Research article

Revisiting soil texture analysis: Practices towards a more accurate Bouyoucos method

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HIGHLIGHTS

- Use of 10% Calgon as the dispersant increased accuracy.
- Use of 100% H_2O_2 to remove soil organic matter increased accuracy.
- Shaking and temperature corrections improved estimation accuracy.

GRAPHICAL ABSTRACT
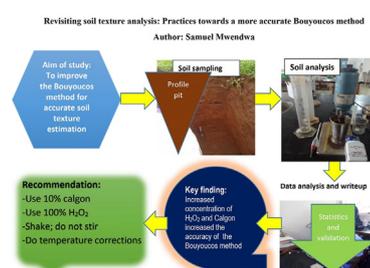
ABSTRACT

The Bouyoucos method lacks sample pre-treatment whereby samples are dispersed for only 2 min after being soaked in 5% sodium hexametaphosphate (calgon) for 15–20 h. This study aimed to improve the accuracy of the Bouyoucos (Hydrometer) method of particle size analysis by proposing the best sample pre-treatment and analysis practices. The Pipette method was used as standard reference due to its precision and reproducibility. Treatments modified from the hydrometer method were compared with the Pipette method through Pearson's correlation. The treatments involved variation in the concentration of the pre-treating and dispersing material, time of hydrometer readings, method of agitation and that of dispersing. The proposed improvement suits the Food and Agriculture Organization (FAO) and United States Department of Agriculture (USDA) standard 2–50 μm system. Measurements made using the hydrometer variations overestimated the sand fraction in all samples. There was a positive correlation in the clay proportion between the Pipette method and Shaking + Stirring treatment (r = 0.644, p-value = 0.044). Treatments involving shaking instead of stirring, increased concentrations of hydrogen peroxide and calgon estimated the clay proportion with sufficient accuracy. These observations are indicative of the need for soil pre-treatment with hydrogen peroxide to remove organic matter and also the use 10% calgon as a dispersing agent.

1. Introduction

Soil texture plays a vital role in soil degradation and hydrologic transport processes, controlling soil quality and productivity. This paper aims to guide in the analysis of soil texture through modification and simplification of the Bouyoucos method, which is the most commonly used procedure for soil texture analysis (Glendon and Doni, 2002; Van Reeuwijk, 2002). Soil is a basic component of the environment and its

texture is a key aspect of environmental regulation as it determines the movement of pollutants from one area to another. Particle size distribution has become a fundamental parameter in pedological, agronomic and environmental studies therefore its analysis, calculation and interpretation are paramount. It is useful for the characterization of a land's suitability for various agricultural, geotechnical, landscaping and reclamation purposes. Soil texture affects the soils' water and nutrients holding capacities whereby fine textured soils generally have a higher capacity to retain water, whilst sandy soils have more capacity to leach owing to its large pores, soil structure notwithstanding. The texture is not readily subject to change due to farm practices therefore, it is considered a permanent soil attribute (Brady and Weil, 2007). There exists a direct relationship between the particle size distribution and other soil characteristics including the shear induced volume change, porosity, saturated hydraulic conductivity and nutrient retention (Hommel et al., 2018). The USDA Soil Taxonomy and the World Reference Base (WRB) systems of soil classification have 12 textural classes based on percent sand, silt, and clay in the soil (Kettler et al., 2001). The USDA soil textural triangle is used to assign a sample its texture class after calculations. It is worth noting that a Soil Texture Wizard has been appended in R statistical functions to classify and to transform soil texture data. Soil texture can be determined qualitatively by the feel method and quantitatively using a myriad of methods. The Pipette method is precise and reproducible (Arriaga et al., 2006) and some labs use it routinely.

The Bouyoucos method was first invented in the year 1927 (Bouyoucos, 1927) as a method for mechanical analysis of soils. Bouyoucos slightly modified it in 1928 and 1929 then compared it with the Pipette method in 1934. An improved protocol was published in 1936 (Bouyoucos, 1936) before recalibrating the method in 1951 (Bouyoucos, 1951). His final publication (Bouyoucos, 1962) is the procedure used by most research organizations to date. The 1962 dispersing technique consisted of soaking the soils in 5% of calgon overnight or 15–20 h, and dispersing them for 2 min only by the dispersing machine running at a speed of 16000 revolutions per minute.

