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Estimation of Saprolite Thickness Needed to Remove *E. coli* from Wastewater

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Abstract: Saprolite, weathered bedrock, is being used to dispose of domestic sewage through septic system drainfields, but the thickness of saprolite needed to remove biological contaminants is unknown for most saprolites. This study developed and tested a simple method for estimating the thickness of saprolite needed below septic drainlines to filter *E. coli* from wastewater using estimates of the volume of pores that are smaller than the length of the coliform (≤10 μm). Particle size distribution (texture) and water retention data were obtained for 12 different saprolites from the Piedmont and Mountain regions of North Carolina (N.C.). Saprolite textures ranged from clay loam to coarse sand. The volume of pores with diameters ≤10 μm were determined by water retention measurements for each saprolite. The data were used in an equation to estimate the saprolite thickness needed to filter *E. coli*. The estimated saprolite thicknesses ranged from 36 cm in the clay loam to 113 cm for the coarse sand. The average thickness across all samples was 58 cm. Saprolite thickness estimates increased as silt percentage decreased and as sand percentage and in situ saturated hydraulic conductivity increased. Silt percentage may be most useful for estimating appropriate saprolite thicknesses in the field.

Keywords: coliforms; piedmont soils; mountain soils; septic systems; weathered bedrock

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1. Introduction

On-site wastewater management systems (OSWMS), commonly referred to as septic systems, are used to treat and dispose of sewage in areas not served by a municipal sewer system. Approximately 20% of the households in the US, and one-half of those in North Carolina (N.C.), use these systems to manage their domestic sewage on-site [1]. A conventional OSWMS consists of a septic tank and a drainfield [2]. The septic tank provides primary treatment to the sewage by allowing solids to settle and go through anaerobic digestion. The liquid from the septic tank (referred to as wastewater) containing dissolved and suspended organic materials, microbial organisms (e.g., *Escherichia coli* (*E. coli*)), and chemical pollutants are dispersed into the soil through a series of trenches in the drainfield [3]. In the unsaturated and aerated environment below the trenches, some pathogenic bacteria are removed through physical filtration, and the anaerobic bacteria typically die off in the aerobic soil environment [4,5].

In N.C. and many other states, most OSWMS are installed at sites with a suitable soil that is at least 60 cm thick [6]. However, in the Southeastern part of the United States (US), saprolite is being increasingly used for OSWMS where soils are thinner. Saprolite (commonly known as rotten rock) is isovolumetrically-weathered bedrock that is porous and friable (similar to soil), but it has had some of its original minerals dissolved and removed, creating pores between the mineral grains that were in the original rock [7,8]. The structure of saprolite is described as "massive-rock controlled," meaning that the planar voids commonly found between the structural units of soil (i.e., soil peds) are absent in saprolite. Saprolite is found under nearly all soils in the Piedmont and Mountain regions of the Southeastern US and extends from the bottom of the soil solum to solid bedrock [9].

The thickness of saprolite materials is variable and can range from <1 m where bedrock is shallow to over 50 m thick where the bedrock is deep [9].

Coliforms, such as *E. coli*, can be removed from soil water by: (1) attachment to soil particles, (2) consumption by larger soil microorganisms, or (3) straining by which coliforms are trapped in pore throats that are too small for the organisms to pass through [4]. Bradford et al. [10] showed that straining or filtering was an important mechanism responsible for removing colloid-size particles (<10 μm diameter and including bacteria) from water moving through granular media. They noted that in their study, colloid straining occurred even for particles 0.45 μm in diameter. Colloid straining was controlled by the size of the colloid and the pore sizes in the medium through which the colloid was passing through.

Our previous research has shown that 60 cm of aerated, unsaturated sandy loam saprolite can effectively remove *E. coli* from simulated wastewater [11]. Similar results have been found for soils of comparable texture [12,13]. Saprolite materials with a sandy loam texture have pores small enough to filter or strain organisms such as *E. coli*. However, due to the presence of a significant amount of pores, which are >10 μm in diameter, *E. coli* may not entirely be removed by a 60 cm thick layer of sandy saprolite. Therefore, the main objective of this work was to develop a simple method for estimating the thickness of saprolite needed to filter *E. coli* from wastewater for textures ranging from clay loam to sand. For this, we propose a unique method for determining the thickness of saprolite in use, which is required for the complete filtration of *E. coli* and has a volume of pores smaller than 10 μm.

