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COFFEE GROUNDS AS A SOIL CONDITIONER: EFFECTS ON PHYSICAL AND MECHANICAL PROPERTIES – I. EFFECTS ON PHYSICAL PROPERTIES

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Abstract. Coffee grounds (CG) improved some soil physical properties (dry density, γ_d; porosity, *n*; aggregation; hydraulic conductivity, K_s; and infiltration rate, IR). Effects on other properties were inconsistent (e.g., sorptivity, S), or unfavorable (e.g., available water, AW). γ_d decreased and *n* increased with CG. CG decreased K_s in sand. In calcareous soil, maximum increase was associated with 10% and 15% CG before and after wetting-and-drying cycles (WDC), respectively. K_s increased with CG in clay, with greatest increase attained at 10% CG. IR decreased with CG in sand. In calcareous and clayey soils, IR decreased with CG before WDC but increased after WDC where maximum increase in clay was linked to 10% CG. No solid trends of soil sorptivity (S) were identified. Before WDC, S had the order: sand > calcareous > clay. For most cases, adding CG increased total water holding capacity (WHC). However, after WDC, the increase in water content at field capacity (FC) with CG was accompanied by a greater increase in wilting point (WP) and therefore a decrease in AW. CG improved soil structure and aggregation and increased non-water-stable aggregates in calcareous and clayey soils. Mean weight diameter (MWD) indicated an increase in water-stable aggregates in sand at 5% and 10% CG. In clay, MWD increased only at 5% CG. Although results did not show coherent responses with some tested properties, they, mostly, indicate some beneficial effects of CG, particularly in relation to improving aggregation and water flow.

Keywords: coffee grounds, physical properties, soil amendments, soil conditioners

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INTRODUCTION

Organic amendments are major sources of many physical, biological and chemical reactions in soils. They interrelate in the soil complex system in the processes of formation and degradation of soil aggregates (Emerson 1959, Harris *et al*. 1966). The role played by microorganisms in improving aggregate formation is a direct function of the nutrient status of the soil substrate, among several other factors such as soil moisture, temperature and pH (Alexander 1977). Improved soil structure and aggregation are important for better water flow and water holding characteristics. Adding organic matter therefore helps all poor soils, whether they are too sandy or made of too much clay.

One of the oldest sources of organic matter for increasing crop productivity is the recycling of agricultural waste such as straws, stalks, husks, etc. For example, rice husk was used as a partial substitute of the expensive traditional medium components for producing high quality greenhouse and nursery crops (El-Torky and Bedaiwy 1998) as well as many other crops (Cerff *et al*. 1985, Sawan *et al*. 1986).

Fresh farm waste disposal material is fermented by composting. With organic substances, compost creates suitable living conditions for micro-organisms. It plays an essential role in giving the top soil the desired structure (Hauck 1982, Sumner 2000) and considerable savings in water and fertilizers (Im 1980, Hauck 1982). Beneficial effects of organic material additions to sandy soils comprise improving aggregate formation, aggregate water-stability, and water holding characteristics (Marshall and Holmes 1988, Sumner 2000). In loam and clay soils, organic substances improve aeration, water infiltration, and drainage.

An organic material that gained attention in the last few years is coffee grounds (CG). Hundreds of thousands of tons of used CG are discarded every year. Many house owners and gardeners used the grounds as an amendment for their lawns and front yards, realizing that CG make a good soil amendment, providing nitrogen, phosphorus, potassium, magnesium, and copper to the soil and the plants. Basic observations and initial research work in the U.S. (e.g., *Sunset Magazine*, 2017) revealed that up to 35% by volume CG will improve soil structure over the short term and over the long term. Coffee grounds are presented by Pennsylvania State Cooperative Extension (2007) as an excellent source of soil nutrition when mixed with other materials, acting as a green material with a carbon-nitrogen (C-N) ratio of approximately 20-1. They are also reported to make an excellent addition to compost. According to the data of Pennsylvania State Cooperative Extension (2007), Feather (2008), and Soil and Plant Laboratory Inc. Bellevue, WA (In: *Sunset Magazine*, 2017), CG are rich in nitrogen (1.45%–2.28%) and have considerable concentrations of phosphorous (0.06%–0.30%), potassium (0.12%–0.60%), calcium (0.039%) and magnesium (0.045%).

The objective of the work presented here is to quantitatively determine the effects of adding CG to different soils in order to evaluate the feasibility of using them as a reliable soil conditioner. This work is a part of a study directed at examining the effects of CG on some of the basic physical and mechanical properties that could influence soil processes and productivity. The research related to the effects on physical properties is presented in this article. The effects on some soil mechanical properties will be addressed in a subsequent paper.

MATERIALS AND METHODS

Soils

Experimental work was performed on three typical Egyptian soils known to have different physical, hydro-physical, mechanical and fertility properties: 1) sandy soil from the desert west of the Delta (Bustan area), 2) clayey soil from the center of the Delta (Kafr El-Zayat area) and 3) calcareous soil from south east of Alexandria (North Tahrir area). Soil samples were dried and processed according to standard methodologies. Soil was passed through a No. 4 (4.75 mm) sieve for most physical analysis. For some specific analyses (e.g., particle size analysis and chemical analysis), soil passing through a No. 10 (2 mm) sieve was used. Mixing of soil and CG was done at air-dry moisture contents for both.