Different other modifications have been suggested by various researchers aiming to make the hydrometer method more accurate (Gee and Bauder, 1986; Kettler et al., 2001; Ashworth et al., 2001; Coates and Hulse, 2012; Beretta et al., 2014). These modifications revolve around how the soil sample is pre-treated before analysis, concentrations of the dispersing solution and the timing for the first and second hydrometer readings. They expose a limitation with the original Hydrometer method in the light of accuracy and therefore presents the statement of the problem. The Bouyoucos method is based on Stokes's law of sedimentation (Jury and Horton, 2004) which relates the particle size and the rate of sedimentation in a water column. The Stokes's law assumes that fluid flow around a particle is in the creeping or laminar flow regime, that particles are rigid and spherical and that the hydrodynamic interactions among particles in the suspension are neglected. In the hydrometer method, the size of the solids in the suspension is estimated from the density of the solution using the hydrometer. The Pipette method and the Bouyoucos methods differ in pre-treatment of the samples before sedimentation whereby the Pipette method recommends destruction of organic matter using hydrogen peroxide whilst the Bouyoucos method does not consider this pre-treatment (Bouyoucos, 1962). The clay fraction is read after two hours of sedimentation using the Bouyoucos method (Gee and Or, 2002).

The Bouyoucos method uses calgon as a dispersant to separate the soil aggregates. The effectiveness of the calgon is improved by shaking on a mechanical reciprocal shaker or by stirring using a high-speed electric stirrer. A blank having water and the dispersing agent is used to calibrate the hydrometer readings, to correct for variation in solution density and is subtracted from each hydrometer reading. The first reading which represents clay and silt is used to calculate percent sand that has already settled and is taken 40 s after agitation. The second reading is taken after 2 h of settling without agitation and used to calculate percent clay while the silt is calculated from percentages of sand and clay. The use of the

ASTM 152H-Type hydrometer is based on a standard temperature of 68 °F (20 °C) and a particle density of 2.65 gcm^{-3} and units are expressed as grams of soil per liter. The sand fraction may be quantified by sieving the soil sample through a 53μ sieve as suggested by (Gee and Bauder, 1986). Errors in estimates of particle fractions of sample weight can be caused by variation in the amount or type of dispersing chemical used, using suspension volumes other than 1000 ml, using inappropriate reading times, or applying a temperature correction to the hydrometer reading in addition to an actual blank adjustment. The objective of this study was to improve the accuracy of the Bouyoucos method of particle size analysis. This study had hypothesized that the use of 10% Calgon as the dispersant, use of 100% H$_2$O$_2$ to remove soil organic matter, shaking and temperature corrections would improve the estimation accuracy of soil texture particles using the Bouyoucos method.

2. Materials and methods

2.1. Study site

Experiments were done at the University of Nairobi, Upper Kabete Campus, in Soil Physics and Water Management Laboratory. Soil samples were air-dried and passed through a two-millimeter sieve then analyzed under different treatments modified from the Bouyoucos method. Selected samples had been collected from the top, eluvial soil horizons of profile pits opened in Upper Kabete Campus field, and classified as Mollic Nitisols - moNT (WRB); Very fine, mixed, isothermic Oxic Humiustalf (Soil Taxonomy) according to (Mwendwa et al., 2020).

2.2. Treatments

The arrangement was a Complete Randomized Design (CRD) with ten replications per treatment. The ten samples used for each treatment had been carefully sieved to ensure that there was no separation of coarser particles. Unless otherwise specified, samples were digested for 10 days using 35% H$_2$O$_2$ until when no more effervescence could be observed, dispersed with 50ml of 10% calgon, stirred on high-speed electric stirrer for 3 min and inverted to agitate before taking the first hydrometer reading. "Digestion" as used in this study connotes the removal of organic matter using H$_2$O$_2$. Treatment variations are presented in Table 1:

2.3. Lab analysis

The analytical procedure was modified from the methodology adopted by Beretta et al. (2014). Fifty grams of air-dry samples was placed in beakers and successive aliquots of hydrogen peroxide (H$_2$O$_2$) slowly added until effervescence stopped, except for samples digested for 5 days or samples that did not undergo this pre-treatment. The H$_2$O$_2$ was added to remove organic matter from the soil samples which ranged from 4.32 to 6.93% in the selected samples.