2. Materials and Methods

2.1. Theory

The size and shape of bacterial cells are important parameters that play a key role in particle retention [14]. The typical size of an individual *E. coli* cell is about 1.1 to 2 μm in width and 2 to 10 μm in length [4,14]. Due to the size and rod-shape of the bacterial cell, *E. coli* should be filtered when wastewater that is applied to a soil passes through pores that are <10 μm in diameter [15]. The diameter of pores that can hold water as a function of soil water potential can be estimated according to the capillary rise equation by:

$$D\ (\mathrm{cm}) = -0.3/h\ (\mathrm{cm}) \tag{1}$$

where D is the diameter of the pore, and h is the soil water pressure head (-cm) [16]. For pores $\leq$10 μm (0.001 cm) in diameter, the pressure head h is -300 cm. Our previous study [11] showed that a sandy loam saprolite column that was 60 cm long filtered out *E. coli* that was in a simulated wastewater, which had an *E. coli* concentration of 1×10^5 CFU/100 mL, while saprolite-filled columns of 30 and 45 cm allowed some *E. coli* to pass through. We hypothesize that 60 cm of a sandy loam saprolite has a sufficient volume of pores <10 μm in diameter to remove *E. coli.* Water retention measurements in our previous study showed that the sandy loam saprolite's water content at a soil water pressure head of -300 cm was 0.28 $\mathrm{cm^3/cm^3}$, which is equivalent to the volume of the pores having diameters <10 μm in the material. We used this information to develop a general equation for predicting the minimum thickness of saprolite that needs to be used to filter *E. coli* out of wastewater. The total volume of pores $\leq$10 μm in diameter ($PV_{10\ \mu\mathrm{m}}$) per unit cross-sectional area of a column of saprolite of thickness T can be estimated from:

$$PV_{10\ \mu\mathrm{m}} = \theta_{-300} \times T \tag{2}$$

where θ_{-300} is the volumetric water content of saprolite at -300 cm of pressure head as determined from its respective water retention curve. For the sandy loam saprolite material studied previously, where θ_{-300} was 0.28 $\mathrm{cm^3/cm^3}$ and T was 60 cm, $PV_{10\ \mu\mathrm{m}}$ was 17 $\mathrm{cm^3/cm^2}$, which we suggest is the minimum volume of pores with diameters of <10 μm needed to filter *E. coli* from saprolite. Using this value and rearranging Equation (2), we obtain a general equation for estimating the minimum thickness (T) of saprolite needed to remove *E. coli* from wastewater:

$$T\ (\mathrm{cm}) = 17\left(\mathrm{cm}^3/\mathrm{cm}^2\right)/\theta_{-300}\left(\mathrm{cm}^3/\mathrm{cm}^2\right) \quad (3)$$

We hypothesize that Equation (3) can be used to estimate the minimum thickness of saprolite material that can be used for on-site wastewater disposal if the water content at −300 cm of pressure head (i.e., θ_{-300}) is known.

2.2. Sampling Sites

Saprolite data were obtained from a previous study that characterized saprolites at 15 different sites in the Piedmont and Mountain regions of N.C. for on-site wastewater management [17]. Due to the lack of a complete data set at some locations, we chose 12 of the sites for this study (Figure 1). The sites were selected to represent a wide range of soil and saprolite conditions that could potentially be used for wastewater disposal. Table 1 presents the location and general soil information for each of the 12 sites. Common rock types from which the saprolite formed are also shown in Table 1. All these saprolites developed from either igneous or metamorphic rock and represent the most common types of saprolite found in N.C. Saprolites from sedimentary rock are not widespread in N.C. and have not been used in OSWMS in the state.

