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Oil yields for *Allanblackia parviflora* (tallow tree) in Ghana: the effects of oil extraction methods, tree morphology and environmental characteristics

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This study provided understanding of the oil yields from *Allanblackia parviflora* fruits in Ghana. The study sought patterns of variations in oil yield between 157 trees, 16 communities and 3 ecological zones. Ecological zone and soil properties were considered as surrogates for growing conditions associated with tree and fruit morphology. Kernel and seed oil yields were determined using the manual screw press ranged from 31.3 to 61.8% and 0.2 to 36.8%, respectively. Large variations were observed between individual trees, and significant oil yield differences were observed between the 16 communities. There were no relationships between oil yields and soil properties, even though tree-to-tree differences were observed. The farmers' estimated ages of the trees predicted kernel oil yields: very young and very old trees revealed medium and low kernel oil yields, respectively. Kernel oil yields were also seen to be influenced by ecological zone. Most of the low kernel oil yielding trees were identified in the semi deciduous forest zone (SD), and more trees in wet evergreen forest zone (W) were identified as very high kernel oil yielding trees. Trees selection for domestication can be based on tree phenotype and providing environmental conditions similar to the wet evergreen forest zone.

Key words: *Allanblackia parviflora*, oil, yields, extraction, morphology, soil, tree-to-tree, ages.

INTRODUCTION

Globally, it is estimated that about 176.9 million metric tons of fats and oils are consumed annually; 80% is used for human food and the remaining 20% is used for industrial application (Rosillo-Calle et al., 2009; Statista, 2017). To address the continuing demand for vegetable oils, exploration in alternative sources is a priority (Imed and Arbi, 2011). Worldwide, commercial vegetable oil production has been from conventional crops such as soybean, sunflower, rapeseed, coconut, palm nut and shea butter (Sagi et al., 2013; Rosillo-Calle et al., 2009). The need to investigate the physical and chemical characteristics of new, unconventional sources of vegetable oils is necessary to evaluate their suitability as raw materials for food and industrial applications (Noumi et al., 2011; Pengou et al., 2013). In West Africa (Cameroon, Nigeria and Ghana), indigenous forest plants

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including *Allanblackia* spp, *Pycnanthus angolensis,* and *Treculia africana* (Ellis et al., 2007; Irvine, 1961; Noumi et al., 2011) are increasingly recognized as valuable sources of raw materials such as vegetable oils for the food and cosmetic industries.

Allanblackia (Family Guttiferae) is a wild, uncultivated tree genus, with nine species (Jamnadass et al., 2010; Shrestha and Akangaamkum, 2008) in the rainforest regions of Africa (Bürkle and Palenberg, 2009) from Sierra Leone to Tanzania. The trees are common and frequently used as shade for cocoa plants (Shrestha and Akangaamkum, 2008). The only species found in Ghana is *A. parviflora* (tallow tree). It is locally known as Sonkyi, Kusiadwe (rats nuts), Apesedua (porcupine tree) or Osono dokono (elephant 'kenkey') and is found growing in the Western, Central, Eastern and Ashanti regions of southern Ghana (Peprah et al., 2009) (see supplementary material Figure 5).

Previous research by Peprah et al. (2009) focused on the reproductive biology and characterisation of *A. parviflora* to allow for selection of trees for breeding purposes, but oil yields from the seeds and kernels of *A. parviflora* trees were not examined, and have not yet been considered for selective breeding. Moreover, the current commercial extraction of oils from *A. parviflora* in Ghana, involves milling of the entire seeds and not just the kernels. However, the impact of this method on the yield is unknown, and it is hypothesized that the oil extraction efficiency may improve when seeds are dehulled and only kernels are processed. Processing seeds with hulls may also impact further properties like the introduction of bioactive substances and fibre into the oils and seed cakes (Niewiadomski, 1990; Shafig and Din, 1997). The literature sourced on bulked *Allanblackia* kernels indicated a proximate composition of 62 to 70% of oil through soxhlet extraction (Noumi et al., 2011; Pengou et al., 2013) and not from seeds as is used by the commercial oil companies. Also, previous data by Sefah, Adubofour and Oldham (2010) indicated 48.6% at 100°C with 13% moisture content as the optimum conditions for oil yield from bulked *Allanblackia* kernels using the manual screw press.