Coffee grounds

Coffee grounds were obtained through special arrangements with a number of the major chain coffee shops in Alexandria, Egypt.

Soil treatments

Coffee grounds were applied to each of the three soils at rates of 5%, 10%, and 15% by volume, in addition to a control. Experiments were done in two to three replications.

Wetting-and-drying cycles (WDC)

Two sets of measurements were made: One shortly (approximately one week) after CG were applied to soils, and another after approximately seven months of wetting-and-drying cycles (WDC). For the before-WDC treatments, treated soils were wetted to field capacity only one time then allowed to dry in open air before physical measurements were made.

Physical properties and chemical analysis

Physical and hydro-physical properties determined in different soils (CG-treated soils and control) included: dry density (γ_d), porosity (n), saturated hydraulic conductivity (K_s), infiltration rate (IR), soil sorptivity (S), soil water characteristics (SWC), dry aggregate/particle analysis (dry sieving), and wet aggregate/particle analysis (wet sieving). Treated soils were packed into tin pots, 20 cm in diameter and 20 cm high, where they were subjected to WDC. Samples were taken from pots for SWC and aggregation tests. For hydraulic conductivity tests, brass cylinders, 10 cm tall and 7 cm in diameter were used. Other treated soil samples were packed into transparent acrylic cylinders, 50 cm high and 8.4 cm in diameter for infiltration tests. Within each test, packing was performed such that each soil type maintained as closely as possible the same bulk density. The packing density of the infiltration columns was slightly lower than that of the hydraulic conductivity brass cylinders. The hydraulic conductivity cylinders were shaken automatically to allow for particle settling, whereas infiltration columns were only tapped manually due to their larger size. This point was overlooked since the focus was on comparing results within each individual experiment. Saturated hydraulic conductivity and infiltration rate were determined under a constant inlet water head of 3 ±0.2 cm.

Chemical analysis of the test soils included: soluble cations, soluble anions, pH, soil salinity (EC) in soil extract, nitrogen, phosphorous, and potassium contents (Page 1982), total calcium carbonate content, $CaCO_3$% (volumetric calcimeter method, soil organic matter, OM) (Black 1965).

RESULTS AND DISCUSSION

Basic physical and chemical properties of the three soils are presented in Table 1. Physical and chemical properties of CG are shown in Tables 2a and 2b, respectively.

1. Effect of CG on the bulk (dry) density (γ_d) of the soils

Table 3 and Fig. 1 display the changes in bulk (dry) density (γ_d) in response to applied CG, before and after WDC. Table 3 displays also the values of soil porosity (*n*), corresponding to the resulting densities. For all soils, γ_d decreased with CG, and the effect increased with CG rate. More substantial decrease was seen in clay before WDC (-16.5%, compared with -12.6% in sand and -8.6% in the calcareous soil (Table 3)). Density correlated negatively with CG content over the tested range for all soils (r^2 = 0.87 to 0.99 – linear function). After WDC, the general trend remained, with the largest drop in γ_d taking place in sand (-13.3%), followed by the calcareous soil (-12.3%) and clay (-11.5%). Negative linear correlations were obtained between γ_d and CG for all cases (r^2 = 0.88 to 0.91). Apparently, CG reduced γ_d through two effects, 1) mixing of the low-density CG (γ_d of coffee ground ranged from 0.41 to 0.77 $Mg{\cdot}m^{-3}$) to the denser soils; and 2) the possible effect on soil structure. Adding CG enhances aggregate formation and improves soil structure. It has been reported (Thompson and Troeh 1978, Marshall and Holmes 1988) that structures of heavy-textured soils such as clays can benefit from the application of organic matter through enhancing aggregate formation. Soil aggregates form a structure that comprises bodies of solid particles surrounding voids and macropores, and containing both micropores and macropores inside. The increase in macropores loosens the structure of the soil, causing its dry density to decrease. The difference in γ_d between before and after WDC was small in sand. In the calcareous soil, this difference was marked, which might be attributed to the initially strongly cemented particles of the calcareous soil. Upon repeated WDC, the grains of CG might have a better opportunity to interact with the soil and loosen its structure. In clay, the decrease percent after WDC was smaller than before WDC. With WDC, some of the less stable aggregates formed before WDC would break down and some macropores may be lost. This could result in the slight increase in density at the 15% CG rate in relation to before WDC (Table 3). Density values were very comparable before and after WDC for the 5% and 10% CG, suggesting that CG particles were likely fixed in stable soil aggregates. It also appears that CG beyond the 10% rate were only effective before WDC. With repeated wetting and drying at the high rate of 15%, some CG grains are possibly leached out with drained water. Expectedly, and as γ_d decreased with CG, calculated total soil porosity (n), increased in all soils with CG (Table 3).