The first hydrometer reading was taken after 40 s of agitation while the second reading was taken after 2 h except for one batch where the readings were taken again after 60 s. Temperature readings were taken alongside the hydrometer readings for correction of variation in temperature between the samples and the hydrometer calibration temperature. A blank having water and the dispersing agent was used to calibrate the hydrometer readings. Three drops of pentan-1-ol (amyl alcohol) solution was added to the suspension after agitation to knock off frothing.

2.4. Hydrometer readings correction

The actual blank reading (Br) was made in the dispersing solution (with no soil) at the same temperature as that of the soil suspensions according to Sheldrick and Wang (1993) and Gee and Bauder (1986). A blank sample with water only measured 1 g/L, with 10% calgon measured 5 g/L while with 4% calgon measured 2.5 g/L. These densities are indicative of the importance of taking away blank readings from

Table 1. Treatment variations.

Treatment	Description
1. 10 Days Digestion	Digestion for 10 days. The samples for 10 days digestion were duplicated and subjected to heat after addition of hydrogen peroxide as an observational procedure to test whether heating would accelerate removal of the organic matter by using presence of effervescence as an indicator.
2. 5 Days Digestion	Digestion for 5 days.
3. 40% H_2O_2	Digestion using 40% H_2O_2.
4. 100% H_2O_2	Digestion using 100% H_2O_2. The removal of soil organic matter was according to Jensen et al. (2017).
5. No Digestion	Analysis without pre-treatment with H_2O_2.
6. 4% Calgon	Dispersing using 4% calgon.
7. Shaking	Shaking for 6 h on reciprocating shaker.
8. Shaking + Stirring	Shaking for 6 h on reciprocating shaker and stirring for 3 min on electric stirrer.
9. Plunger	Plunging the samples using one of the selected above treatments with the number of inversions and plunger strokes was maintained constant at 10.
10. 60 s 6 h	40 s versus 60 s for first hydrometer reading and 2 h versus 6 h (60 s 6 h) for the second hydrometer reading were compared using one of the selected above treatments.
11. Pipette	One batch of samples was analyzed for particle size distribution using the Pipette method. The more accurate Pipette method was used as a basis for comparison of the percent sand, silt and clay by the various Bouyoucos treatments through Pearson's correlation in SPSS.

temperature corrected hydrometer readings to increase the accuracy of particle estimates. This observation supports the view that blank-adjusted readings indicate with sufficient accuracy the density D (in gL^{-1}) of suspended solids according to Eq. (1):

$$D = Hr - Br \qquad (1)$$

where: D = Density in gL^{-1}, Hr = Temperature corrected hydrometer reading, Br = Blank reading at the same temperature as the sample.

The practice of subtracting an actual Br from Hr was aimed to offset any discrepancies in environmental conditions between the lab and the hydrometer calibration.

2.5. Temperature corrections

Temperature correction was done in all samples whose temperatures deviated from 20° Celsius (68° Fahrenheit). This is the temperature at which the used ASTM (E100) 152H soil hydrometer has been calibrated at. Similar corrections were also done by Beretta et al. (2014). The temperature corrections were adopted from Okalebo et al. (2002).

2.6. Calculations for the hydrometer method

The percentage proportions of sand, silt and clay in each sample were calculated as follows (Eqs. (2), (3), and (4)): Similar calculations were done by Beretta et al. (2014). The hydrometer reading is a reflection of what is suspended.

$$Percent\ Sand = \left(50 - \frac{H1 - Br}{50}\right) * 100 \qquad (2)$$

$$Percent\ Clay = \frac{H2 - Br}{50} * 100 \qquad (3)$$

$$Percent\ Silt = 100\% - (\%Sand + \%Clay) \qquad (4)$$

where: 50 = Amount of soil sample weighed in grams; $H1$ = Temperature corrected first hydrometer reading after 40 s of agitation and $H2$ =

Temperature corrected second hydrometer reading after 2 h of settling, Br=Temperature corrected blank reading.