Other studies have documented the chemical composition of the oils as well as the morphological characteristics of different varieties of *Allanblackia* in some African countries (Atangana et al., 2011; Boudjeko et al., 2013; Pengou et al., 2013; Peprah et al., 2009). These works confirm key knowledge gaps, namely the efficacy of mechanical extraction due to an exclusive focus on solvent extraction which measured the percentage of oil per sample, and the effect of dehulling since only the kernels have been used in oil yield estimations. In addition, there are no studies on the oil yield variation within and among wild populations of *A. parviflora* and its relationship with morphological characters of trees and fruit, location conditions (communities and ecological zones) and soil properties (growing conditions) in Ghana. This chapter seeks to determine the nature of these relationships.

MATERIALS AND METHODS

Study area

The study was conducted in the three (3) ecological zones in Ghana described by Peprah et al. (2009) as the distribution range of *A. parviflora* in Ghana. These ecological zones included the semi-deciduous forest zone (SD) covering 66000 km^2; the moist evergreen forest zone (ME) and the wet evergreen forest zone (W) both covering about 9500 km^2. The zones differed from one another based on their average annual rainfalls (1250 to 1500 mm for SD; ME 1500 to 1750 mm; and W > 1750 mm) (Peprah et al., 2009; RESPTA, 2008). To ensure maximum coverage, a total of 157 trees were sampled from 16 communities across these ecological zones (eight communities from SD because of its wider coverage, and four each from ME and W) (Table 1; supplementary material Figure 5).

Tree selection and harvesting

For each tree, the location (latitude, longitude and altitude) were determined by Garmin Etrex 10 GPS. Selection and fruit collection for *Allanblackia* trees occurred between December 2014 and April 2015. In each community a maximum of 10 trees, each spaced at least 100 m apart (and no more than two per farm property) were selected. Selected trees conformed to a healthy status (not heavily infested with mistletoes, free from fungal infection, without wilting, dead or broken branches, and with healthy fruits), and of sufficient maturity (trees of at least 10 cm diameter at breast height (DBH)). Individual trees were visited at least four times during the fruiting season and recently fallen fruits were collected to avoid the possibility of harvesting immature fruits or collecting rotten fruits and seeds. Harvested fruits were kept for 4 days in nylon sacks to enhance fermentation. The period of fermentation soften the fruit pulps in order to facilitate seed extraction.

Morphological characteristics

Tree height was measured using a clinometer, where the tangent ratio and height of eyes above ground level relationship were applied. The trunk diameter at breast height (DBH) was measured at 1.3 m above ground level. From each tree, ripe fallen undamaged and mature fruits (n = 45) were randomly selected for morphological assessment. Fresh weight, length and width of individual fruits were determined using portable digital scale and tape measure. Fruit pulp and seeds were separated; seeds were washed to remove the pulp (white mucilaginous substance surrounding the seeds) from the seeds.

For each individual tree the mean number of seeds per fruit and the mean seed weight per fruit was calculated. The average length and width of seeds from each tree were measured using digital vernier caliper, by subsampling 200 seeds, selected at random from the bulked seed samples. Fruit pulp weight was measured by subtracting seed weight from fruit weight. Fruit and seed shape dimensions were estimated by determining the ratios of lengths and widths. To determine the proportion of shell to kernel (shell weight) per tree, dried seeds (2 kg from each tree) were manually dehulled (removal of shell, where shell can also be referred to as hull, husk or seed coat) by cracking using two wooden sticks/batons. The kernels were separated from the shells and were weighed to determine an average proportion of shells and kernels per tree.