Table 1. Some pertinent properties of experimental soils

Soil		Sand	Calcareous	Clay
Particle-size analysis	Sand (%)	96.12	56.53	32.90
	Silt (%)	2.25	14.27	22.06
	Clay (%)	1.63	29.19	45.04
Soil texture designation		Sand	Sandy clay loam	Clay
Dry density (γ_d), $Mg{\cdot}m^{-3}$		1.83	1.16	1.21
Saturated hydraulic conductivity (K_s), $cm{\cdot}min^{-1}$		0.814	0.044	0.005
Basic infiltration rate (lab. determined), $cm{\cdot}min^{-1}$		1.90	0.17	0.03
EC, $dS{\cdot}m^{-1}$		5.08	2.67	3.81
pH		7.68	8.22	7.56
Sodium adsorption ratio (SAR)		5.3	4.3	2.5

Table 2a. Some pertinent physical properties of the coffee grounds

Air-dry moisture content, $\theta_{air\text{-}dry}$, %	Saturation percent, θ_{sat}, %	Mean weight diameter (MWD), mm	Geometric mean diameter, (GMD), mm	Unit weight, $\gamma_{air\text{-}dry}$, $Mg{\cdot}m^{-3}$ (Range measured) min.	max
7.15	≈175–250	0.519	0.996	0.41	0.77

Table 2b. Basic pertinent chemical properties of the used coffee grounds

EC dS·m^{-1}	Cations, %				N, %	P, %	K, %	Fe, ppm	Zn, ppm	Mn, ppm	Cu, ppm	OM %
	pH	Ca^{++}	Mg^{++}	Na^{+}								
3.19	5.91	1.0	0.2	0.1	2.24	0.15	0.47	70.6	11.9	24.5	22.2	78.4

Table 3. Effect of applying different rates of coffee grounds (CG) on the dry density (γ_d) and total soil porosity (n), of the three soils before and after wetting-and-drying cycles (WDC)

CG (% vol.)	Before WDC		After WDC	
	γ_d, Mg·m^{-3}	n, %	γ_d, Mg·m^{-3}	n, %
Sand				
0	1.83	30.94	1.81	31.70
5	1.79	32.45	1.79	32.45
10	1.70	35.85	1.72	35.09
15	1.60	39.62	1.57	40.75
Calcareous (sand clay loam)				
0	1.16	56.23	1.22	53.96
5	1.16	56.23	1.20	54.72
10	1.08	59.25	1.09	58.87
15	1.06	60.00	1.07	59.62
Clay				
0	1.21	54.34	1.22	53.96
5	1.15	56.60	1.14	56.98
10	1.09	58.87	1.09	58.87
15	1.01	61.89	1.08	59.25

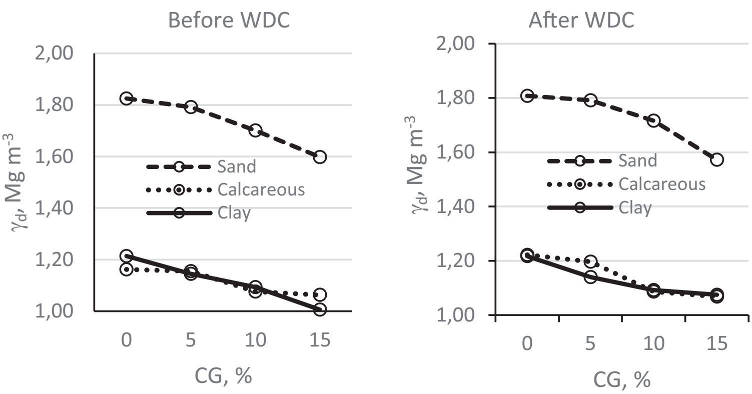

Fig. 1. Decrease in the dry density (γ_d) in response to different application rates of coffee ground (CG) to the sandy, calcareous (SCL) and clayey soils, before and after subjecting the soils to wetting-and-drying cycles (WDC)

2. Effect of CG on the saturated hydraulic conductivity (K_s)

Results of the effect of CG on the saturated hydraulic conductivity (K_s), before and after WDC are shown in Table 4. In the sandy soil, a steady decrease in K_s with added CG was seen. At 15% CG, K_s decreased before WDC to only 7.5% of its initial value, and decreased to <25% of that value after WDC. The effect is expected to take place in two ways, 1) changing the particle packing system from a rather open system to a denser, more close-packed structure as a result of introducing the small particles of CG into the system. Close-packing results in a significant decrease in infiltration of water in the soil (Bedaiwy and Rolston 1993); and, 2) forming soil aggregates and the development of more micropores within these aggregates, decreasing the amount and the sizes of the large pores. Aggregation is boosted by the microbial activities in the soil, which are stimulated by WDC. Decreased K_s is a favorable effect in sandy soils. Low water permeability means less water loss by deep percolation. Figure 2 summarizes the effect of CG on K_s for the three soils.

