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Organosilicone surfactants as innovative irrigation adjuvants: Can they improve water use efficiency and nutrient uptake in crop production?

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ABSTRACT

In a time of resource reduction and climate variability, water conservation is critical to improve agroecosystem sustainability. Non-ionic surfactants were recently hypothesized as irrigation adjuvants, but so far researchers obtained contrasting results. The first objective of this work was to evaluate the capillary adsorption properties of organosilicone surfactants by providing two robust tests on standard porous media. Results showed smaller capillary mobility and higher wetting power ("superspreading") compared to pure water. An innovative non-ionic surfactant formulation, the organosilicone PET (PolyEther-modified Trisiloxane), was then investigated as irrigation adjuvant in a pot trial on lettuce in absence of fertilization. Overall, the system was characterized by an improvement in the processes of resource acquisition, i.e. water and nutrients. Results indicated higher lettuce leaf area, reduced root dry weight and root:shoot ratio and a positive main effect on the uptake, availability and/or use efficiency of P, K and some micronutrients. The N use efficiency and recovery increased 3–15%, with higher N concentration and content against changes in plant weight. Fresh yield data showed a particularly high irrigation use efficiency (+77–60%), and the adjuvant productivity (variation of lettuce yield due to PET) increased by 12–26%. Our experimental findings can be explained by hypothesizing that PET affected both capillary and adsorption processes during water diffusion along concentration gradients, which constitute the main driving force for solutes movement towards the roots. A theoretical model is provided to explain how PET improved the thickening and interconnection of conductive adsorbed water film in soil.

1. Introduction

Globally, agriculture accounts for approximately 70% of freshwater used, mainly for irrigation (FAO, 2016; Fischer et al., 2007). However, the water withdrawal for irrigation largely exceeds the crop requirements (FAO, 2016; Knox et al., 2012). In a time in which the demand for water is increasing at a rate twice that of population growth (FAO, 2016; Gil and Kamanda, 2015), agriculture is called to meet the economic and social challenges of increasing food demand and rising competition for scarce resources. Securing a more efficient use of irrigation water becomes essential to face the reduction in water resources and the extreme weather due to climate change (Elliott et al., 2014; Tilman et al., 2002; Wallace, 2000).

Non-ionic surfactants (surface-active agents) have been recently hypothesized as potential adjuvants for improving irrigation efficiency and agroecosystem sustainability (Baratella et al., 2016; Chaichi et al., 2015; Lehrsch et al., 2011). Surfactants or wetting agents are essentially long chain polymers of varying complexity with a hydrophilic head and a hydrophobic tail (amphiphilic structure), operating at air/water or water/solid interfaces by lowering the surface tension (Krogh et al., 2003). There are four basic groups of surfactants, according to the nature of their hydrophilic group: anionic, cationic, non-ionic, and amphoteric. Non-ionic surfactants, traditionally used as pesticide adjuvants, generally possess low potency to both terrestrial and aquatic organisms and are therefore preferred for agricultural applications (Bonnington, 2003; Krogh et al., 2003). Organosilicone surfactants fall within this category. Under aerobic conditions, non-ionic surfactants are easily biodegraded by microorganisms and are mineralised slowly in anaerobic conditions and when adsorbed to the soil minerals (Valoras et al., 1976; Ying, 2006). During adsorption to clays and organic materials, surfactants have direct effect on hydraulic soil properties, by weakening the cohesive forces and allowing water to easily penetrate and wet the soil (Kuhnt, 1993; Wiel-Shafran et al., 2006). Therefore, their use as adjuvants for irrigation in agronomic production can potentially improve irrigation use efficiency and crop quality by requiring less water, capturing rainfall more effectively and reducing the nutrient losses through run-off erosion or leaching (Cooley et al., 2009; Karagunduz et al., 2001; Starr et al., 2005).

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Previous attempts of surfactants application on water-repellent soils, as a mean to improve water penetration and preferential flows, gave positive results (Feng et al., 2002; Müller and Deurer, 2011; Oostindie et al., 2008). On the contrary, there are no clear findings on the potential improvement of water movements in hydrophilic soil. This debate dates back to the 60s, and researchers obtained contrasting results (Karagunduz et al., 2015; Krogh et al., 2003; Tumeo, 1997; Wiel-Shafran et al., 2006). Often these studies limited the experiments to a single application of the surfactant, and different results might have been achieved by repeated administrations to allow the adsorption of the surfactant in the matrix (Mobbs et al., 2012; Feng et al., 2002).

From the agronomic perspective, the addition of wetting agents to irrigation water may ultimately affect the transport and availability of water and nutrients to crops. The potential effects of non-ionic surfactants on plant uptake and growth have been poorly investigated so far, with contrasting results. McCauley (1993) evaluated the effect of a non-ionic surfactant formulation on soybean (*Glycine max* L.) and found that both yields and irrigation efficiency increased with surfactant application. In Brumbaugh and Peterson (2001), non-ionic surfactants increased the growth of corn root. Inversely, Wolkowski et al. (1985) have reported no effects on plant growth after surfactant application to corn (*Zea mays* L.), soybean, wheat (*Triticum aestivum* L.), and potato (*Solanum tuberosum* L.). Banks et al. (2013) examined corn nutrient uptake in different soils, observing no consistent surfactant effects. Baratella et al. (2016) performed a first agronomic trial on lettuce, testing a non-ionic surfactant formulation (45% fatty acid ester, 45% sorbitan sesquioctanoate and 10% propylene glycol) as irrigation adjuvant. The authors found a dose-related contrasting effect of the formulation, especially on roots growth, with a strong interaction with the mineral N fertilization (urea). The recent work of Chaichi et al. (2015) investigated the addition of a non-ionic surfactant to irrigation water in corn production under Mediterranean climate, observing an increase of the irrigation water use efficiency and, consequently, higher corn yield and dry matter.