2.7. The pipette method

Ten grams of air-dry soil samples that had passed through 2 mm sieve was placed in a beaker and digested using 100% H_2O_2 to remove the organic matter. 50 ml of 10% calgon solution was added into the sample and shaken for 6 h to facilitate the dispersion of individual particles. The suspension was then sieved through a 53µ sieve whereby the retained proportion was washed into a beaker, decanted and oven dried at 105 °C for 24 h, then gravimetrically quantified as sand. The suspension that passed through the sieve and consisted of particles of silt, clay and the dispersant was transferred in a 500 ml measuring cylinder. The sample was agitated by inverting 10 times. A pipette was used to extract 10 ml of the suspension in the upper 10 cm from the surface after 4.5 min, 50 min and 7 h 36 min of settling at suspension temperature of 21 °C. These reading times were sufficient for the aim of this study; they could be read for up to 24 h if the study aimed to characterize the finer fractions. The samples taken by the pipette were transferred to beakers of known weights and oven dried for at 105 °C for 48 h. The samples taken after 7 h and 36 min were containing clay and the dispersing agent only and was calculated according to Eq. (5). This methodology was adopted from Day (1965). It should be recognized that Eq. (5) does not seem to reflect that after the first sample is taken out, both the remaining volume as well as the relative concentration of particle-sizes will change, which is a possible source of error.

$$\frac{\left(\frac{Dry\ weight}{Pipete\ volume}\right) - \left(\frac{Weight\ of\ dispersing\ agent}{Volume\ of\ suspension}\right)}{\left(\frac{Weight\ of\ soil}{Volume\ of\ suspension}\right)} * 100 \qquad (5)$$

where: Dry weight = Oven dry weight of the sample; Pipette volume = 10 ml; Weight of dispersing agent in 500 ml suspension = 0.01 g; Volume of suspension = 500 ml; Weight of soil = 10 g.

2.8. Data analysis

Data analysis was done using Genstat 14th Edition and SPSS. Means were separated using Fischers Protected Least Significant Difference for multiple comparisons. Mean differences within any treatment pairs greater than the LSD was indicative of significant difference between the treatments.

3. Results and discussions

3.1. Sand reading

There was a linear relationship for the batch of 10 samples selected for the Pipette method and samples under Shaking treatment (Table 2). Percent sand in the Pipette method was determined gravimetrically using the particles retained on a 53µ sieve whereas in Shaking treatment, the sand fraction was calculated from blank-adjusted 40-seconds hydrometer readings ($Hr40s$) in 1000 ml suspensions (Equation 2).

Percent sand obtained through the Pipette method significantly correlated with that obtained through Shaking treatment (r = 0.862; p-value = 0.001) and that obtained through Shaking + Stirring (r = 0.737; p-value = 0.015) as shown in Table 2. This observation can be attributed to the extended time of vigorous shaking on a reciprocal shaker that could have completely dispersed the sample into individual aggregates. It is indicative of the importance of careful consideration of the duration and the magnitude of shaking of the soil samples to enhance the action of sodium hexametaphosphate. The sand measurements made using the hydrometer treatments overestimated the sand fraction in the soil samples. This finding is consistent with the observations of Norambuena

Table 2. Means of percent sand and correlation with the Pipette method.

Treatment	Mean	Std. Deviation	Coe. Correl.
Pipette	7.57[a]	2.229	1.000
Shaking + Stirring	33.2[b]	2.86	0.737*
Shaking	34.2[b]	2.741	0.862**
100% H_2O_2	36.8[c]	1.033	0.127
60 s 6 h	38.8[c]	1.033	0.127
Plunger	42.8[d]	1.932	-0.397
40% H_2O_2	43.6[de]	3.098	0.267
10 Days Digestion	44[de]	2.667	-0.366
4% Calgon	45.6[e]	0.843	0.401
No Digestion	48.8[f]	1.033	0.053
5 Days Digestion	54.8[g]	4.638	-0.122

Overall p-value = <0.001

Least Significant Difference (LSD) = 2.126

Where Correl. Coe. = Correlation coefficient (r) with the Pipette method.

[**] Correlation is significant at the 0.01 level (2-tailed).

[*] Correlation is significant at the 0.05 level (2-tailed).

Table 3. Means of percent clay and correlation with the Pipette method.