Table 4. Effect of coffee grounds (CG) application on the saturated hydraulic conductivity (K_s)

CG (% vol.)	Saturated hydraulic conductivity (K_s) and relative change in K_s											
	Sand				Calcareous (SCL)				Clay			
	K_s cm·min^{-1}		Rel. change in K_s, %		K_s cm·min^{-1}		Rel. change in K_s, %		K_s cm·min^{-1}		Rel. change in K_s, %	
	Before WDC	After WDC	Before WDC	After WDC	Before WDC	After WDC	Before WDC	After WDC	Before WDC	After WDC	Before WDC	After WDC
0	0.814	0.714	0	-12.29	0.044	0.064	0	45.45	0.005	0.021	0	320
5	0.414	0.451	-49.1	-44.59	0.046	0.089	4.55	102.27	0.030	0.072	500	1340
10	0.356	0.333	-56.2	-59.09	0.073	0.124	65.9	181.82	0.057	0.223	1040	4360
15	0.061	0.197	-92.5	-75.80	0.035	0.175	-20.5	297.73	0.017	0.105	240	2000

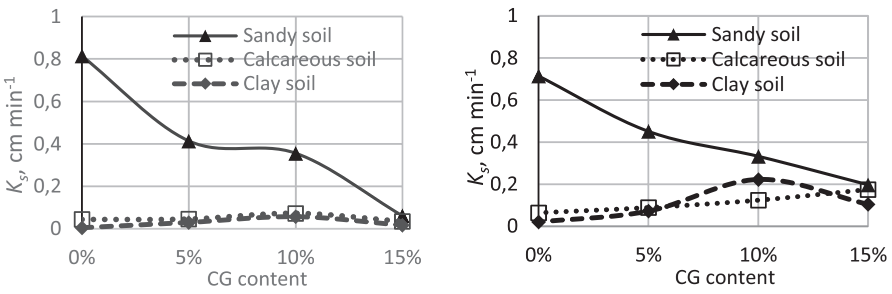

Fig. 2. Effect of coffee grounds (CG) on the saturated hydraulic conductivity (K_s) of the three soils before (left) and after (right) seven months of cycles of wetting and drying

For the calcareous soil (SCL texture), the 5% CG rate did not result in marked change in K_s (Table 4). The 10% CG rate produced a pronounced increase in K_s. At the 15% rate, however, K_s dropped again to a value that is even smaller than that of the untreated control. This decrease is believed to be resulting from the swelling and clogging associated with this high CG concentration. After WDC, the calcareous soil showed a different pattern than before WDC. Here, K_s rose steadily with CG. A possible explanation of the discrepancy could be that the excess CG that was believed to induce swelling and clogging at the high CG rate of 15% was washed out through repeated WDC, leaving behind only the CG employed in aggregation. Results also indicate that K_s increased markedly for all CG rates at the end of WDC relative to before WDC. Apparently, reactions between the acidic CG and the alkaline calcareous soil were boosted by WDC.

The hydraulic conductivity of the clayey soil increased as a result of applying CG. The improvement of K_s before WDC was substantial, where it increased sixfold at the 5% and over tenfold at the 10% rate. The trend was the same after WDC and the relative increase was much greater. The greatest effect took place at the 10% rate although the 15% rate still showed a remarkable improvement in K_s. This was true both before and after WDC. It is possible that at the 15% rate excessive CG existed, and the swelling and clogging effects caused the blocking of some of the water paths. Results revealed also that K_s values were greater after WDC than prior to WDC. This trend is similar to that observed in the calcareous soil (Table 4). Apparently, this is a result of improved soil structure and aggregation with time and the development of more macropores among aggregates. It is noticeable that K_s in the non-treated soils (0% CG), was also affected by wetting and drying. It decreased in sand and increased in the other two soils. This reflects the process of particle rearrangement and the dense, close-packing that takes place in sand (and to a lesser degree in the other two soils) upon repeated wetting and drying, and also reiterates the role of microorganism in aggregate formation in all soils.

The increase in K_s is favorable in calcareous and clayey soils, as both usually have water infiltration and drainage problems. Water conductance in soil depends on the shapes and sizes of voids and pores, which essentially reflect the condition, geometry and stability of soil structure and aggregates. An important mechanism is associated with the microbial growth and activities in the soil. The presence of the organic coffee grains enhances the growth of bacteria, algae, fungus and actinomycetes. These microorganisms produce exudates that work as cementing agents, binding soil particles together. The hyphal and filamentous growths produced by fungi and actinomycetes function as binding threads that physically bring individual particles together into larger aggregates (Hillel 1982, Marshall and Holmes 1988). After seven months of WDC, the microbial activity was very high. Visually, algal and fungal growths were obvious in the transparent soil columns (Fig. 3). Aggregation involves different organic binding agents at different scales. According to the theory of aggregate hierarchy (Oades and Waters 1991), large aggregates (>2,000 μm) are held together by a fine network of roots and hyphae in soils with high soil organic carbon (SOC) content (>2%), while 20–250 μm aggregates consist of 2–20 μm particles, bonded together by various organic and inorganic cements. Water stable aggregates of 2–20 μm size, in turn, consist of <2 μm particles, which are an association of living and dead bacterial cells and clay particles. The concept of aggregate hierarchy suggests that organic matter controls aggregate stability, and that degradation of large (relatively unstable) aggregates creates smaller, more stable aggregates. Particulate organic matter (CG in this case) serves as a substrate for microbial activity, resulting in the production of microbial bonding materials for micro-aggregates. Fresh or "active" part of soil organic matter (SOM) (consisting of mono- and polysaccharides, exudates from roots and fungal hyphae), was reported to be largely responsible for stabilization of aggregates (Tisdall and Oades 1982).

