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# Mildly hydrophobic biobased mulch: A sustainable approach to controlling bare soil evaporation

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## Abstract

Mulching with polyethylene film is the conventional approach to decrease evaporative water loss from agricultural soils, but it is not environmentally sustainable. In this study, a laboratory experiment was conducted to test the potential utility of partially polymerized soybean oil (PSO) coated sands as a surface treatment to reduce bare soil evaporation. Evaporation was tracked for 23.8 d from saturated sand columns treated with a surface layer (1 or 2 cm) of either coated medium sand (MS-PSO) or coated coarse sand (CS-PSO). The water drop penetration time (WDPT) was used to assess the hydrophobicity of fresh PSO-coated sands; the saturated hydraulic conductivity ( $K_s$ ) and particle density ( $\rho_s$ ) were measured as well. The WDPT was also tested on MS-PSO and CS-PSO samples aged in four separate environmental conditions for 20–21 d. Both PSO-coated sands were mildly hydrophobic, and the surface treatment layers reduced evaporative loss by 83–96% over bare soil, which is similar to previous work using extremely hydrophobic chemically treated sands. Freshly coated MS-PSO had a higher WDPT score and lower  $K_s$  than CS-PSO. After the environmental aging tests, the MS-PSO and CS-PSO samples remained mildly hydrophobic. Notably, CS-PSO had a low initial WDPT ( $\sim 1.09$  to  $\sim 2.58$  s) and a high  $K_s$  ( $2.66 \times 10^{-1} \text{ cm s}^{-1}$ ), suggesting coarse PSO-coated sands will permit infiltration. Given these findings, PSO-coated sand has the potential to be developed into a sustainable alternative to polyethylene film mulch.

## 1 | INTRODUCTION

Application of a surface cover (mulch) is a widely used approach to decrease evaporative water loss from bare agricultural soil (e.g., Adhikari et al., 2016; Kader, Senge, Mojid, & Ito, 2017). In recent decades, polyethylene film

(PF) mulch has largely supplanted low-cost biodegradable alternatives (e.g., straw, grass clippings) because its usage leads to increased crop yields and water conservation (He, Wang, Li, & Malhi, 2018; Kader et al., 2017). Use of PF mulch has adverse side effects on agricultural efficiency, including restricting infiltration, increasing runoff, and limiting soil–atmosphere gas exchange (Kader et al., 2017). In addition, the production, use, and disposal of PF mulch incur substantial adverse environmental impacts (Steinmetz et al., 2016). Of particular concern is the release

**Abbreviations:** CS, narrow-distribution, washed coarse sand; MS, narrow-distribution, washed medium sand; PF, polyethylene film mulch; PSO, partially polymerized soybean oil.

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of microplastics into the soil profile, hydrosphere, and food chain. These issues suggest a need for an environmentally neutral alternative to PF mulch that significantly inhibits bare soil evaporation while allowing the free passage of both gases and liquid water (rain, irrigation).

Bare soil evaporation occurs through two distinct mechanisms or stages (e.g., Or, Lehmann, Shahraeeni, & Shokri, 2013). In Stage 1, capillary rise brings water to the soil surface, where it evaporates directly into the atmosphere. For drier conditions, the evaporation surface recedes downwards into the soil profile (Stage 2), and water vapor must diffuse upwards through the overlying soil to reach the atmosphere (Lehmann, Assouline, & Or, 2008; Shokri & Or, 2011). Under Stage 1 conditions, the evaporative flux ( $E_f$ ) is expected to approach the atmospheric evaporative demand ( $E_d$ ), which is a function of relative humidity and temperature (e.g., Shokri & Or, 2011). Although  $E_d$  also drives Stage 2 evaporation, the need for diffusional transport to the soil surface causes  $E_f$  to be substantially lower (Shokri, Lehmann, & Or, 2009). Soil parameters play a significant role in that fine-grained hydrophilic soils exhibit substantial capillary rise (Stage 1), whereas large and well-connected soil pores promote Stage 2 diffusion (Lehmann et al., 2008; Or et al., 2013).