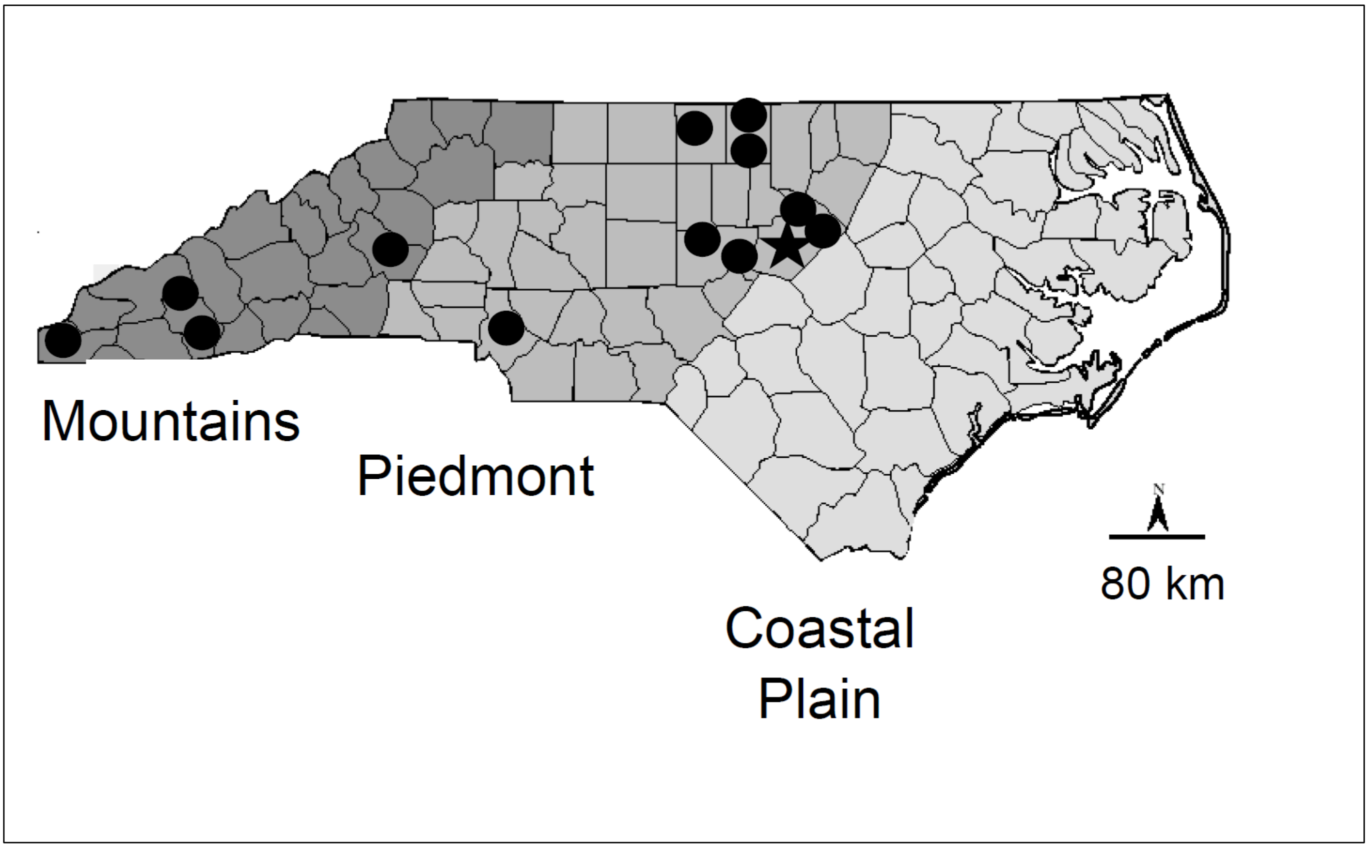

Figure 1. Map of North Carolina (N.C.) showing locations of sites sampled across the Mountain and Piedmont physiographic regions. Star indicates Raleigh, the capital city of N.C.

Table 1. Site number, county location, soil series, soil classification, and common parent rock type for the saprolite at the 12 sites in the Piedmont and Mountain Regions of North Carolina. Site numbers and names are those used by [17].