Tree ages were based on the estimated ages of trees provided

Table 1. Ecological zones and number of trees sampled from each community with approximate GPS locations of communities with codes.

Ecological zone (code)	Community (code)	Latitude (N)	Longitude (W)	Altitude (m)	Number of trees
Moist semi-deciduous forest zone (SD)	Adansi Akrofuom (SD-AA)	06°07'12.5"	001°39'03.8"	171	10
	Afosu (SD-AF)	06°22'58.1"	001°00'02.7"	180	10
	Akoase (SD-AK)	06°24'53.8"	000°51'55.9"	262	10
	Anwona (SD-AN)	06°05'26.5"	001°30'50.0"	137	10
	Atwereboana (SD-AT)	05°58'17.6"	001°16'44.3"	128	10
	Fenaso (SD-F)	06°04'34.9"	001°51'22.8"	139	8
	New Edubease (SD-NE)	06°02'03.0"	001°20'31.9"	127	10
	Wassa Akropong (SD-WA)	05°46'49.8"	002°05'29.5"	81	10
Moist evergreen forest zone (ME)	Benso (ME-B)	05°11'59.9"	001°52'43.2"	90	10
	Daboase (ME-D)	05°20'58.6"	001°40'26.1"	80	10
	Samreboi (ME-S)	05°37'06.8"	002°28'12.8"	67	10
	Sefwi Bodi (ME-SB)	06°15'27.2"	002°50'31.5"	192	10
Wet evergreen forest zone (W)	Asonti (W-AS)	05°07'22.7"	002°17'00.5"	42	10
	Banso (W-BA)	05°06'30.4"	002°14'29.2"	32	10
	Kwansima (W-KS)	05°05'05.6"	002°16'57.8"	41	10
	Nzema Akropong (W-NA)	05°04'42.2"	002°17'50.5"	33	9

farmers (owners of the trees).

Subsamples of seeds (150 seeds) were randomly taken from the 200 seeds used for seed length and width assessment to determine the seed shell thickness. Each seed was cut perpendicularly in half, the kernel was removed, and the shell thickness measured at midlength with digital vernier caliper.

Oil extraction and oil yield determination

The oil extraction and oil yield determination involved four steps: (1) seed treatment, (2) milling, (3) oil expression/extraction, and (4) oil yield determination. To prevent lipase activities and acid hydrolysis of triacylglycerols, seeds were sun-dried for seven days to ensure that the moisture content was reduced to below 10% (Allal et al., 2013). Dried seeds were manually dehulled as above and separated to reveal kernels. Seeds without kernels or considered incomplete were discarded. All the samples (kernels and seeds) were then labelled and stored at room temperature. For each tree, seed oil yield (SOY) was determined for a bulked sample of seed (consisting of kernel plus shell), and kernel oil yield (KOY) from a bulked sample of kernel only.

The milling of seeds/kernels and subsequent extraction of oil took place at the Technology Consultancy Centre (TCC), Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. Kernels and seeds from each tree (n=157 trees) were milled separately and in that order. Both were milled to fine particle sizes (93.5% passing through a 1.18 mm standard sieve) using the Disc miller. To prevent cross contamination, the disc miller was cleaned after each tree sample.

Previous work conducted by Sefah et al. (2010) established the optimal conditions for extracting oils from seed kernels. Briefly, seeds or kernels (400 g) for milling were weighed exactly and stabilized to 13% moisture content by adding warm water. The stabilized sample was then placed in dry linen cloth-bag and heated in a thermostatically controlled oven for 2 h at 100ºC. The oils were expressed using a manual screw (plate) press. The percentage oil yield per tree was expressed as the exact weight of the amount of oil produced by individual trees based on the exact weight of samples measured. The oils, pressed kernel and seed cakes (the residual materials left after the oil has been extracted from the seed) were collected for further analysis.