Usage of PF lowers evaporation for both mechanisms (Stages 1 and 2) by decoupling soil water from  $E_d$  and creating a humid environment beneath the film. An alternate approach would be to restrict the more significant Stage 1 mechanism by blocking capillary rise to the soil surface with a hydrophobic (water-repellant) mulch. Experiments in sand-filled columns (Shokri, Lehmann, & Or, 2008) and drip-irrigated pots (Gupta et al., 2015) have shown that a thin (<3 cm) surface layer of chemically treated hydrophobic sand can reduce evaporative water loss by up to 90% relative to untreated soil. From a mechanistic standpoint, the evaporation plane rapidly drops to the base of the hydrophobic layer, effectively skipping Stage 1 and going directly to the much less efficient Stage 2 mechanism. The silane-based treatments used in previous work result in extreme hydrophobicity (Chan & Lourenço, 2016) and would be of limited utility for large-scale agriculture; polymerized plant oils (de Espinosa & Meier, 2011) have potential as a low-cost and renewable alternative. Preliminary laboratory tests have shown it possible to create a loose hydrophobic mulch by coating agricultural waste products with fast-drying linseed oil that polymerizes at room temperature (Vaicekauskaite et al., 2019). The polymerization of slow-drying vegetable oils (e.g., soybean [*Glycine max* (L.) Merr.]) can be accelerated through heat treatment (Lozada, Suppes, Hsieh, Lubguban, & Tu, 2009) or the addition of catalysts (Shogren, 2000).

Here, we test the utility of sand coated with partially polymerized soybean oil (PSO) as a potential alternative to

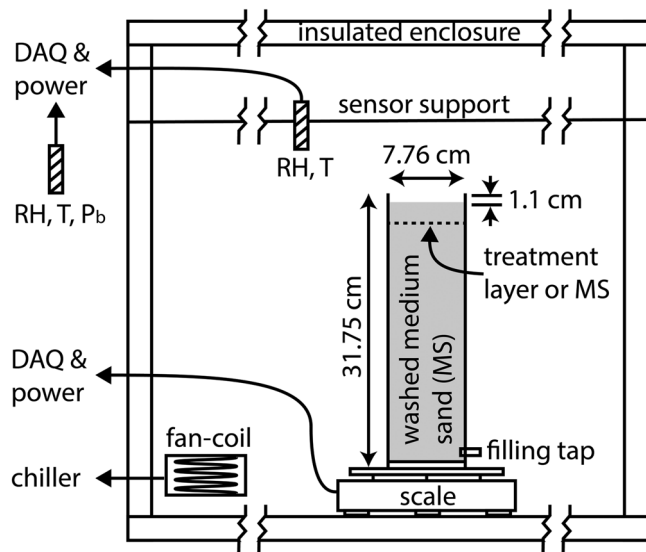
### Core Ideas

- Partially polymerized vegetable oil is used to form a mildly hydrophobic coating on sand grains.
- Performance at reducing evaporative loss is comparable with chemically coated grains.
- Mildly hydrophobic coarse grains are expected to facilitate infiltration.
- Coarse and fine mildly hydrophobic grains reduce evaporative loss at a comparable rate.
- Coated grains may offer a potentially effective and sustainable mulch alternative.

PF mulch for reducing evaporative loss. Individual grains of silica sand (medium or coarse) are coated with PSO using a thermal process, then packed into thin layers (1 or 2 cm) at the top of laboratory columns filled with saturated hydrophilic sand. An additional column filled with sand is used as a reference for evaporation from bare soil. Measured data show that a surface layer of the mildly hydrophobic PSO-coated sand leads to a significant reduction in evaporative flux ( $E_f$ ) with respect to bare soil. Results serve as a first step towards using biobased soil coatings as an environmentally neutral alternative to PF mulch that not only reduces evaporative loss but also allows free passage of liquid water, heat, and gasses.

