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Shaking Speed and Depth Effects on Wet-Sieved Aggregate Stability under Arable, Cocoa and Oil Palm Soils

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Abstract

Soil aggregate stability, a key indicator of structural quality, is commonly assessed by wet sieving, yet the shaking speed applied is rarely standardized for tropical soils. This study evaluated wet-sieved aggregate stability of soils under arable, cocoa and oil palm land use at two depths (0 - 15 and 15 - 30 cm) on the Kumasi Series, Ghana, testing whether 30, 40 and 60 revolutions per minute (rpm) produced values statistically comparable to the conventional 50 rpm standard. Composite samples were analyzed for particle size, bulk density, organic carbon, pH, available phosphorus, exchangeable bases and porosity, and aggregate stability was determined by the modified Kemper and Rosenau (1986) method at each speed. Stability was higher in topsoils (95.9% - 98.5%) than subsoils (92.3% - 97.5%) and declined progressively with increasing rpm. Paired t-tests showed that 30 and 40 rpm did not differ from the 50-rpm standard on the sandier arable and cocoa topsoils, whereas 60 rpm produced significant departures on most soils, particularly the oil palm topsoil ($t = 26.0$, $P = 0.0015$). Stability correlated positively with organic carbon and negatively with exchangeable sodium, higher in the clay-enriched subsoils. Lower shaking speeds (30 - 40 rpm) are adequate substitutes for the 50-rpm standard on sandy topsoils, whereas clay-rich soils require the higher speed to fully express aggregate breakdown; shaking speed should be reported explicitly when comparing aggregate stability data across tropical soil studies.

Subject Areas

Agricultural Science

Keywords

Aggregate Stability, Revolutions Per Minute, Soil Organic Carbon, Tropical Soil, Wet Sieving

1. Introduction

A soil aggregate is a group of primary soil particles that cohere to one another more strongly than to surrounding particles [1], and aggregate stability describes the capacity of these aggregates to resist degradation when subjected to disruptive forces. Stability depends jointly on the strength of the binding forces holding particles together and the magnitude of the stresses applied to break them apart [2], and it is widely used as an indicator of soil structural condition and degradation risk [3]. Because good soil structure underpins infiltration, aeration, root growth and resistance to erosion, maintaining high aggregate stability is central to sustainable land management [2].

Among the available techniques, wet sieving is the most widely used approach for quantifying aggregate stability, as it mimics the slaking and mechanical disruption that aggregates experience under rainfall and irrigation [2] [4] [5]. The method rests on the principle that weakly bound aggregates disintegrate more readily than well-cemented ones when immersed and agitated in water [4], and the mean weight diameter of the remaining aggregates is commonly used to express the outcome [2]. However, because the disruptive procedure used across studies is standardized in protocol but not in the amount of mechanical energy applied, values obtained by grinding, sieving or shaking are difficult to compare directly between laboratories [2] [6]. Shaking speed, conventionally set at around 50 revolutions per minute (rpm) in many published protocols, is one of the parameters most likely to influence the apparent stability recorded, yet it is seldom varied systematically or validated against alternative speeds, particularly for tropical soils under mixed land use.

Aggregate breakdown during wet sieving is governed by several interacting mechanisms, including slaking from compressed entrapped air, differential swelling, raindrop or splash impact, and physico-chemical dispersion driven by osmotic stress [7]. The relative importance of these mechanisms, and therefore the sensitivity of measured stability to shaking speed, is expected to vary with soil texture, organic matter content and exchangeable sodium, all of which differ markedly between cultivated land uses and with depth [8] [9]. Soils with a higher proportion of sand and lower clay and organic matter, such as many surface soils under continuous cultivation, may disperse more readily at higher shaking speeds, whereas more clay-rich subsoils may require greater mechanical energy before comparable disruption is observed.

This study therefore examined how shaking speed and soil depth jointly influence wet-sieved aggregate stability of soils under three common land uses, arable cropping, cocoa and oil palm, on the Kumasi Series in Ghana. The specific objective was to evaluate soil aggregate stability by the wet-sieving method at four shaking speeds (30, 40, 50 and 60 rpm) and to determine whether the values obtained at 30, 40 and 60 rpm differ significantly from those obtained at the conventional 50 rpm standard, with a view to identifying whether lower, less energy-intensive shaking speeds can substitute for the standard speed on specific soil types.

2. Materials and Methods

2.1. Study Site

The study was conducted using soils from the Crop Plantation Section of the Department of Crop and Soil Sciences, Faculty of Agriculture, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. The site lies within the semi-deciduous rainforest agro-ecological zone, which experiences a bimodal rainfall pattern comprising a major season from March to July (interrupted by a short dry spell in August) and a minor season from September to October, with mean annual rainfall of approximately 1375 mm and annual temperatures ranging from 25˚C to 35˚C. The soils belong to the Kumasi Series, a well-drained, loamy-sand-textured soil that is generally easy to cultivate.