Site No. †	County	Soil Series	Soil Classification	Common Rock Types ††
1	Chatham	Enon, taxadjunct	Fine, mixed, thermic, Typic Hapludalf	Diorite
2	Chatham	Vance	Clayey, mixed, thermic, Typic Hapludult	Granite
3	Caswell	Wilkes	Loamy, mixed, thermic, Typic Hapludalf	Hornblende schist
5	Mecklenburg	Mecklenburg	Fine, mixed, thermic, Typic Hapludalf	Gabbro
6	Burke	Pacolet	Clayey, kaolinitic, thermic Typic Kanhapludult	Granite
7	Person	Enon, taxadjunct	Fine, mixed, thermic, Typic Hapludalf	Diorite
8	Person	Mecklenburg, taxadjunct	Fine, mixed, thermic, Typic Paleudalf	Gabbro
9	Jackson	Hayesville	Clayey, oxidic, mesic, Typic Hapludult	Granodiorite
10	Jackson	Watauga	Fine-loamy, micaceous, mesic, Typic Hapludult	Mica schist
12	Cherokee	Junaluska	Fine-loamy, mixed, mesic, Typic Hapludult	Slate
Wake	Wake	Cecil	Clayey, kaolinitic, thermic Typic Kanhapludult	Mica schist
Knight-dale	Wake	Appling	Clayey, kaolinitic, thermic Typic Kanhapludult	Mica schist

† Site 4 was omitted because no water retention data were collected. Site No. 11 was located on a steep slope on the side of the mountain in Jackson County, and no intact cores could be collected from the site. One site was located in the Triassic Basin of N.C. with sedimentary parent materials. These sites were not included in our analyses. †† Rock types were obtained from the Official Series Descriptions as reported by the USDA Natural Resources Conservation Service.

Sites numbered 1–12 were in natural areas, and pits were excavated to describe the soil profile, classify the soil, and collect saprolite samples for characterization. Pits were dug by machine where possible, and by hand otherwise. Pit dimensions varied from site to site but were deep enough to expose the saprolite. Major soil horizons were identified on one wall of the pit to determine the depth to the C horizons, which consisted of saprolite. Disturbed samples were then collected from each horizon identified in the field and stored in plastic bags. Intact (undisturbed) "cores" were collected from the soil surface down to a depth well within the saprolite in close proximity to the observation pit at each site. Core samples were collected with a Giddings hydraulic soil probe (Giddings Equipment Co., Fort Collins, CO, USA) using a 3-inch diameter (7.6 cm) soil sampling tube equipped with a 6.5 or 6.6 cm diameter, quick relief cutting head. All cores were wrapped in plastic and transported to the laboratory in long semi-circular trays to maintain an "undisturbed" state as much as possible. Sites labeled Wake and Knightdale in Table 1 were located on developed homesites that had septic systems. Pits could not be dug at these locations, and so disturbed and undisturbed samples were collected by hand near the septic drainfields at both sites.

2.3. In Situ Saturated Hydraulic Conductivity

Due to variations in soil horizon boundaries, in situ saturated hydraulic conductivity (K_{sat}) was measured at predetermined depth intervals associated with different horizons around the observation pit at each site by the constant-head well permeameter technique [18]. Due to the presence of rocks, tree roots, and other constraints preventing the boring of an auger hole, K_{sat} was not measured at all depths/horizons. Moreover, the locations and number of K_{sat} measurements (10 at four sites; 5 at four sites; 2, 4, 7, and 8 at each of the other four sites) were varied among the sites because of the differences in the landscape conditions and soil profile variations. For most cases, the area around the observation pit was divided into 10- by 10-m square areas, and one measurement for each of the selected depth interval/horizon was conducted within each of these areas. The Compact Constant Head Permeameter [19] was used to measure the steady-state flow rate of water (Q) under about 15 cm of water head (H) in a 6 cm diameter (r = 3 cm) auger hole dug to the desired depth. The Glover equation [20] was used to calculate K_{sat}.

2.4. Laboratory Analyses

The saprolite cores collected in the field were inspected in the laboratory, and any intact section longer than 8 cm was coated with paraffin to enable handling [21]. The cores were then cut into sections ranging from 7 to 10 cm in length for water retention measurements. Each core was wrapped with two layers of duct tape and again coated with paraffin to secure the material.