## 2 | MATERIALS AND METHODS

Individual grains of washed, narrow-distribution medium (MS) and coarse (CS) silica (>99%) sands were coated with PSO. The MS (0.177–0.420 mm in diam.) was prepared by passing Quickcrete medium sand through a No. 40 sieve, washing it twice with distilled water on a No. 80 sieve, and then oven drying it for >24 h at 100 °C. We applied the same process to prepare the CS (0.841–1.68 mm in diam.) from Quickcrete pool filter sand, substituting the No. 12 and No. 20 sieves. Based on preliminary tests, a partial thermal polymerization process (see Lozada et al., 2009) was used to coat individual grains without linking them together. A 2.3-kg portion of each sand (MS or CS) was mixed into a roughly equal volume of food-grade soybean oil (~830 g) and allowed to soak overnight. After draining the excess fluid, each oil-sand mixture was cured for 1 h in a muffle furnace preheated to 335 °C, then allowed to cool. Residual liquid oil was removed from the coated sands (MS-PSO and CS-PSO) by gently washing each batch in distilled water, then repeating the process before allowing them to air dry.



**FIGURE 1** Conceptual design of evaporation experiments (not to scale). Five test columns were placed on individual electronic balances (0.01- or 0.1-g precision) inside a five-sided enclosure (front face was open to the laboratory environment). Two fan-coil units inside the enclosure circulated constant temperature air. Three sets of sensors (relative humidity [RH], temperature [T]) were suspended from a horizontal support rod above the columns. A fourth set of sensors, including barometric pressure ( $P_b$ ), was located just outside the enclosure. Sensors and scales were monitored using a National Instruments LabView-based data acquisition system (DAQ)

Laboratory columns were used to test thin (1- or 2-cm) surface layers of MS-PSO and CS-PSO as potential treatments for reducing bare soil evaporation from the underlying MS. Five columns were constructed by cutting 31.75-cm lengths of 3-inch (7.62-cm) Schedule 40 polyvinyl chloride (PVC) pipe with a 7.76-cm inside diameter and sealing each at the bottom (Figure 1). Loose-dry media was added to each column in  $\sim 100$ -g increments (Table 1), then compacted with a 7.6-cm-diam. wooden pestle and mallet (after Oliviera, Demond, & Salehzadeh, 1996). The process was repeated until the packed media reached a thickness of 29.5 cm, leaving the top 1.1 cm of each column

unfilled (Figure 1). One column (labeled “bare soil”) was filled solely with uncoated MS to act as a reference. Two columns (labeled MS-PSO-1 and CS-PSO-1) were packed with 28.5 cm of uncoated MS before filling the remaining 1 cm with PSO-coated sand. Columns labeled MS-PSO-2 and CS-PSO-2 contained 27.5 cm of uncoated MS topped with 2 cm of PSO-coated sand. Prior to adding water (Table 1), each column was flooded with  $\text{CO}_2$  to reduce air entrapment, and the surface was weighted to prevent the possibility of the treatment layer rising. Distilled water was then added through the base (Figure 1) until a thin, free-standing layer covered the soil surface.

The evaporation test was conducted in an open-faced enclosure (Figure 1). Constant-temperature air was circulated within the enclosure to buffer diurnal thermal effects and promote mixing with the room air. Over the 23.8-d test, the mass of each column was measured at 1-min intervals, along with temperature ( $T$ ) and relative humidity (RH) within the enclosure. Mass change was used to calculate the evaporative flux ( $E_f$ ) exiting each column in centimeters per day. Measured values of RH were used to estimate evaporative demand ( $E_d$ ) inside the enclosure by assuming a steady-state Fickian process (after Shokri et al., 2008):

$$E_d = D_o C_{\text{sat}} \frac{1 - \text{RH}/100}{L_D} \quad (1)$$

where  $D_o$  is the diffusion coefficient for water vapor in air,  $C_{\text{sat}}$  is the saturated air density, and  $L_D$  represents the diffusion length. Variation in  $T$  during the experiment (average = 26.1 °C,  $\sigma = 0.1$  °C) was sufficiently small that  $D_o$  ( $2.16 \times 10^4 \text{ cm}^2 \text{ d}^{-1}$ ) and  $C_{\text{sat}}$  ( $2.7 \times 10^{-4} \text{ g cm}^{-3}$ ) were assumed to be constant. The diffusion length ( $L_D = 0.6 \text{ cm}$ ) was estimated through calibration of (Equation 1) to evaporation from a water-filled vessel. Immediately after the evaporation test ( $t = 23.8 \text{ d}$ ), each column was split vertically, then sectioned in 1- to 2-cm horizontal intervals to obtain the gravimetric moisture content ( $\theta_g$ ); a small, unquantified amount of liquid water and MS was lost during the sectioning process.