Fig. 3. Algal and fungal growths in the sandy soil taken as an example seven months after wetting-and-drying cycles

3. Effect of CG on infiltration rate (IR) and sorptivity (S)

a. Infiltration rate

The infiltration rate-time data were fitted to the equation of Philip (1957) of the form

$$i(t) = at^{-0.5} + b \qquad (1)$$

where: $i(t)$ is infiltration rate ($cm \cdot min^{-1}$), t is time (min), $a = ½S$, where S is an estimate of soil sorptivity ($cm \cdot min^{-0.5}$), b is basic (steady-state) infiltration rate ($cm \cdot min^{-1}$).

In the sandy soil, basic IR decreased substantially with increasing CG, both before and after WDC. Before WDC, IR decreased threefold as CG rate increased from 0% to 10% and decreased more than fivefold as CG increased from 0% to 15% (Table 5). As discussed before, two main effects take place as CG are added to the soil: changing the structure from an open system to a denser, close-packed system; and aggregation and structure improvement, where CG function as a binding material. The first effect is more likely to occur in sand due to its loose nature and is believed to be boosted by the swelling of CG grains upon wetting. It is worth noting that while these two effects appear to be rather opposing with regards to water flow, the impact of each effect differs in different soils depending on their individual nature and composition. The decrease in IR was particularly clear at 15% CG after WDC, where it decreased by more than 96% of the initial value (Table 5). After WDC, the sandy soil maintained the same pattern of falling IR with CG (Fig. 4) and IR was lower than before WDC for the 10% and 15% CG. For example, while there was a fivefold drop in IR at 15% CG before WDC, the drop was as high as approximately 26-fold after WDC (Table 5). The effect of CG became more evident with time even with some CG leaching out with draining water.

Table 5. Basic (steady-state) infiltration rate (IR), for the three soils at different rates of CG, before and after seven months of wetting-and-drying cycles (WDC)

CG (% vol.)	IR, $cm \cdot min^{-1}$					
	Sand		Calcareous (SCL)		Clay	
	Before WDC	After WDC	Before WDC	After WDC	Before WDC	After WDC
0	1.90	1.83	0.17	0.27	0.03	0.19
5	0.78	1.55	0.11	0.49	0.03	0.41
10	0.60	0.55	0.05	0.63	0.02	0.67
15	0.37	0.07	0.05	1.37	0.02	0.14

In the calcareous soil (SCL), IR increased with CG after WDC although it showed a decrease with CG before WDC. The increase at 15% CG was particularly marked (Fig. 4). The decrease in IR at the 15% rate before WDC is consistent with that of K_s (Table 4). The behavior at 10% CG rate, however, appears inconsistent with that of K_s at that CG rate, where an increase in K_s was seen. Values of IR for the calcareous soil are shown in Table 5.

For the clayey soil, at 5% CG, noticeable improvement in infiltration rate occurred after WDC (Fig. 4). The trends associated with 10% and 15% CG rates before WDC were rather similar to those of the calcareous soil (i.e. IR decreasing in comparison with the 5% rate and the control). Before WDC, IR values in clay were lower than those of the sandy and calcareous soils for all CG rates (Table 5). The 10% and 15% rates appear to have some adverse effect (lower IR) in the clayey soil over the short term (before WDC). This could be attributed to particle-rearrangement and dense packing, as discussed before, with small particles (soil and CG) filling in the pores among larger particles, in addition to swelling, and clogging actions. These adverse effects disappeared after WDC. After WDC, IR values were smaller than those of the sandy soil for the 0% and 5% CG rates only. At 10% CG, IR was comparable with that of the other two soils.

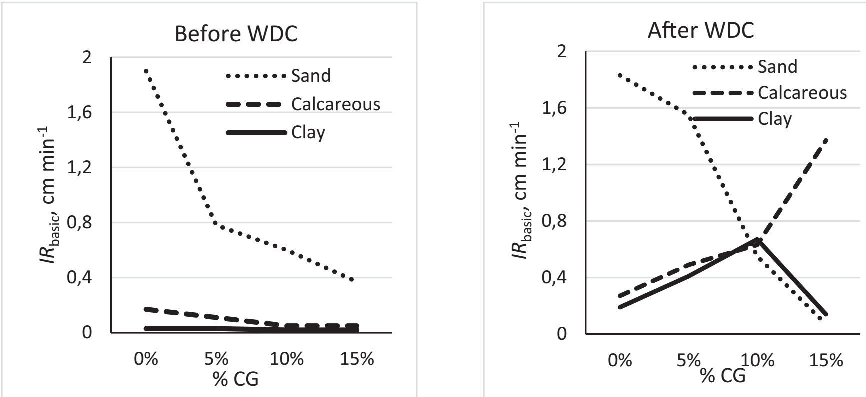

Fig. 4. Basic infiltration rate (IR) of the three soils as affected by coffee grounds (CG) rate before and after the wetting-and-drying cycles (WDC)

b. Sorptivity (S)

Sorptivity (S) was determined as the slope of the regression curves of cumulative infiltration (I) vs. time (t) for the early part (several minutes) of the infiltration curve, with the intercept set to zero. Results are presented in Table 6. In general, determined S values are high compared with some reported values (e.g., Lien 1989, Raut and Chakraborty 2008), but comparable with others (e.g., Culligan *et al*. 2005, Shaver *et al*. 2013). High S values possibly resulted from the fact that soils were tested at air-dry moisture content, and under a positive inlet head pressure (3.0 ± 0.2 cm of water).