2.4.1. Soil Water Retention

Each core was placed in a Buchner funnel fitted with a porous plate and saturated from the bottom to the top to eliminate entrapped air. After saturation, excess water from around the core in the Buchner funnel was removed, and a positive air pressure equal to 5 kPa (equivalent to −50 cm of soil water pressure head) was applied to the funnel [22]. The pressure was maintained for at least 24 h before the total outflow was measured. The air pressure in the funnel was then increased to 10 kPa (equivalent to −100 cm of soil water pressure head), and the outflow was measured at least 24 h later. This step was repeated consecutively after increasing the air pressure in the funnel to 20 and 30 kPa (−200 and −300 cm of soil water pressure heads, respectively). At the end of the measurement, the core was removed from the funnel, and its total mass was determined immediately. To determine the water content of each core, the paraffin and duct tape cover of the sample was removed and cleaned of saprolite material. The weight of the cover was subsequently subtracted from the mass of the total core to obtain the mass of the wet saprolite at the end of water-retention measurement. All saprolite materials from the cores were then placed in an oven and dried at 105 to 110 °C for 24 h. After determining the mass of dry saprolite, the water content at each level of water pressure (i.e., pressure level applied to the funnel) was calculated using the volume of water drained from the core after each pressure increment and the amount of water retained by the core at the end of the measurement. These data were then used to determined θ_{-300} for each saprolite core.

2.4.2. Other Properties

The disturbed soil samples collected from the horizons in the pits were used for particle size distribution and chemical analyses. These materials were air-dried, crushed, and passed through a 2-mm (No. 10) sieve. Particle size distribution was determined by the pipet method [23] using 10 to 20 g of the air-dried specimen. Each specimen was first treated with 30% H_2O_2 and heated in a constant temperature bath to remove its organic matter. The mineral particles were then passed through a 300 mesh (0.05 mm) sieve into a 1000 mL cylinder. The sand portion that was retained by the 300 mesh sieve was oven-dried at 105 to 110 °C and fractionated by dry-sieving through a nest of sieves. The silt and clay fractions were determined by sampling the suspension in the 1000 mL cylinder using a 25 mL pipet [23]. The cation exchange capacity (CEC) for each of the disturbed saprolite samples collected from each pit was determined at pH 7 using a procedure for acid soils [24].

Regression analyses were performed to assess the relationships between selected saprolite properties and the calculated saprolite thickness for removing *E. coli* using R-Studio's (lm) function (R Studio, Boston MA) for general linear models. Variables in the regression models that had significance values of 0.05 or less were included here.

3. Results and Discussion

3.1. Saprolite Properties

Selected properties of the saprolites studied are shown in Table 2. The sites are listed in increasing estimated thickness of saprolite below septic drainlines needed to remove *E. coli* from wastewater. Three saprolite horizons were included for Site 5, which had a thick saprolite zone, bringing the total number of samples to 14 for the 12 sites overall. Due to the differing thicknesses in the overlying soil, the depths of saprolite ranged from 50 to 395 cm across sites. Textures ranged from sand to clay loam, and clay percentages ranged from 2 to 30%. In situ K_{sat} values ranged from 0.7 cm/d (highest clay percentage) to 233 cm/d (highest sand percentage). However, on average, the sites had K_{sat} values < 10 cm/d.

Table 2. Selected properties for saprolites studied and estimated thickness of saprolite needed to filter *E. coli* from wastewater using Equation (3). Correlation coefficients show relationship between a property and estimated saprolite thickness.