**TABLE 1** Mass of material added to columns (medium sand [MS], treatment, water) prior to the experiment and initial saturation ( $S$ ). Mass change and percentage water loss during the 23.8-d test are also shown

Column	MS	Treatment	Water	Initial $S$	Mass change	Water loss
	g			$\text{cm}^3 \text{ cm}^{-3}$	g	
Bare soil	2,194.11	0.00	483.46	0.87	245.61	51
MS-PSO-1	2,106.74	93.64	525.84	0.96	14.84	2
MS-PSO-2	2,038.22	170.71	503.23	0.94	10.82	3
CS-PSO-1	2,110.22	90.70	523.22	0.95	42.10	7
CS-PSO-2	2,033.57	167.03	531.03	0.98	38.56	8

Note. Saturation was calculated from measured particle densities ( $\rho_s$ ) for medium sand (MS), coarse sand (CS), MS coated with partially polymerized soybean oil (MS-PSO), and CS coated with partially polymerized soybean oil (CS-PSO). All mass change is attributed to evaporation of the liquid water phase

Water drop penetration time (WDPT) tests were used to characterize the water repellency of the test media (Papierowska et al., 2018). The WDPT was measured on individual samples of the CS-PSO and MS-PSO, both when freshly coated and after being aged at 26 °C under four different environmental conditions: exposed to the laboratory atmosphere for 21 d (open), held in an airtight jar for 21 d (sealed), near 100% humidity for 20 d (humid), and covered with distilled water for 20 d (submerged). The humid and submerged samples were air dried for 1 d after aging. Before measuring WDPT, all samples were packed with a mallet and pestle as described above. The saturated hydraulic conductivity ( $K_s$ ) of the uncoated and freshly coated sands were obtained through constant head tests, and a pycnometer was used to measure particle density ( $\rho_s$ ). Density of the PSO coating was estimated through acetone digestion.

### 3 | RESULTS

Evaporative demand ( $E_d$ ) during the column experiment averaged  $0.80 \text{ cm d}^{-1}$ , with a standard deviation ( $\sigma$ ) of  $0.062 \text{ cm d}^{-1}$  (Figure 2a). Temporal variation in  $E_d$  showed a strong diurnal cycle superimposed on longer-wavelength change (i.e., weather shifts). During the first  $\sim 30$  min of the experiment, evaporative flux ( $E_f$ ) from all five columns closely mimicked  $E_d$ , confirming that the soil surface was covered with a thin water film. Afterward,  $E_f$  for the bare soil declined along a roughly linear path until Day 7, when it dropped from  $\sim 50\%$  of  $E_d$  to  $<15\%$ . After this rapid change, the bare soil  $E_f$  declined gradually for the remainder of the experiment (Figure 2b). In the treated columns,  $E_f$  exhibited a power-law decline to  $<5\%$  of  $E_d$  by the end of Day 2 (Figure 2a). The two columns topped with MS-PSO showed concurrent behavior up through Day 12; afterward,  $E_f$  displayed a gentle upward trend for MS-PSO-1, whereas values for MS-PSO-2 remained roughly constant (Figure 2b). Evaporative flux for CS-PSO-1 leveled off abruptly at  $t \sim 1.5$  d, then began a gradual decline after Day 15. Conversely,  $E_f$  for the CS-PSO-2 showed a significant dip on Day 4, then recovered to remain mostly constant through the end of the experiment. Diurnal cycling in  $E_d$  was reflected in  $E_f$  for all five columns (Figures 2a and 2b); the strongest effects were for the bare soil, followed in order by CS-PSO-1, CS-PSO-2, MS-PSO-1, and MS-PSO-2.