Treatment	Mean	Std. Deviation	Correl. Coe.
5 Days Digestion	23.2[a]	1.687	0.015
4% Calgon	28.6[b]	2.675	-0.712*
No Digestion	36.4[c]	4.3	-0.234
10 Days Digestion	36.6[c]	4.006	0.482
Plunger	36.6[c]	4.006	0.482
40% H_2O_2	41.8[d]	3.458	0.238
60 sec 6 h	42.4[d]	3.502	-0.081
100% H_2O_2	47.2[e]	3.553	0.589
Shaking	56.6[f]	3.658	0.577
Shaking + Stirring	57.6[f]	3.239	0.644*
Pipette	68.5[g]	4.314	1.000

Overall p-value = <0.001.

Least Significant Difference (LSD) = 2.707.

Where Correl. Coe. = Correlation coefficient (r) with the Pipette method.

[*] Correlation is significant at the 0.05 level (2-tailed).

et al. (2002) and Beretta et al. (2014). Differences in the procedures for destroying soil organic matter and the dispersion of the samples between the Pipette method and the Bouyoucos treatments could have significantly affected the quantity of estimated sand. Therefore, the observed differences can be attributed to variation in analytical procedures. Gee and Or (2002) also reported a similar finding of overestimated sand by the Bouyoucos method compared to the Pipette method. In this study, Bouyoucos treatments overestimated the sand proportion by between 25.63 to 47.23%. This observation is consistent with findings of Norambuena et al. (2002) who reported a 9.69% sand overestimation when estimating the sand proportion in 29 samples from the Andean region using the Bouyoucos method. This observation should, however, be taken with caveats especially when analyzing soils with considerable quantities of concretions. This is because these concretions may be fine enough to pass through a 2-mm sieve and be quantified as sand. This could overestimate the sand fraction and result to a parabolic decrease in the clay proportion. The near 1:1 relationship between Pipette and Shaking treatments (r = 0.862), despite a staggering difference of 26.63% sand, supports the empirical choice of 40 s for the sand reading time. This very high difference in the sand proportions can also signal an error in the methodological approach. Sample agitation can be done through inversion or through plunging as long as the latter does not induce circular movements within the column as this may affect the settling velocity of the sand particles.

3.2. Time of clay reading

Clay content obtained after 6 h (60sec6hrs) was lesser than that taken after 2 h (100% H_2O_2) as shown in Table 3. Using a 6-hour reading could have removed any bias in percentage clay associated with a 2-hour reading as noted by Gee and Bauder (1979). However, taking the second hydrometer reading after 6 h may only be practical for researchers having relatively few samples but impractical for students' demonstration in a lab whereby practical lectures run for at most 3 h using already pre-treated samples or in the case whereby a researcher has many samples. In a real laboratory environment, whereby clients need soil analysis results at close intervals, a 2-hour reading is recommended.

3.3. The clay proportions

The means of percent clay and their correlation with the Pipette method are presented in Table 3. All samples done by the Pipette method were classified as clay with little proportion of sand. In the 100% H_2O_2 treatment, 100% of the samples was also classified as clay. In the 60 s 6 h

treatment, in which 60 s and 6 h represents the time of first and second hydrometer reading respectively, 90% of the samples was classified as clay whilst 10% was clay loam. In the 40% H_2O_2 treatment, 60% of the samples was classified as clay, with 30% being sandy clay and 10% being sandy clay loam. In the 10 Days Digestion treatment with 35% H_2O_2, only 40% of the samples was classified as clay, with the rest being coarser, having 10% clay loam, 20 % sandy clay and 30% sandy clay loam. In 5 Days Digestion treatment, none of the samples was clay, with 100% of the samples classified as sandy clay loam. In the 4% Calgon treatment, none of the samples was clay, with 40% being loam and 60% sandy clay loam. In samples where organic matter was not removed, none of the samples qualified as clay, with 50% being sandy clay loam and 50% qualifying as sandy clay.