Site No.	Depth Range	Sand	Silt	Clay	TEXTURAL CLASS	In Situ K_{sat}	Cation Exchange Capacity	No. of Cores	Volume of Pores $\leq$ 10 μm Diam. ††	Estimated Saprolite Thickness for OSWMS
	cm		———%——-			cm/d	$cmol^+/kg$		cm^3/cm^3	cm
Wake	95–120	44	26	30	Clay loam	0.7 †	4	19	0.47 ± 0.08	36
9	185–255	57	21	22	Sandy clay loam	21	1	22	0.38 ± 0.09	45
5-C1	80–142	79	14	7	Loamy sand	3	6	14	0.37 ± 0.08	46
5-C3	125–200	83	15	2	"	6	6	10	0.37 ± 0.15	46
12	76–90	73	23	4	Sandy loam	13	1	14	0.36 ± 0.08	47
8	370–395	66	28	6	"	41	29	11	0.34 ± 0.08	50
6	135–200	73	21	6	"	69	2	9	0.33 ± 0.05	52
3	60–90	79	16	5	Loamy sand	7	9	15	0.32 ± 0.05	53
2	195–210	62	28	10	Sandy loam	77	3	15	0.31 ± 0.06	55
1	115–210	68	27	5	"	27	11	8	0.28 ± 0.10	61
5-C4	200–246	87	11	2	Sand	-	6	2	0.25 ± ND	68
7	50–150	87	8	5	Loamy sand	9	9	6	0.25 ± 0.11	68
Knight.	115–135	77	16	7	"	5	2	21	0.23 ± 0.06	74
10	135–200	91	4	5	Sand	233	1	15	0.15 ± 0.06	113
r values		0.63 *	−0.66 *	−0.40	–	0.80 *	−0.16	–	0.93 *	1.0

† Geometric mean, number of measurements made per site ranged from 2 to 11 with a mean of 6. †† Mean ± standard deviation. * Indicates *r* value is significant at the 0.05 level.

Cation exchange capacities were generally low (<10 $cmol^+/kg$ (Table 2)), suggesting that physical filtration is the major factor in the removal of *E. coli* rather than adsorption of *E. coli* onto the negatively-charged mineral particles. Madumathi [25] conducted batch sorption experiments to understand the attachment kinetics of bacteria in the presence of humic acid and clay colloids. Results indicated that the adsorption of bacteria onto porous media was enhanced by the presence of high surface area and high cation exchange capacity clay-textured soil, unlike the materials studied here.

The number of cores analyzed for water retention (for θ_{-300} calculations) at each site varied from 2 to 22 (Table 2) and depended, in part, on how efficiently the Giddings hydraulic probe collected material. For example, saprolite with a relatively high clay content tended to remain intact in the sampling tube, allowing for more cores to be obtained from the extracted materials. The volume of pores having diameters $\leq$10 μm ranged from 0.15 to 0.47 cm^3/cm^3 across the sites. The differences were related to saprolite texture, with the site with the most silt and clay having the largest volume of pores with diameters $\leq$10 μm, and the site with the greatest sand percentage having the lowest amount of such pores (Table 2).

3.2. Effective Thickness of Saprolite

The thicknesses of saprolite below septic drainlines that would be needed to filter *E. coli* from wastewater were estimated using the mean values of the pore volume measurements. Thicknesses ranged from 36 to 113 cm and had a mean value of 58 cm across all sites (Table 2). The largest thickness (113 cm) was found for a saprolite consisting of coarse sand with only 4% silt and 5% clay. Coarse sands have a majority of the sand grains in the 0.5 to 1.0 mm diameter class. These particles form relatively large packing pores that *E. coli* would move through without filtration.

While pore size distribution (from water retention analyses) was used to estimate the saprolite thicknesses needed to filter *E. coli* from wastewater, such measurements are time-consuming and expensive to conduct. Using other measures related to pore size to estimate the saprolite thicknesses would be more convenient for field personnel to use. As shown in Table 2, saprolite thicknesses for OSWMSs that were **<** 60 cm had textural classes of loamy sand, sandy loam, and clay loam. Saprolite thicknesses between 68 and 74 cm had textural classes of sand and loamy sand. Despite the apparent relationship between texture and thickness of saprolite for removing *E. coli*, using textural class alone to determine saprolite thickness in the field may not produce a reasonable value because loamy sand textures showed a broad range in saprolite thicknesses. Correlation coefficients were used to identify other properties that could be used to estimate saprolite thickness (Table 2). Percentages of silt and sand, along with K_{sat}, had significant r values as shown.

Regression equations relating silt and sand percentages along with K_{sat} to saprolite thickness are shown in Figure 2. A quadratic relationship between the thickness of saprolite and silt percentage had an R^2 of 0.74 (Figure 2A). Silts are defined as particles having diameters between 2 to 50 μm. Fine silts (2 to 10 μm diam.) are close to the size of *E. coli* and should form packing pores that can filter the organism out of wastewater. Saprolite materials with silt percentages <16% were generally estimated to require >60 cm thickness to filter *E. coli* (Figure 2A).