Initial saturation ( $S$ ) of the bare soil column was 0.87 and 0.94–0.98 for the treated columns (Table 1). Total water loss during the 23.8-d experiment was 51% for the bare soil and 2–8% for the treated columns (Table 1). Water loss was higher for columns topped with the CS-PSO than for the MS-PSO, whereas thickness of the treatment layer

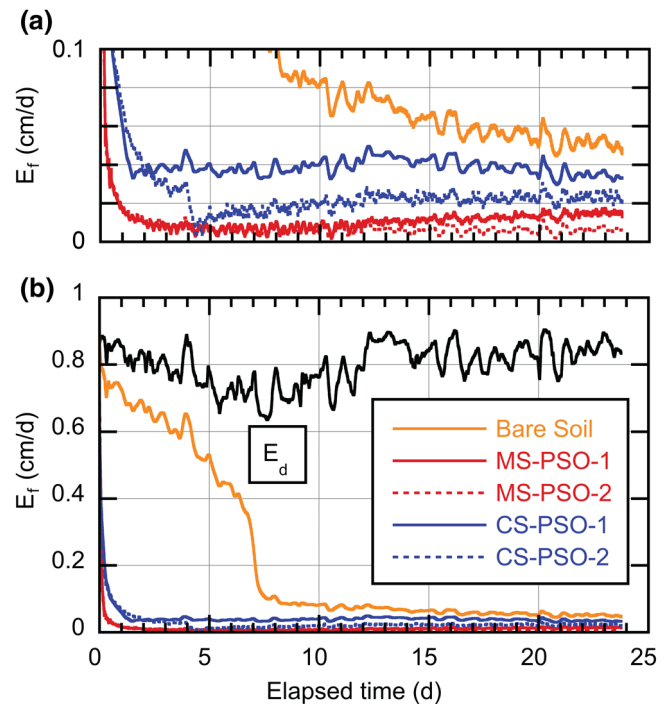


FIGURE 2 (a) Evaporative demand ( $E_d$ ) during the 23.8-d experiment (9 June 2019 to 3 July 2019) is shown along with evaporative flux ( $E_f$ ) exiting the test columns; units for both are centimeters per day. (b) Vertical scale expanded by 10 $\times$  to focus on  $E_f = 0.0$ – $0.1 \text{ cm d}^{-1}$ . MS-PSO, medium sand coated with partially polymerized soybean oil; CS-PSO, coarse sand coated with partially polymerized soybean oil

had only a small effect. At the end of the experiment ( $t = 23.8$  d), the bare soil column was air dry at the surface ( $\theta_g \sim 0$ ) and exhibited an almost linear increase in moisture with depth (Figure 3). Conversely, water loss in the treated columns was limited to the top 10 cm; the treatment layers were nearly dry, and  $\theta_g$  in the underlying MS increased rapidly to  $\sim 0.26$  at a depth of 7–10 cm. The treated columns all showed a slight decrease in  $\theta_g$  at depths of 15–25 cm before returning to  $\sim 0.26$  near the base (Figure 3). The moisture profiles were insensitive to thickness of the treatment layer, whereas the columns topped in CS-PSO were slightly wetter than the MS-PSO columns at depths of 3–8 cm. Both of the MS-PSO layers (1 and 2 cm) solidified into a hard, porous crust during the experiment. Conversely, the CS-PSO layers remained flexible and disaggregated easily but showed clear evidence of congealing from the surface downwards. The uncoated MS directly below the 2-cm layer of CS-PSO showed light yellowing to a depth of 4–6 mm, whereas the MS underlying the other three treatment layers appeared to be unaffected.

The WDPT was negligible for the uncoated MS and CS, whereas finite values were obtained for all tests on the coated sands (Table 2). Under dry initial conditions, WDPT was 36.9 s for freshly treated MS-PSO and 2.6 s for the

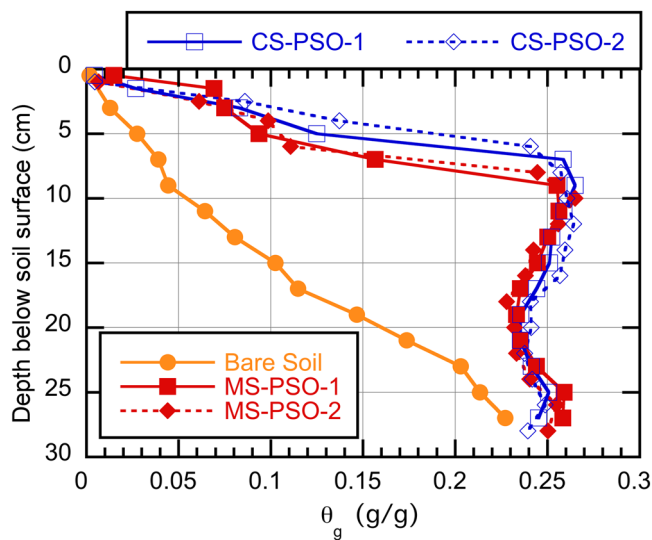


**TABLE 2** Measured water drop penetration time (WDPT) for medium sand and coarse sand coated with partially polymerized soybean oil (MS-PSO and CS-PSO, respectively) aged under various environmental conditions