Soil properties

Soils were collected from three different points under the leaf canopy of each tree using a soil auger and hand trowel. Soil samples were taken at depth of 0 to 40 cm and put in a bigger receptacle. The samples were then bulked to form a single soil sample and mixed thoroughly. Subsamples (500 g) were taken for analysis. Soil parameters were determined at the Council for Scientific and Industrial Research (CSIR), Soil Research Institute of Ghana, Kwadaso, Kumasi. Soil organic matter and organic carbon were determined by a modified Walkley-Black method (Nelson and Sommers, 1982); soil pH was determined by glass electrode pH meter (Hanna instruments, 211 microprocessor, Portugal); soil nitrogen was determined by the Kjeldahl method (Okalebo et al., 1993); soil phosphorus was determined by the modified Bray-1 solution method (Olsen and Sommers, 1982); soil potassium was determined by the flame photometry (PFP7, UK); and Soil particle size by the Bouyoucous hydrometer (ASTM 152H, Braid and Tatlock, London) method (Indorante et al., 1990).

Statistical analysis

To describe spatial variability in the tree and fruit morphological characteristics, soil properties and percentage yield of oils, statistical analysis was performed at two different levels: communities and trees. Untransformed data were used for the descriptive statistics (maximum and minimum ranges; means). The data were tested for normality and transformed. Redundant variables were removed; only one of two tightly correlated variables were considered for multivariate analysis. Analysis of variance (ANOVA) was performed using SPSS version 23 to determine whether tree and fruit morphological characteristics, soil properties and percentage yield of oils differed between communities. The choice of ANOVA was informed because there is one continuous dependent variable (percentage yield of oils) and one categorical variable (communities) with more than two categories. The correlation analysis among the dependent variables (percentage seed oil yield (SOY) and kernel oil yield (KOY)) and the independent variables was determined using Pearson's moment correlation analysis. For each of the dependent variables, the difference between trees within a community and between communities was tested. For that purpose, the null hypothesis, H_0, of equality of means between groups was tested by ANOVA. The Tukey Post hoc test was used to analyse pair-wise comparison of group means when the null hypothesis was rejected at 5% level of significance. In addition to ANOVA, multivariate analyses included Principal Component Analyses (PCA) and Hierarchical Cluster Analyses (HCA) was performed using PRIMER/PERMANOVA package. These analyses were carried out to detect eventual groups of sites presenting similar morphological traits, soil properties and oil yields at different scales. Euclidean distance measures were employed for HCA. For community level analysis, the mean values of trees from the communities were used.

RESULTS AND DISCUSSION

Kernel and seed oil yields

Kernel and seed oil yields were measured for 157 trees sampled (Table 2). The percentage kernel oil yield (KOY) for *A. parviflora* ranged between 31.3 and 61.8%. The mean KOY for all the trees sampled (51.8%) was comparable to the mean (48.6%) reported for bulked kernel samples of *A. parviflora* obtained from trees grown in the SD-NE community (Sefah et al., 2010). The oil was extracted using similar conditions and the manual screw press. The mean-kernel oil yield for *A. parviflora* using soxhlet extraction is higher (67.6%; Sefah et al., 2010) but not surprising given the more exhaustive nature of the extraction, when compared to the manual press method.

The percentage KOY, showed considerable variation: from tree to tree, between communities and within communities. Across all communities, the highest yielding trees had remarkably consistent KOY between 55.0 and 61.8% suggesting that there could be upper limit for kernel oil yield using manual screw press for oil extraction. It has been suggested that most commercial oil-bearing seeds contain about 30 to 40% or above (Ellis et al., 2007). However, to aid interpretation of our data the % KOY for each tree was categorized (low, medium, high and very high, see Table 2 for details).

There were 31 trees identified as very high yielding (>56% KOY), and these trees were spread across all but two of the communities (SD-F and SD-AF), and across the three ecological zones. There were 14 trees categorised as low yielding (30 to 44.9%) and these trees were located in just six of the 16 communities.