A linear relationship was found between sand percentage and saprolite thickness (Figure 2B). The sand relationship contained two samples (site 5′s C4 horizon and site 7, Table 2) with identical values for sand percentage and saprolite thickness, so only 13 data points appear in Figure 2B. A linear relationship was used because quadratic terms were found to be insignificant (i.e., p values >0.05). The R^2 value for the sand relationship was lower than the R^2 value found for the silt relationship (Figure 2A). Sand may not be as effective a filter for *E. coli* as silt. The size of sand particles range between 0.050 mm (very fine sand) to 2.00 mm for very coarse sand. Pores between the larger sand particles may be too large to filter *E. coli*. Finer sands would form smaller pores than the larger fractions and aid in the filtration of *E. coli*.

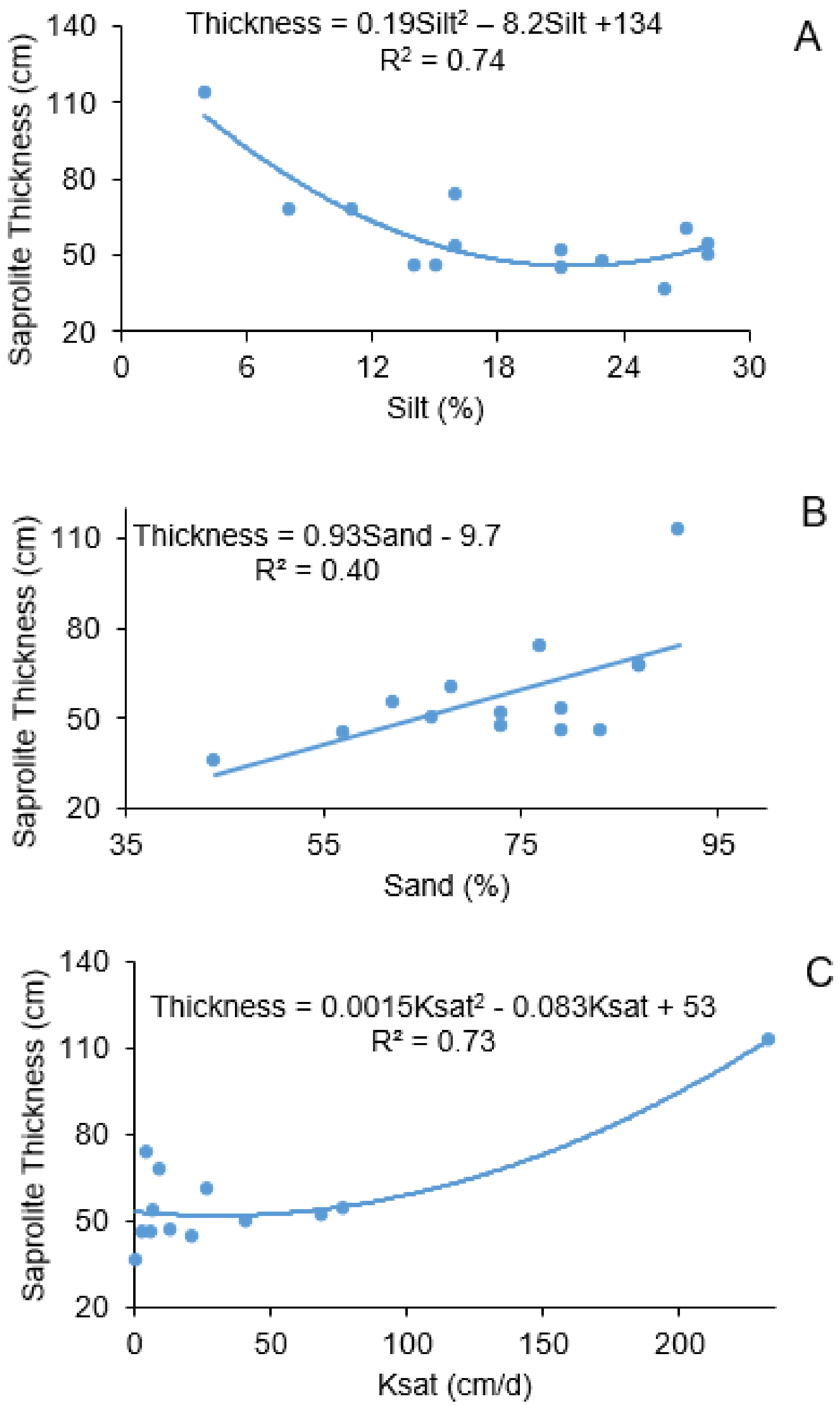

Figure 2. Relationships between (**A**) silt percentage, (**B**) sand percentage, and (**C**) saturated hydraulic conductivity (K_{sat}) and saprolite thickness needed to filter *E. coli.*

The relationship between saprolite thickness and K_{sat} is shown in Figure 2C. Thirteen values are reported because Site 5′s C4 horizon did not have an in situ K_{sat} measured. The quadratic (nonlinear) relationship shown in Figure 2C was significant with a relatively high R^2 of 0.73. The high R^2 was due in large part to one high K_{sat} value (233 cm/d) as shown for site 10. Without considering site 10, there was no significant relationship between in situ measured K_{sat} and thickness of saprolite needed for removing *E. coli*. Based on the data presented in Figure 2C, in situ K_{sat} measurements do not provide any reasonable estimates of saprolite thickness needed to filter *E. coli*. We should note that in general, we expect saturated hydraulic conductivity to vary with particle size distribution, with finer textured materials producing smaller K_{sat} values, but root channels and other macropores may also be present, which could increase K_{sat} by by-passing the pores created by the packing of sand or silt grains.

While Equation (3) was developed for saprolites, it may be applicable to some soils that do not possess a strong soil structure. For example, using the water-retention data for the sandy loam soil material reported by Stall et al. [13], we estimated the material would require approximately 212 cm of soil thickness to filter *E. coli*. Nevertheless, experimental data showed that 60 cm would more than enough. However, the