Condition	Aged d	MS-PSO		CS-PSO	
		Dry	Prewetted	Dry	Prewetted
Fresh	0	36.87 (2.07) <sup>a</sup>	16.22 (2.05) <sup>a</sup>	2.58 (0.20) <sup>b</sup>	1.09 (0.14) <sup>b</sup>
Sealed	21	12.14 (2.65) <sup>a</sup>	6.89 (1.15) <sup>a</sup>	9.06 (2.38) <sup>a</sup>	4.38 (0.56) <sup>b</sup>
Open	21	21.09 (5.01) <sup>a</sup>	12.46 (2.41) <sup>a</sup>	252.32 (49.99) <sup>c</sup>	106.10 (22.85) <sup>c</sup>
Humid	20	160.62 (39.42) <sup>c</sup>	56.93 (20.2) <sup>a</sup>	90.19 (11.72) <sup>c</sup>	30.55 (6.68) <sup>a</sup>
Submerged	20	57.29 (18.73) <sup>a</sup>	25.87 (8.48) <sup>a</sup>	5.86 (0.27) <sup>a</sup>	2.64 (0.86) <sup>b</sup>

Note. Values are reported as the average of four to five replicate tests, with standard deviation ( $\sigma$ ) in parentheses. Higher WDPT times correspond to greater hydrophobicity. The WDPT for uncoated MS and CS was negligible. Environmental conditions: fresh, newly coated; sealed, isolated from the atmosphere in a sealed jar for 21 d; open, atmospheric conditions identical to the test columns for 21 d; humid, near 100% humidity for 20 d, air dried for 1 d; submerged, covered with distilled water for 20 d, air dried for 1 d.

<sup>a</sup>Slightly hydrophobic. <sup>b</sup>Wettable. <sup>c</sup>Moderately hydrophobic (see Papierowska et al., 2018).



**FIGURE 3** Final gravimetric moisture content ( $\theta_g$ ). The uppermost measurement represents the 1- or 2-cm-thick treatment layer (except for the bare soil column); the second is for the 1-cm-thick layer directly below the treatment. Remaining measurements were taken at 2-cm intervals. MS-PSO, medium sand coated with partially polymerized soybean oil; CS-PSO, coarse sand coated with partially polymerized soybean oil

CS-PSO; prewetting the freshly coated sands lowered the WDPT by 55–60%. All of the ageing processes that were considered led to a statistically significant (>95% confidence level) change in the WDPT, except for the MS-PSO exposed to submerged conditions. All of the CS-PSO samples experienced an increase in WDPT during aging, as did the MS-PSO under humid and submerged conditions (Table 2). Magnitude of the aging-induced changes was much larger for the CS-PSO (127 to 9,680%) than for the MS-PSO (–67 to 335%). Both sets of open and humid samples were observed to form spongy clusters during aging, whereas the appearance of the sealed and submerged sam-

ples showed little change. There was no detectable change in mass for any samples during the aging process.

Installation of the PSO coating reduced the hydraulic conductivity ( $K_s$ ) of the MS by a factor of  $\sim 20$  ( $8.60 \times 10^{-2}$  to  $4.01 \times 10^{-3}$   $\text{cm s}^{-1}$ ) and lowered particle density ( $\rho_s$ ) from  $2.62$  to  $2.15$   $\text{g cm}^{-3}$ . The coating had a smaller effect on the CS in that  $K_s$  dropped by a factor of  $\sim 2$  ( $5.43 \times 10^{-1}$  to  $2.66 \times 10^{-1}$   $\text{cm s}^{-1}$ ) and  $\rho_s$  was reduced from  $2.63$  to  $2.35$   $\text{g cm}^{-3}$ . Density of the PSO coating ( $1.07$   $\text{g cm}^{-3}$ ) was slightly higher than liquid soybean oil ( $0.99$   $\text{g cm}^{-3}$ ). Average thickness of the PSO coating was estimated to be on the order of  $60$   $\mu\text{m}$  by treating the MS and CS as uniform spheres with diameters of  $0.03$  and  $0.13$  cm, respectively.