2.2. Soil Sampling

Three independent composite soil samples were obtained for each land-use × depth combination and used as field replicates. Each replicate was subjected to all four shaking-speed treatments. For each independent composite sample, fifteen (15) subsamples were collected per plot and depth and bulked to form the composite sample, with the sampling intensity falling within the recommended range of 10 - 20 sampling points per hectare [10]. Samples were air-dried and passed through 4 mm and 2 mm sieves (4 mm placed above the 2 mm sieve) before being transported to the Soil Science Laboratory of the Faculty of Agriculture, KNUST, for physicochemical and aggregate stability analyses.

2.3. Soil Physical and Chemical Analysis

Particle size distribution was determined by the hydrometer method [11], chosen because it permits non-destructive, repeated measurement on the same settling suspension. Dry bulk density was determined from intact soil cores collected in the field with a core sampler [11], and total porosity was subsequently calculated from bulk density assuming a particle density of 2.65 $g \cdot cm^{-3}$. Soil organic carbon was determined by the modified Walkley-Black dichromate digestion method [12], and soil pH was measured in a 1:2.5 soil-to-water suspension using a pH meter. Available phosphorus was extracted with the Bray No. 1 ($HCl:NH_4F$) procedure [13] [14] and quantified spectrophotometrically by the ammonium molybdate blue method with ascorbic acid as the reducing agent. Exchangeable calcium, magnesium, potassium and sodium were extracted with 1.0 M ammonium acetate; calcium and magnesium were determined by titrimetric and potassium and sodium by flame photometry.

2.4. Aggregate Stability Determination

Wet-sieved aggregate stability was determined for each land use and depth using the modified Kemper and Rosenau [15] method. Air-dried aggregates in the 2 - 4 mm size range were prepared, and 20 g sub-samples were placed on a 0.25 mm sieve and pre-wetted with an atomizer spray to minimize slaking shock prior to

immersion. The sieves were mounted on an orbital (Eijkelkamp-type) wet-sieving shaker and subjected to orbital motion with a stroke length of 13 mm for 30 minutes at each of the four speeds (30, 40, 50, and 60 rpm), with the aggregates kept fully submerged throughout. After sieving, the material retained on each sieve was oven-dried at 105˚C for 24 hours to constant mass (M). A parallel 20 g sub-sample was oven-dried directly at 105˚C for 24 hours to constant mass to provide the reference dry mass. Aggregate stability was expressed as the percentage ratio of the wet-sieved, oven-dried mass to the reference oven-dried mass. The 50-rpm treatment served as the conventional standard against which the 30, 40 and 60 rpm treatments were compared.

2.5. Statistical Analysis

For each land-use × depth combination, three independent field replicates were analyzed. Aggregate stability at 30, 40, and 60 rpm was individually compared with the 50-rpm reference using two-tailed paired-samples t-tests (n = 3 paired observations; df = 2; critical t at P = 0.05 = 4.303). For each land-use × depth combination, the observation at each test speed was paired with the observation from the same field replicate at 50 rpm. Thus, the pairing controlled for variation among field replicates, while the 50-rpm measurement served as the within-replicate reference. Relationships between soil physicochemical properties (organic carbon, exchangeable sodium) and aggregate stability were examined descriptively. Statistical computations were performed with GraphPad Prism software.

3. Results and Discussion

3.1. Soil Physicochemical Properties

Topsoils (0 - 15 cm) were texturally sandy loam (arable) to loamy sand (cocoa and oil palm), while all three subsoils (15 - 30 cm) were sandy loam, indicating a higher clay content at depth than at the surface across all three land uses (**Table 1**). Soil pH was moderately acidic throughout, ranging from 4.94 to 5.45. Organic carbon ranged from 0.69% to 0.86% in the topsoils and was consistently lower in the subsoils (0.69% - 0.86%), consistent with the concentration of plant litter and root inputs near the surface. Exchangeable sodium, in contrast, tended to be higher in the subsoils relative to the topsoils (**Table 1**).

Organic carbon showed a positive association with aggregate stability across land uses and depths, consistent with the well-established role of organic binding agents produced during litter and root decomposition in cementing soil particles together [8] [16] [17]. Exchangeable sodium, which was more concentrated in the subsoils, is associated with the opposite effect: sodium promotes clay dispersion and thereby weakens inter-particle cohesion [9]. These two contrasting influences, organic-matter-driven cementation at the surface and sodium-driven dispersion at depth, provide a plausible explanation for the depth-related pattern in aggregate stability described below.

Table 1. Physical and chemical properties of soils under three land use at two depths.