There was a positive correlation in the clay proportion between the Pipette method and Shaking + Stirring treatment (r = 0.644, p-value = 0.044). Treatments involving shaking estimated the clay proportion with sufficient accuracy, which can be attributed to enhanced dispersion and conversion of the relatively resistant, moderately coarse and coarse material to finer proportions on complete dispersion. This calls for increase in the amount of time if the samples are stirred instead of shaking and also consideration of the stirrer revolutions per minute (r.p.m) which should be at least 16000. Bouyoucos (1962) suggested the use of a mixer running at a speed of about 16000 r.p.m for 2 min. There was a negative correlation between the clay proportion obtained using the Pipette method and No Digestion treatment (r = -0.234). This finding can be attributed to entanglement of the clay particles by organic matter that could have cemented some clay particles, preventing its breakdown and resulting to clay underestimation. This observation is consistent with the findings of Jensen et al. (2017), who reported underestimation of the clay content in samples where organic matter was not removed. The 4% calgon treatment was negatively correlated with the Pipette method (r = -0.712; p-value = 0.021) which can be attributed to the low concentration of the dispersant that may have led to incomplete dispersion. It is therefore recommended to use 10% sodium hexametaphosphate as the dispersing agent during soil texture analysis. This finding is consistent with the observations of Gee and Bauder (1986) and Jensen et al. (2017), who also reported clay underestimation by the Bouyoucos method. These observations are indicative of the importance of using of hydrogen peroxide to remove organic matter before soil texture analysis. This suggestion can be attributed to the fact that organic matter is a cementing agent that entangles clay particles. Using H_2O_2 is therefore recommended as sample pre-treatment to avoid underestimation of the clay proportion. It also lucidly exposes the need to use 10% instead of 5% calgon proposed in the Bouyoucos procedure. The importance of removal of organic matter was also supported by Jensen et al. (2017).

Norambuena et al. (2002) reported that the Bouyoucos method did not differ from the sieve, even without the destruction of the Soil Organic Matter (SOM) in the samples. Those results can, however, be attributed to very low SOM concentration (<3.44%) in the samples analyzed by the researchers. Day (1965) determined a minor difference in clay content obtained using the Hydrometer method in comparison to that obtained using the Pipette method when the soil samples were pretreated to destroy the soil organic matter. This finding can also explain why samples digested for 5 days underestimated the clay fraction (Table 3). The underestimation of clay can be attributed to incomplete dispersion of soil aggregates. Silt-sized micro-aggregates composed of organic matter-clay complexes could have settled faster and quantified as silt instead of clay. This suggestion is consistent with that of Watts et al. (2000) and Jensen et al. (2017) who suggested a possibility of flocculation after dispersion of samples which would classify as silt.

3.4. The silt fraction

None of the treatments correlated significantly with the pipette method, with the highest correlation observed in the 10 Days Digestion treatment (r = 0.512; p-value = 0.130, Table 4). The means of percent silt obtained through the Pipette method was statistically significant (p-value=<0.001) compared to the Bouyoucos treatments. The silt fraction is, however, determined through calculation using percent clay and sand therefore more emphasis should be put on accurate determination of sand and clay.

Since all the Bouyoucos treatments evaluated in this study estimated the silt concentration as the difference between 100 percent and the sum of percent sand and clay (Equation 4), any analytical errors would impact the estimation of the silt content when determining the latter two fractions. This finding is consistent with the observations of Jensen et al. (2017) who reported that the silt fraction was systematically overestimated when soil organic matter was not removed. The average silt content determined using the Bouyoucos methods was 6.89% (p=<0.001) lesser than that determined using the Pipette method. This observation can mathematically be attributed to overestimation of sand fraction accentuate in the hydrometer method. It is consistent with the findings of Day (1965) who observed a 9.58% silt underestimation when comparing the Bouyoucos method with the Pipette method.

When considering the magnitude of error in the proportions of sand and clay obtained from the hydrometer treatments and those from the standard Pipette method, Shaking + Stirring, Shaking and 100% H2O2 treatments have the least magnitude of error (Tables 2 and 3). Runs involving these three treatments would therefore present the smallest analytical error when compared to the particle size distribution obtained through the Pipette method. The effect of combining these individual treatments was not tested in this study and therefore there is no empirical

Table 4. Means of percent silt and correlation with the Pipette method.

Treatment	Mean	Std. Deviation	Correl. Coe.
Shaking	9.2[a]	2.86	0.279
Shaking + Stirring	9.2[a]	1.687	-0.005
40% H_2O_2	14.6[b]	2.503	0.489
No Digestion	14.8[b]	4.237	-0.221
100% H_2O_2	16[b]	2.981	-0.358
60 s 6 h	18.8[c]	2.86	-0.229
10 Days Digestion	19.4[cd]	3.134	0.512
Plunger	20.6[cd]	3.273	0.511
5 Days Digestion	22[de]	3.651	0.026
Pipette	23.93[ef]	3.751	1.000
4% Calgon	25.8[f]	3.19	-0.435

Overall p-value = <0.001.
Least Significant Difference (LSD) = 2.665.
Where Correl. Coe. = Correlation coefficient (r) with the Pipette method.

data on the combined effects. These observations are consistent with the findings of Beretta et al. (2014) who suggested that the hydrometer can be used instead of the Pipette method only in cases where the pre-treatment of the sample completely destroys the SOM and a total dispersion of the sample is achieved.