Table 6. Sorptivity (S) of the different soils as affected by coffee grounds (CG) rates before and after wetting-and-drying cycles (WDC)

	Sorptivity, S ($cm \cdot s^{-0.5}$)					
	Sand		Calcareous (SCL)		Clay	
CG (% vol.)	Before WDC	After WDC	Before WDC	After WDC	Before WDC	After WDC
0	0.370	0.230	0.110	0.217	0.024	0.362
5	0.319	0.250	0.120	0.179	0.043	0.461
10	0.271	0.229	0.055	0.354	0.085	0.296
15	0.117	0.257	0.356	0.596	0.129	0.355

Mostly, no clear trends of S were identified. Before WDC, the sandy soil had greater sorptivity than the other two soils. After WDC, values showed no particular pattern. The clayey soil had higher S values than the other two soils for the 0% and 5% CG contents while the calcareous soil showed the greatest values for the 10% and 15% treatments. The sandy soil had greater S before than after WDC for all CG treatments except the 15%. For the calcareous and clayey soils, S was significantly greater after than before WDC. Apparently, the initial affinity of sand to absorb water was greater than that of added CG, and that the other two soils had an initially lower sorptivity than that of the CG as well as that of the sandy soil.

The sandy soil showed a pattern of decreasing S with CG content before WDC. After WDC, however, no particular pattern was seen. Decreasing S with CG in sand before WDC could be a result of the higher initial air-dry moisture content of the CG (approximately 7.15%, weight basis, Table 2a) relative to that of the sandy soil (approximately 1.10%, weight basis). For the calcareous soil, no pattern was seen before WDC. After WDC, S increased with CG content for the 10% and 15% CG contents. In the clayey soil, S increased with CG content only before WDC. These sporadic results suggest that further work on this point may be appropriate.

4. Effect of CG on soil-water characteristics (SWC) and water holding capacity

The effects of CG on SWC of the three soils are displayed in Fig. 5. The curves show the amount of water retained in each of the soils at different levels of suction in relation to CG rates. For all cases (except clay before WDC) adding CG resulted in an increase in water holding capacity (WHC). The effect is more marked in the sandy and calcareous soils. The change in the available water (AW), defined as the difference between water contents at field capacity (FC) and at wilting point (WP) can be seen in Fig. 5. The field capacity is taken here as water content at 0.1 bar of suction in sand and 0.3 bar in calcareous and clay soils. The wilting point is taken as the water content at 7.0–9.0 bars for sand and 15 bar for the calcareous and clay soils. Before WDC, the available water decreased in sand at 5% and 10% then increased at 15% to a maximum of 3.75% (weight basis), which is slightly larger than that of the non-treated soil (3.40%). The calcareous soil had the highest AW at 5% (12.3%) compared to 11.08% of the control treatment. The trend of the clayey soil was similar to that of the sand where AW decreased at 5% and 10% then increased at 15% to 12.81% compared to 10.28% for the non-treated soil. This indicates that although CG increased both FC and WP water contents, some AW increase was achieved at the 15% rate. This was not true, however, after WDC where AW decreased with CG, particularly in the calcareous and clay soils (Fig. 5), suggesting that the increase in WP was greater than in FC. This effect was very marked in the calcareous soil where the rise in water content near WP was much sharper than that of FC. Apparently, the effect of the high WHC of CG would be more marked near WP where the soil is drier. Whether subjecting the soil to WDC enhances CG capacity to retain water, and also the nature of reactions between the acidic CG and the high $CaCO_3$ content of the calcareous soil that may be boosted by WDC seem to require further investigation.