sandy loam of Stall et al. [13] had a silt content of 30%, and when using the regression line in Figure 2A, a saprolite thickness of 59 cm would be predicted to be sufficient to remove *E. coli* for this percentage of silt. This is in line with the experimental results of Stall et al. [13]. The 212 cm thickness value is approximately three times the thickness we computed for the coarse sand texture. The sandy loam material used by Stall et al. [13] was dried and passed through a 2-mm-mesh sieve before packing into cylinders for the experiments. Because water retention was determined using repacked cores, it is likely that the water retention results did not take into account all pores within the soil's aggregates formed by sieving. On the other hand, the water retention data for the saprolites used in our assessment were obtained using intact cores of non-aggregated saprolite. Non-aggregated materials consist mainly of interparticle pores (i.e., pores between mineral grains), and their volumes are more directly assessed in the water retention measurement procedure.

4. Summary and Conclusions

We developed and used an equation to estimate the thickness of saprolite needed to filter *E. coli* from wastewater below septic drainlines at 12 field sites. The equation computed the minimum volume of pores < 10 μm, which were small enough to filter *E. coli*. The equation was derived from results of prior experiments with saprolite columns, which used simulated wastewater having an *E. coli* concentration of 1×10^5 CFU/100 mL. The saprolite textures evaluated from the 12 sites ranged from coarse sand to clay loam, with most being sandy loam. The estimated thicknesses of saprolite needed to filter *E. coli* ranged from 35 to 113 cm with a mean of 58 cm. In general, the silt percentage was the best saprolite property to use to estimate in the field the thickness of saprolite required for safe wastewater disposal. Saprolite thickness estimates increased as silt percentage decreased. These estimates pertain to non-aggregated material such as saprolite and may not apply to aggregated (i.e., well structured) soils. The results of this study show that water retention measurements can be used for assessments of the thickness of porous materials needed to filter bacteria such as *E. coli* from wastewater. More work in the area of wastewater treatment by saprolite is needed to verify the findings of this study under field conditions, particularly for the very sandy saprolites.

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