Depth (cm)	Property	Arable	Cocoa	Oil palm
0 - 15	Texture	Sandy loam	Loamy sand	Loamy sand
0 - 15	pH (1:2.5)	5.33	5.45	4.95
0 - 15	Bulk density ($g \cdot cm^{-3}$)	1.57	1.60	1.57
0 - 15	Organic carbon (%)	0.86	1.31	1.11
0 - 15	Sodium ($cmol \cdot kg^{-1}$)	0.24	0.20	0.19
0 - 15	Calcium ($cmol \cdot kg^{-1}$)	5.00	6.80	3.80
0 - 15	Phosphorus ($mg \cdot kg^{-1}$)	5.74	2.63	3.94
0 - 15	Magnesium ($cmol \cdot kg^{-1}$)	1.20	2.40	1.00
0 - 15	Potassium ($cmol \cdot kg^{-1}$)	0.17	0.11	0.23
0 - 15	Total porosity (%)	41	40	41
15 - 30	Texture	Sandy loam	Sandy loam	Sandy loam
15 - 30	pH (1:2.5)	5.09	4.94	4.96
15 - 30	Bulk density ($g \cdot cm^{-3}$)	1.56	1.54	1.48
15 - 30	Organic carbon (%)	0.69	0.73	0.86
15 - 30	Sodium ($cmol \cdot kg^{-1}$)	0.25	0.21	0.23
15 - 30	Calcium ($cmol \cdot kg^{-1}$)	3.80	3.00	2.00
15 - 30	Phosphorus ($mg \cdot kg^{-1}$)	3.49	2.19	2.63
15 - 30	Magnesium ($cmol \cdot kg^{-1}$)	0.40	0.80	0.20
15 - 30	Potassium ($cmol \cdot kg^{-1}$)	0.14	0.08	0.07
15 - 30	Total porosity (%)	41	42	44

3.2. Aggregate Stability at Different Shaking Speeds

Aggregate stability declined progressively as shaking speed increased from 30 to 60 rpm for every land use and depth combination (Table 2), reflecting the greater mechanical disruptive energy delivered to the aggregates at higher speeds. Averaged across speeds, top-soil aggregate stability (95.9% - 98.5%) exceeded subsoil aggregate stability (92.3% - 97.5%) in every case, and arable soils were consistently more stable than cocoa and oil palm soils. The higher stability of the topsoils is consistent with their greater organic carbon content and lower exchangeable sodium relative to the subsoils, while the comparatively higher stability of the arable soil may reflect differences in root architecture, litter inputs and historical management between the three land uses.

The consistent decline in stability with increasing rpm across all soils confirms that shaking speed is not a neutral methodological choice: it determines the amount of disaggregating energy delivered during wet sieving and therefore directly affects the stability value obtained, in line with the general observation that disruptive procedures in aggregate analysis are standardized in protocol but not in the force actually applied [2] [6].

Table 2. Wet-sieved aggregate stability (%) of soils under three land uses at four shaking speeds and two depths.

rpm	Arable 0 - 15	Arable 15 - 30	Cocoa 0 - 15	Cocoa 15 - 30	Oil palm 0 - 15	Oil palm 15 - 30
30	98.5	97.5	97.6	95.2	97.7	96.0
40	98.2	97.1	97.5	94.2	97.3	95.6
50 (standard)	97.6	96.7	97.4	93.7	96.8	95.4
60	96.8	95.7	96.8	92.3	95.9	95.2

3.3. Comparison of Shaking Speeds with the 50-rpm Standard

Paired t-tests comparing aggregate stability at 30, 40 and 60 rpm against the 50-rpm standard (Table 3 and Table 4) showed that the outcome depended on both land use and depth. At 0 - 15 cm, aggregate stability at 30 and 40 rpm did not differ significantly ($P > 0.05$) from the 50-rpm standard on the arable and cocoa soils, whereas the oil palm topsoil showed significant differences at both 30 rpm ($t = 5.90$, $P = 0.028$) and 40 rpm ($t = 8.70$, $P = 0.013$). At 60 rpm, the cocoa ($t = 7.20$, $P = 0.019$) and oil palm ($t = 26.0$, $P = 0.0015$) topsoils differed significantly from the standard, while the arable topsoil did not ($t = 3.20$, $P = 0.086$).

At 15 - 30 cm (Table 4), the picture reversed: 30 rpm differed significantly from the standard on all three land uses (arable $t = 6.30$, $P = 0.025$; cocoa $t = 7.70$, $P = 0.016$; oil palm $t = 20.0$, $P = 0.0025$), while 40 rpm did not differ significantly on arable ($t = 2.10$, $P = 0.166$) or oil palm ($t = 0.62$, $P = 0.597$) subsoils, though it did on the cocoa subsoil ($t = 5.20$, $P = 0.035$). At 60 rpm, the arable ($t = 4.50$, $P = 0.046$) and cocoa ($t = 5.90$, $P = 0.028$) subsoils differed significantly from the standard, whereas the oil palm subsoil did not ($t = 1.30$, $P = 0.319$).