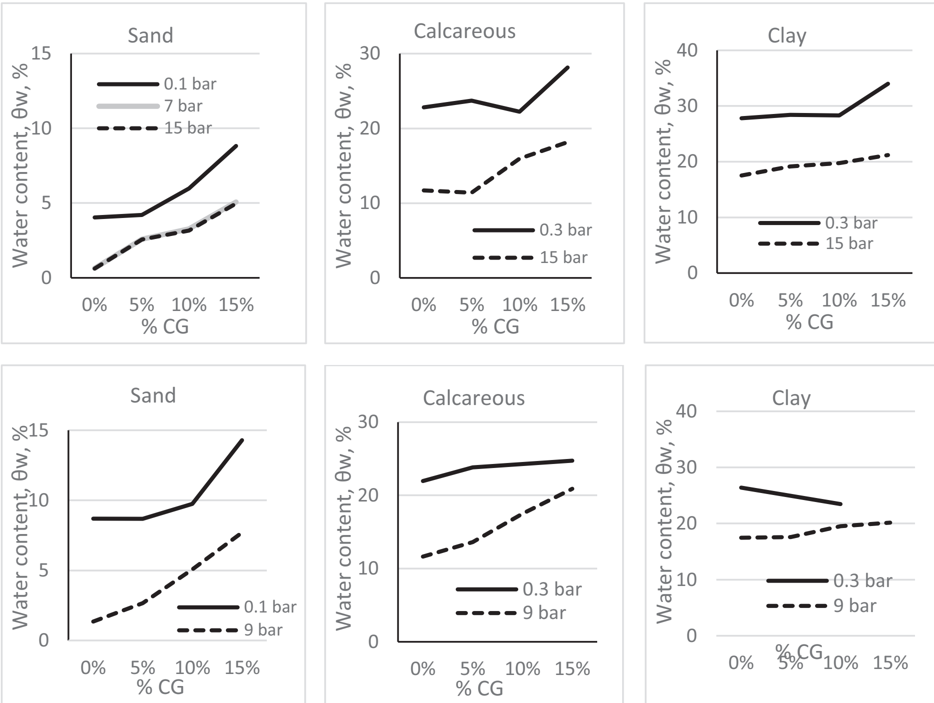

Fig. 5. Effect of different rates of coffee ground (CG) on water retention at different suctions for the sandy, calcareous and clayey soils before wetting-and-drying cycles (WDC) (top graphs) and after WDC (bottom graphs)

5. Effect of CG on soil aggregates

The effect of CG on soil aggregation was evaluated through dry and wet sieving analyses and the calculation of the mean weight diameter (MWD). The area between wet and dry sieving curves reflect the amount of aggregates that did not hold under wet sieving and disintegrated upon being submerged and shaken in water in the test. These could be defined as weak aggregates (poorly water-stable or non-water stable aggregates). While these aggregates may have some impact on stability of the soil under non-submerged conditions (e.g., stability against wind erosion), they are likely to break down under rain or irrigation practices, particularly practices that involve water drop impact such as sprinkle irrigation or flooding. Examples from the three soils (at 15% CG) are shown in Fig. 6. Other CG treatments had essentially the same trend. In sand, the amount of aggregates is virtually negligible as indicated by the very little difference between the wet and dry sieving curves. Calcareous and clay soils, on the other hand, had substantially larger amounts of aggregates.

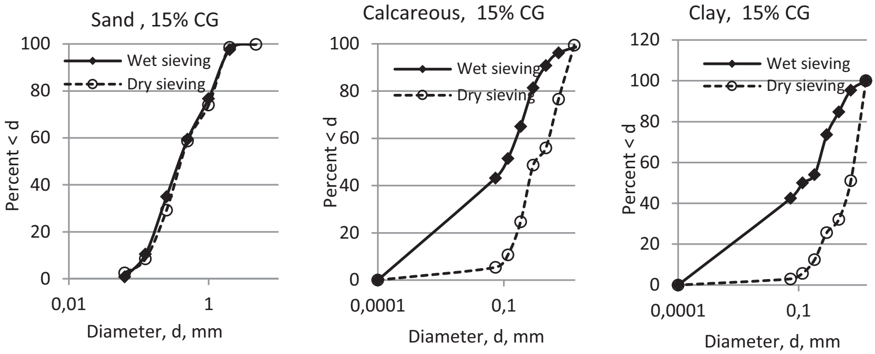

Fig. 6. Dry and wet sieving curves for the three soils at the 15% coffee ground rate

The amount of water-stable aggregates was estimated by calculating the aggregate MWD from wet sieving results at the end of WDC. Table 7 presents calculated MWD for the three soils at different CG rates. The calcareous soil had initially the largest MWD of all soils, followed by clay then sand. Adding CG to the sandy soil led to improving water-stable aggregation and MWD increased at 5% and 10% CG. Improved aggregation is a favorable effect of CG in sand as sandy soils have virtually no aggregates under normal conditions. The decrease in MWD at 15% CG could indicate that CG addition beyond the 10% rate did not produce any more water-stable aggregates, and hence, the small sizes of CG grains reduced MWD. A similar effect was observed in clay, but the effective CG rate appeared to be around the 5% level. In the calcareous soil, no increase in MWD was detected, and it decreased at all CG rates relative to the control treatment. Apparently, this decrease reflects the predominantly smaller size particles of CG. Large aggregates of strongly cemented particles are dominant in the calcareous soil (Table 7) and that is probably why adding CG did not result in further aggregation. Referring back to the effects of CG on other processes and properties, it was noted that CG did improve the saturated hydraulic conductivity and infiltration rate in the calcareous soil, and that was attributed to improved aggregation. This seems not to agree with the lacking aggregation effect mentioned above. However, it should be noted also that weak and moderately stable aggregates which may form as a result of applying CG may hold and do not disintegrate during water infiltration while they break down under the vigorous test of wet sieving where the soil is subjected to a much greater destructive energy.

