Flo – non-ionic soil surfactant treated soil; significant differences between infiltration rates were represented with low case and capital letters for –2 and –5 cm pressure heads adjusted, respectively; $P < 0.01$

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fractions after surfactant applications, ensuring the sustained advantages derived from organic amendments and nitrogen fertilizers.

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