3.5. Effects of organic matter removal

Samples digested for longer period of time showed a higher clay content which can be attributed to complete destruction of the clay-cementing organic material leading to release of entangled clay. The concentration of hydrogen peroxide seems to affect the proportions of sand, silt and clay with samples digested using 100% H2O2 having the highest proportion of clay content (Tables 2, 3, and 4). However, using more but lower concentration of peroxide for longer time could have the same effect as using less amount and less time of higher concentration of the peroxide. This also would also depend on the amount of organic matter in the soil. Bouyoucos (1936) and Bouyoucos (1962) suggested that particle size distribution may, for practical purposes, be characterized by analysis done on whole soil and that, if desired, lime and organic matter can be quantified separately. The time of digestion of the sample is also contributing to differences in the proportions of the texture components as shown by the results of 10 Days versus 5 Days Digestion. This can be addressed through heating the sample as effervescence stopped within few minutes by virtue of the kinetic molecular theory of matter. This observation leads to the conclusion that, in the interest of accuracy, samples should be subjected to complete digestion by either increasing days of digestion, increasing the concentration of hydrogen peroxide and/or heating the sample. This finding is consistent with the observations of Jensen et al. (2017) who reported that failure to remove organic matter underestimated the clay proportion. The destruction of organic matter used for Bouyoucos method has been done and published earlier (Beretta et al., 2014). Compared to values obtained from the Pipette method, 100% hydrogen peroxide is recommended. Results of this study show that the destruction of organic matter should be complete to avoid underestimation of the clay proportion.

3.6. Textural classification

Particle size distribution was reported as percentages of the mineral fraction namely the percent sand, silt and clay. Soil texture was based on the USDA textural triangle which can be done manually or online.

4. Conclusions

The current study helped to make recommendations on the best practices to improve the Bouyoucos method as the experiments worked well to address the objective of the study. The hypothesis for this study was confirmed as the use of 10% Calgon as the dispersant, use of 100% H2O2 to remove soil organic matter, shaking and temperature corrections improved the estimation accuracy. Errors in estimates of particle fractions can be caused by variation in the amount or type of dispersing chemical used, using suspension volumes other than 1000 ml, using inappropriate reading times, or applying a temperature correction to the hydrometer reading in addition to an actual blank adjustment. Temperature readings should be undertaken alongside blank correction to avoid discrepancies that may be caused by differences in settling due to temperatures different from hydrometer calibration league of 68ºF (20 °C). This is because based on the kinetic theory, higher temperatures would favor faster settling while lower temperatures would lower the settling velocity of particles. Digestion can take significantly less time if the concentration of hydrogen peroxide is increased, if the sample is heated or if the samples are coarser than clay by the feel method. Hydrometer readings should be done as accurately as possible because for example when estimating the clay content, having used 50 g of soil, an error of ±1 g/L hydrometer reading would result to an error of ±2% clay (Equation

3). Further studies may aim to compare the effectiveness of sodium hexametaphosphate against other dispersants, the effect of using larger sample and using more dispersing solution. Based on results, SOM should be destroyed using 100% H_2O_2 until effervescence stops, the sample dispersed with 10% sodium hexametaphosphate, shaken in a reciprocal shaker for 6 h and inverted 10 times for agitation. The action of H_2O_2 can be accelerated by heating the samples to save on time of analysis.

Declarations

Author contribution statement

Samuel Mwendwa: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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References

Arriaga, F.J., Lowery, B., Mays, M.D., 2006. A fast method for determining soil particle size distribution using a laser instrument. Soil Sci. J. 171, 663–674.

Ashworth, J., Keyes, D., Kirk, R., Lessard, R., 2001. Standard procedure in the hydrometer method for particle size analysis. Commun. Soil Sci. Plant Anal. 32, 633–642.