Table 7. Mean weight diameter (MWD) of soil aggregates under different applied rates of coffee grounds (CG) as determined from wet sieving analysis

CG (% vol.)	MWD, mm		
	Sand	Calcareous (SCL)	Clay
0	0.693	0.751	0.747
5	1.117	0.436	0.769
10	1.570	0.455	0.571
15	0.767	0.503	0.635

CONCLUSIONS

Coffee grounds (CG) appear to have favorable effects on some physical properties of the tested soils; namely, dry density, porosity, hydraulic conductivity, infiltration rate and aggregate formation. Soil bulk density decreased and porosity increased with CG. Saturated hydraulic conductivity and infiltration rate substantially decreased in sand and increased in clay with the application of CG. Non water-stable aggregates increased largely with CG in the calcareous and clay soils. Water stable aggregates increased progressively in sand as CG rates increased to 5% and 10%. In clay, water stable aggregates increased only at 5% CG. Effects on other tested properties were either inconsistent or unclear (e.g., sorptivity) or unfavorable (e.g., available water, AW). Although the total water holding capacity (field capacity, FC) increased with CG, AW decreased, because the increase in the wilting point (WP) moisture content was larger than that of FC. Results – although preliminary – might suggest that CG could still represent a useful, inexpensive and safe soil conditioner to improve some of the soil's physical properties, particularly those related to soil aggregation and water flow.

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REFERENCES

[1] Alexander, M., 1977. *Introduction to Soil Microbiology*, 2nd ed. Academic Press, New York, USA.
[2] Bedaiwy, M.N., Rolston, D.E., 1993. *Soil surface densification under simulated high intensity rainfall*. Soil Technology, 6(4): 365–376.
[3] Black, C.A., 1965. *Methods of Soil Analysis*. American Society of Agronomy. Part 2, No. 2, Madison, Wisconsin, USA.

[4] Cerff, R. le, Mufran, R., Butan, A., 1985. *Yield response of IR 32 to organic and inorganic fertilizers.* International Rice Research Newsletter (Philippines), 10(6): 31–32.
[5] Culligan, P., Ivanov, V., Germaine, J.T., 2005. *Sorptivity and liquid infiltration into dry soil*. Advances in Water Resources, 28(2005): 1010–1020.
[6] El-Torky, M.G., Bedaiwy, M.N.A., 1998. *Possible uses of rice husk as a growing medium for ornamental plants and floricultural crops. 2. Effect of rice husks and nitrogen fertilizer on the production of open field roses and the improvement of soil characteristics*. Alexandria Journal of Agricultural Research, 43(2): 143–162.
[7] Emerson, W.W., 1959. *The structure of soil crumbs*. European Journal of Soil Science, 10(2): 235–244.
[8] Feather, S. 2008. *Coffee grounds around plants– Penn State Extension*, http://www.donnan.com/coffee-on-plants.htm
[9] Harris, R.F., Chesters, G., Allen, O.N., 1966. *Dynamics of soil aggregation*. Advances in Agronomy, 18: 107–169.
[10] Hauck, F.W., 1982. *Organic Recycling to Improve Soil Productivity*. FAO Soils Bulletin 45. Rome.
[11] Hillel, D., 1982. *Introduction to Soil Physics.* Academic Press, New York, USA.
[12] Im, J.N., 1980. *Organic Materials and Improvement of Soil Physical Characteristics*. FAO Soils Bulletin 45. Rome.
[13] Lien, B.K., 1989. *Field measurement of soil sorptivity and hydraulic conductivity* (Master's thesis). The University of Arizona, USA.
[14] Marshall, T.J., Holmes, J.W., 1988. *Soil Physics*, 2nd ed. Cambridge University Press, Cambridge.
[15] Oades, J.M., Waters, A.G., 1991. *Aggregate hierarchy in soils*. Australian Journal of Soil Research, 29: 815–828.
[16] Page, A.L. (ed.), 1982. *Methods of Soil Analysis*. Part 2. American Society of Agronomy, Madison, Wisconsin, USA.
[17] Pennsylvania State College of Agricultural Sciences. 2007. Delaware County Master Gardeners' activities.
[18] Philip, J.R., 1957. Numerical *solutions of equations of the diffusion type with diffusivity concentration dependent. II.* Australian Journal of Physics, 10: 29–42.
[19] Raut, S., Chakraborty, H., 2008. *Influence of water regimes on soil sorptivity and nature and availability of organic matter in inceptisol*. Journal of Agricultural Physics, 8: 5–10.
[20] Sawan, O.N, Elbeltagy, M.S., Mohamedien, S.A., El-Beltagey, A.S., Maksoud, M.A., 1986. *A study on the influence of some transplant growing media on flowering and yield of tomato*. Acta Horticultural, 190: 515–522.
[21] Shaver, T.M., Peterson, G.A., Ahuja, L.R., Westfall, D.G., 2013. *Soil sorptivity enhancement with crop residue accumulation in semiarid dryland no-till agroecosystems*. University of Nebraska – Lincoln. Agronomy & Horticulture Dept. – Faculty Publications.
[22] Sumner, M.E., 2000. *Handbook of Soil Science*. CRC Publishers, London, UK–FL, USA.
[23] Sunset Magazine, 2017. Soil and Plant Laboratory Inc., Bellevue, WA. *The Starbucks coffee compost test*, http://www.sunset.com/garden/earth-friendly/starbucks-coffee-compost-test
[24] Thompson, L.M., Troeh, F.R., 1978. *Soils and Soil Fertility*, 4th ed. McGraw-Hill Publications in the Agricultural Sciences. New York, USA.
[25] Tisdall, J.M., Oades, J.M., 1982. *Organic matter and water stable aggregates in soils*. European Journal of Soil Science, 33: 141–163.