## 4 | DISCUSSION

Coating silica sand with PSO produced loose porous media that exhibited a small, but finite, WDPT (Table 2). Installing a surface layer of mildly hydrophobic PSO-coated sand reduced evaporative flux ( $E_f$ ) from the underlying hydrophilic sand by a total of 83–96% in our 23.8-d experiment (Table 1, Figure 2). For comparison, thin surface layers of silane-treated sand have been reported to reduce evaporative loss from partially saturated soil pots by 78–90% over 3 d (Gupta et al., 2015) and by  $\sim 80\%$  over 30 d for initially saturated vertical columns (Shokri et al., 2008). Although neither of these previous studies reported WDPT, subsequent work (Chan & Lourenço, 2016) has shown silane-treated sands to be extremely hydrophobic (WDPT > 3,600 s). As expected from previous work, effectiveness of the PSO-coated treatment layer at reducing evaporative loss (Figure 2) decreased for coarser grains (An et al., 2018) and increased with layer thickness (Gupta et al., 2015; Shokri et al., 2008).

Measured values of WDPT on the PSO-coated sands decreased with increasing grain size (Table 2), which is

consistent with results for other hydrophobic coatings (Wijewardana et al., 2015). For a water droplet of a given size, entry into dry media will be controlled by the contact angle and the geometry of the air–water–solid interface. At first order, the Young–LaPlace equation predicts that water entry pressure will increase with decreasing pore size. However, the three-dimensional nature of pore geometry is far more complex than a simple capillary tube, thus complicating any attempt to scale WDPT, even for narrow-distribution sands such as those considered here. In comparison with silane-based hydrophobic treatments, the relatively thick nature of the PSO coating would tend to smooth out micro-roughness on grain surfaces, affecting both effective contact angle and geometry of the interface. The PSO-coating also showed evidence of continued polymerization when exposed to both  $O_2$  and water (Table 2). The large difference in WDPT between sealed and humid conditions suggests that polymerization is moisture dependent, whereas the smaller changes for the submerged samples indicates a need for  $O_2$ . The greater effects on the coarser CS-PSO are attributed to the ability of moisture and  $O_2$  to move through the open pore structure. The limited congealing observed for the CS-PSO layers during the evaporation tests is likely due to reduced intergranular contact in comparison with the compacted MS-PSO.

Although the MS-PSO was more effective at blocking evaporative loss than the coarser CS-PSO (Figure 2), the latter has greater potential as an effective mulch. The PSO coating is considerably less hydrophobic than silane treatments (Gupta et al., 2015; Shokri et al., 2008) and is thus expected to be less resistant to infiltration. Coating the MS with PSO reduced  $K_s$  by more than an order of magnitude, suggesting that the relatively thick coating may have deformed during compaction, with a negative impact on pore size and/or connectivity. Conversely, the coating had only a small effect on  $K_s$  for the CS-PSO, resulting in a highly conductive material ( $K_s = 2.66 \times 10^{-1} \text{ cm s}^{-1}$ ) with a small WDPT that will present low resistance to water entry. Paper mulch coated with fully polymerized soybean oil underwent significant degradation during a 12-wk field test (Shogren, 2000), whereas the CS-PSO continued to polymerize when exposed to  $O_2$  and water during our 23.8-d test. Given these results, we expect the CS-PSO to remain mildly hydrophobic through much of a growing season, but additional work is needed to understand degradation of PSO, particularly in the presence of microbial activity. Based on the experiments presented here, we believe that the CS-PSO has significant potential for use as an environmentally neutral mulch that will act as a selective barrier, significantly restricting evaporation while simultaneously allowing infiltration, gas exchange with the atmosphere, and heat transfer.