Table 3. Paired t-test comparison of aggregate stability (%) at test shaking speeds versus the 50-rpm standard, 0 - 15 cm depth (df = 2; critical t = 4.303 at P = 0.05).

Land use	revolutions per minute (rpm)	Mean difference (%)	t	P	Sig.
Arable	30	+0.90	3.60	0.070	-
Arable	40	+0.60	2.90	0.101	-
Arable	60	−0.80	3.20	0.086	-
Cocoa	30	+0.20	0.76	0.529	-
Cocoa	40	+0.10	0.50	0.667	-
Cocoa	60	−0.60	7.20	0.019	*
Oil palm	30	+0.90	5.90	0.028	*
Oil palm	40	+0.50	8.70	0.013	*
Oil palm	60	−0.90	26.0	0.0015	**

- = Not significant; * = Significant at $P < 0.05$; ** = Significant at $P < 0.01$.

Table 4. Paired t-test comparison of aggregate stability (%) at test shaking speeds versus the 50-rpm standard, 15 - 30 cm depth (df = 2; critical t = 4.303 at P = 0.05).

Land use	revolutions per minute (rpm)	Mean difference (%)	t	P	Sig.
Arable	30	+0.80	6.30	0.025	*
Arable	40	+0.40	2.10	0.171	-
Arable	60	−1.00	4.50	0.046	*
Cocoa	30	+1.50	7.70	0.016	*
Cocoa	40	+0.50	5.20	0.035	*
Cocoa	60	−1.40	5.90	0.028	*
Oil palm	30	+0.60	20.0	0.0025	**
Oil palm	40	+0.20	0.62	0.597	-
Oil palm	60	−0.20	1.30	0.323	-

- = Not significant; * = Significant at P < 0.05; ** = Significant at P < 0.01.

Overall, 30 and 40 rpm were not significantly different from the 50-rpm standard on the sandier topsoils (arable and cocoa), where lower clay content and higher organic carbon meant that even a reduced shaking speed was sufficient to disrupt the weaker aggregates present. On the more clay-enriched subsoils, 30 rpm generally differed from the 50-rpm standard, whereas the response at 40 and 60 rpm varied among land uses. This pattern is consistent with the observation that higher shaking speeds cause greater dispersion on sandy soils than on clayey soils [18] [19], and it suggests that a single fixed shaking speed may not be equally appropriate across soils that differ substantially in texture, organic carbon and sodium status.

4. Conclusions and Recommendations

Wet-sieved aggregate stability of soils under arable, cocoa and oil palm land use on the Kumasi Series declined consistently with increasing shaking speed and was higher in topsoils than subsoils, patterns attributable to the combined influence of soil organic carbon, which promotes aggregate cementation, and exchangeable sodium, which promotes dispersion and was more concentrated in the clay-enriched subsoils. Shaking speeds of 30 and 40 rpm produced aggregate stability values statistically equivalent to the conventional 50 rpm standard on the sandier topsoils, indicating that these lower, less energy-intensive speeds can be used as adequate substitutes for the standard when assessing aggregate stability on such soils. In subsoils, the suitability of alternative shaking speeds varied among land uses, with 30 rpm generally differing from the 50-rpm standard, while 40 and 60 rpm produced land-use-specific responses. These findings indicate that shaking speed should be selected with reference to soil texture and reported explicitly in aggregate stability studies, since a speed that is appropriate for one soil type may under- or over-estimate stability on another.

Recommendations

- Organic matter amendments should be prioritized on soils with low aggregate stability, as they enhance inter-particle cohesion and reduce susceptibility to structural breakdown.
- A lower shaking speed (30 - 40 rpm) is recommended for routine aggregate stability assessment of sandy topsoils, for clay-enriched subsoils, the 50-rpm standard should be retained unless alternative speeds have been validated for the specific soil and land-use condition.
- Soil sampling for aggregate stability studies should be planned to capture temporal variation, since important soil attributes can change from season to season and year to year.
- Further studies are recommended across a wider range of soil types and depths beyond 30 cm to more fully characterize the effect of shaking speed on aggregate stability.

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Author Contributions

Joseph Asare: Conceptualization, Investigation, Methodology, Data analysis, Writing original draft. Hope Setsoafia Kwabena Dimakor: Conceptualization, Data Analysis and Synchronization, Writing review & editing. Philip Kwaku Kokonu & Seth Ofori: Conceptualization, Writing review & editing.

Conflicts of Interest

The authors declare no conflicts of interest.

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