These few studies available about the effects of non-ionic surfactants on crop production give evidently contradictory information. Data are still lacking for assessing the potential of non-ionic surfactants to increase water and nutrient use efficiency, which would be of significant value in improving the sustainability of vegetable production systems.

The present study aims to investigate the effects of an innovative non-ionic surfactant formulation, i.e. an organosilicone surfactant, on irrigation water use efficiency and nutrient uptake of lettuce in absence of fertilization.

The first objective was to design a rapid and robust laboratory method for assessing the surfactant properties in relation to the capillary adsorption, which is of importance for comparative studies of surfactants in consideration of their use in soil. From a practical standpoint, there is still a lack of a feasible and rapid alternative to the costly, direct measurements of soil hydraulic properties, i.e. hydraulic conductivity, capillary rise and sorptivity (Mingorance et al., 2007). Common drawback of using direct soil measurements for studies on surfactants is that, since surfactants behave differently for any given soil types, using measures from one type of soil to predict response on another soil is often inappropriate (Mingorance et al., 2007; Mobbs et al., 2012). In the present study, potential changes in the capillary mobility of water in soil induced by surfactants were conceptualized and simulated in laboratory by means of two rapid tests of capillary adsorption on standard porous media.

The second objective was to investigate the effect of non-ionic organosilicone surfactants on the irrigation water use efficiency of crops, and understand possible synergistic or antagonistic effects between the application of the surfactant and the nutrient uptake in absence of fertilization. To this end, a pot trial was carried out on lettuce, administering an innovative organosilicone surfactant formulation by irrigation.

2. Materials and methods

2.1. Organosilicone surfactants properties

For evaluating the variation of water capillary movements induced by different organosilicone surfactants, we tested four different eco-friendly formulations: i) composition of polyether-modified polysiloxanes (concentration 75 ≤ % ≤ 100); ii) composition of polyether-modified trisiloxanes (75 ≤ % ≤ 100); iii) polyether siloxane (50 ≤ % ≤ 75; iv) composition of poly-dimethylsiloxanes (10 ≤ % ≤ 25). Data on their physicochemical properties are given in Table 1.

For the agronomic testing, we selected and tested one surfactant formulation, the polyether-modified trisiloxane (concentration 75 ≤ % ≤ 100) composed by 80% (w/w) of heptamethyl-trisiloxane and about 20% (w/w) of polyether (mono-2-propenyl ether). This non-ionic surfactant, hereafter called PET, belongs to the class of the polyether-methyl-siloxanes, organosilicone polymers containing typically Si—O—Si bonds (siloxanes). Data on the different physicochemical properties of PET are given in Table 1. Other organosilicone classes are volatile methylsiloxanes (VMS) and polydimethylsiloxanes (PDMS). Organosilicone surfactants showed higher efficiency (Hill 2002) and lower environmental persistence and toxicity compared with other non-ionic formulations, indicating their higher potential for application to crop production (Bonnington, 2003; Fendinger et al., 1997; Stevens et al., 2001). Stevens (1995) indicated that organosilicone surfactants are rapidly adsorbed onto soil particles and then quickly inactivated by hydrolysis. Consequently, when entering the soil environment, these non-ionic surfactants are expected to be either adsorbed to the soil or degraded, not leaching to the groundwater (Krogh et al., 2003; Bonnington, 2003).

2.2. Capillary mobility

Two rapid and robust tests on standard porous media were performed in the laboratory to assess potential changes in the capillary mobility of water in soil after application of organosilicone surfactants: a newly designed capillary mobility test, and a capillary rise test.

Theoretical premise is that surfactants alter the capillary movement of water in soil with a magnitude that depends mainly on the fluid

Table 1
Physicochemical properties of non-ionic organosilicone surfactants.

Compound	Concentration (C) (%)	Surface Tension in 0.1% water (mN m^{-1})	Viscosity (dynamic) (mPa s)	pH (40 g L^{-1} at 20 °C)	Density (g cm^{-3} at 25 °C)	References
polyether-modified trisiloxane (PET)	75 ≤ C ≤ 100	23.0 ± 0.5	60–140	6–8	1.030	Wilhelmy Plate Method DIN 51757, 53019 DIN 53015 (Höppler)
polyether-modified polysiloxanes	75 ≤ C ≤ 100	21.5 ± 0.5	40–90	6–8	1.020	
polyether siloxane	50 ≤ C ≤ 75	22.0 ± 0.5	350–650	nd	0.973	
poly-dimethylsiloxanes	10 ≤ C ≤ 25	25.0 ± 0.5	400	nd	1.010	