Evaporative flux ( $E_f$ ) from the bare soil column (Figure 2) generally followed a two-stage process (Lehmann et al., 2008; Shokri et al., 2009) in which a period of rapid evaporation at the soil surface (Stage 1) was followed by a sharp decline to stabilize at a much lower value (Stage 2). However, behavior during Stage 1 ( $t < 7$  d) differed from the conceptual model proposed by Lehmann et al. (2008) in that  $E_f$  declined relative to  $E_d$ , rather than remaining relatively constant (Figure 2). Similar behavior has been observed for evaporation from partially saturated bare soil (An et al., 2018), which suggests that our measurements may have been affected by the low initial saturation in the bare soil column ( $S = 0.87$ ). The low  $S$  likely led to reduced  $E_f$  during Stage 1 and early onset of Stage 2. This suggests that water loss from a fully saturated bare soil would have been considerably higher than what we measured, thus further accentuating the effectiveness of the PSO treatment layers. The sharp decline in  $E_f$  for bare soil in Day 7 (Figure 2) signals the onset of Stage 2 ( $t > 7$  d), where the evaporation surface recedes into the soil profile and is controlled by vapor diffusion (Or et al., 2013; Shokri et al., 2008). The gradual decline in  $E_f$  late in the experiment reflects increased  $L_D$ , and the final moisture distribution (Figure 3) suggests that upwards flow extended to the base of the bare soil column.

The dramatic initial decline in  $E_f$  for the treated columns (Figure 2) is consistent with previous experiments that considered extremely hydrophobic surface layers (Gupta et al., 2015; Shokri et al., 2008). Such behavior can be attributed to the vertical recession of the evaporation plane through hydrophobic surface materials in which drainage is virtually complete. An unexpected observation was the sudden decline in  $E_f$  for CS-PSO-2 that was observed at  $t = 4$  d (Figure 2b). We suspect that a very small amount of liquid soybean oil seeped from the CS-PSO and spread along the top of the underlying MS, partially restricting evaporation. As the wetting front receded, new paths for vapor flow were opened, allowing  $E_f$  to recover. The residual oil then adhered to the uncoated MS, causing the slight yellowing that was only observed in this column. It is likely that the opening of new pathways to the surface is also responsible for the gradual rise in  $E_f$  for MS-PSO-1 at  $t > 11$  d. Despite the evaporation front being located at depth for  $t > 4$  d, all four of the treated columns (Figure 2b) responded to changes in atmospheric demand ( $E_d$ ), which partially conflicts with the theory articulated in Or et al. (2013). Although Stage 2 evaporation is certainly dominated by diffusion through the partially dry layer above the drying front, the process remains driven by  $E_d$ . Thus, one expects a time lag between the two processes, which we leave for future investigation.

## 5 | CONCLUSIONS

A thermal process was shown to be effective for coating individual grains of silica sand with PSO. When used as a surface treatment, the resulting mildly hydrophobic media reduced evaporative loss with an efficacy similar to that of extremely hydrophobic silane-treated sands. This result demonstrates that lack of wettability is the necessary condition for blocking capillary rise to the soil surface, rather than true soil hydrophobicity. The experiments presented here thus have important implications for developing new approaches to control evaporative loss from bare agricultural soils, and also for understanding evaporation from land damaged through low-intensity burns.

As a potential mulch, PSO-coated sand is expected to act as a selective barrier by limiting evaporative loss, while allowing the passage of liquid water (infiltration), gasses, and heat. In contrast, PF is highly effective but is a nonselective barrier that blocks mass fluxes, including those that benefit agricultural production and reduce runoff; it also increases soil temperature (Kader et al., 2017). Future work should compare the performance of PSO-coated sand and other hydrophobic surface treatments with that of PF. In addition, the methodology that we used for preparing and installing the PSO-coated sand would be cost prohibitive at the agricultural scale. Transforming the concept of a biobased coating such as PSO into a cost-effective and sustainable mulch will require considerable effort and may require use of a substrate other than sand, such as paper or agricultural waste.

### CONFLICT OF INTEREST

The authors of this manuscript certify that they have no affiliations with or involvement in any organization or entity with any financial or nonfinancial interest in the subject matter or materials discussed in this manuscript.

### DATA AVAILABILITY


The data that support the findings of this study are available from the corresponding author (M. J. Nicholl) upon reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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