Beretta, N.A., Silbermann, V.A., Paladino, L., Torres, D., Bassahun, D., Musselli, R., et al., 2014. Soil texture analyses using a hydrometer: modification of the Bouyoucos method. Cienc. Investig. Agrar. 41, 263–271.

Bouyoucos, G.J., 1951. A recalibration of the hydrometer method for making mechanical analysis of soils. Agron. J. 43, 435–438.

Bouyoucos, G.J., 1936. Directions for making mechanical analysis of soils by the hydrometer method. Soil Sci. 4, 225–228.

Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analysis of soils. Agron. J. 54, 464–465.

Bouyoucos, G.J., 1927. The hydrometer as a new method for the mechanical analysis of soils. Soil Sci. 23, 343–352.

Brady, N.C., Weil, R.R., 2007. The Nature and Properties of Soils, fourteenth ed. Prentice-Hall, Upper Saddle River, NJ.

Coates, F.G., Hulse, A.C., 2012. A comparison of four methods of size analysis of fine-grained sediments. N. Z. J. Geol. Geophys. 28, 369–380.

Day, R.P., 1965. Pipette method of particle size analysis. In: Methods of Soil Analysis, 9. Agronomy, pp. 553–562. ASA USA.

Gee, G.W., Bauder, J.W., 1979. Particle size analysis by hydrometer: a simplified method for routine textural analysis and a sensitivity test of measurement parameters. Soil Sci. Soc. Am. J. 43, 1004–1007.

Gee, G.W., Bauder, J.W., 1986. Particle size analysis. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, , second ed.9. Soil Science Society of America, Madison, WI, Agron, pp. 383–411.

Gee, W.G., Or, D., 2002. Particle-size analysis. In: Dane, J., Topp, G.C. (Eds.), Methods of Soil Analysis. Book Series: 5. Part 4. Soil Science Society of America, USA, pp. 255–293.

Glendon, W.G., Doni, O.R., 2002. Methods of soil analysis part. In: Dane, J.H., Topp, G.C. (Eds.), Soil Science Society of America Book Series, 4. SSSA, Inc. Madison, Winconsin, USA, pp. 2644–2689. No.5.

Hommel, J., Coltman, E., Class, H., 2018. Porosity–permeability Relations for Evolving Pore Space: a Review with a Focus on (Bio-) Geochemically Altered Porous media, 124. Transp Porous Media, pp. 589–629.

Jensen, J.L., Schjønning, P., Watts, C.W., Christensen, B.T., Munkholm, L.J., 2017. Soil texture analysis revisited: removal of organic matter matters more than ever. PLoS One 12 (5), e0178039.

Jury, W., Horton, R., 2004. Soil Physics, sixth ed. John Wiley & Sons, New Jersey, USA, p. 370.

Kettler, T., Doran, J., Gilbert, T., 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Sci. Soc. Am. J. 65, 849–853.

Mwendwa, S., Mbuvi, J., Kironchi, G., Gachene, C., 2020. A Geopedological Approach to Soil Classification to Characterize Soils of Upper Kabete Campus Field, 23. University of Nairobi, Kenya (2) Tropical and Subtropical Agroecosystems Retrieved from. http ://www.revista.ccba.uady.mx/ojs/index.php/TSA/article/view/2836/1432.

Norambuena, V.P., Luzio, L.W., Vera, E.W., 2002. Comparison between the Pipette and Bouyoucos methods and their relationship with water retention in eight soils of the highland area of the Parinacota province, Chile. Tech. Agric. 62, 150–157.

Okalebo, J.R., Gathua, K.W., Woomer, P.L., 2002. Laboratory Methods for Soil and Plant Analysis: A Working Manual. TSBF, Nairobi.

Sheldrick, B.H., Wang, C., 1993. Particle size distribution. In: Carter, M.R. (Ed.), Soil Sampling and Methods of Analysis. Canadian Society of Soil Science, Ottawa, Ontario, Canada, pp. 499–511.

Van Reeuwijk, L.P., 2002. Procedures for Soil Analysis, sixth ed. ISRIC -World Soil Information, Wageningen, Netherlands. Technical Papers 9.

Watts, C.W., Whalley, W.R., Bird, N.R.A., Ashman, M.R., 2000. The effect of iron concentration, hindered settling, saturating cation and aggregate density of clays on the size distribution determined by gravitation X-ray sedimentometry. Eur. J. Soil Sci. 51, 305–311.