The percentage oil extracted from the intact seed (SOY), which includes kernel and husk, was also measured (Table 2). The SOY ranged between 0.2 and 36.8% for the 157 trees sampled. The SOY was always, and considerably, lower than that reported for the corresponding KOY for the same tree. Within community variation (as standard deviation) for SOY was also consistently greater than that for KOY. The difference between the kernel oil yield (KOY) and the seed oil yield (SOY) might be explained by the fact that the kernel is where the oil is located, and 'seed' includes the shell and kernel so proportionally equal mass of seed will yield less oil compared to equal mass of kernel. Shafig and Din (1997) hypothesised that processing oilseeds without dehulling reduces the extraction efficiency by preventing the flow of oil during pressing. Studies of other plant oil seeds have reported the same. Dehulling the Jatropha kernel was essential to avoid low oil yields due to the shell absorbing the oil (Subroto et al., 2015), and removal of kernel shell for Crambe seeds improved oil extraction efficiency as the thick shell reduced seed bulk density (seeds mass to volume ratio) (Reuber et al., 2001). For *A. parviflora,* a strong negative correlation ($r = -0.56$, $p < 0.05$) between SOY and shell thickness indicates that SOY declines as shell thickness increases and may explain why SOY is a more variable measure than KOY in the present study. Another, and related proposition, might be that the oil extraction conditions, percentage moisture and temperature, used for seed extraction, while optimised for kernel, may not be optimal for seed extraction. In a separate experiment milled seed samples from all 157 trees were bulked. Following the same procedure for establishing optimal yield for kernel oil extraction (see Sefah et al., 2010), oil was extracted from the bulked seed sample at different moisture contents (5 to 33%) and at different temperatures (90, 100 and 110°C) (See Table 3). At any given moisture content, 100°C provided optimal oil yield and this temperature is consistent with the optimised kernel extraction method and that employed in this study. The *A. parviflora* seed oil yield increased with moisture content, however, visual inspection indicated that high amounts of water (25% and higher) led to traces of paste in the expressed oil. Therefore, 23% was determined to be the moisture content that gave optimal extraction, but without impacting on oil quality. This is significantly higher than the 13% moisture content determined for optimal kernel oil extractions and used for both kernel and seed oil extractions in this study.

In summary, the magnitude of difference between SOY and KOY can be attributed in part to the extraction efficiency due to the presence of shell, and the differences in the yield variances due to the variable shell thickness. Furthermore, moisture and temperature conditions used for seed oil and kernel oil extractions can be different and both need to be optimised. As the oil extraction for the seeds was not optimised, only the KOY

Table 2. Mean kernel and seed oil yields, kernel oil and seed oil ranges and the number of trees in each community with low, medium, high or very high yields are presented. The communities are ordered from highest to lowest mean kernel oil yield (Std. Dev. = Standard Deviation).

Community	Kernel oil ranges (%)	Mean kernel oil (%) ± Std. Dev.	Number of trees in each kernel oil yield Category				Seed oil ranges (%)	Mean seed oil (%) ± Std. Dev.
			L	M	H	VH		
Asonti (W-AS)	50.5 - 61.8	55.1 ± 3.56	-	2	4	4	13.0 - 36.8	21.1 ± 6.76
Kwansima (W-KS)	48.5 - 60.3	54.7 ± 3.78	-	2	4	4	7.0 - 29.8	17.6 ± 9.10
Wassa Akropong (SD-WA)	51.3 - 58.3	54.7 ± 2.29	-	2	6	2	11.3 - 27.3	16.5 ± 4.79
Daboase (ME-D)	50.3 - 58.0	54.1 ± 2.28	-	2	6	2	3.5 - 21.8	15.1 ± 5.38
Akoase (SD-AK)	46.5 - 58.9	53.1 ± 4.98	-	5	1	4	4.0 - 24.4	17.9 ± 7.21
Atwereboana (SD-AT)	49.8 - 58.0	52.8 ± 2.78	-	4	5	1	11.3 - 32.0	21.4 ± 7.07
Benso (ME-B)	47.0 - 59.3	52.4 ± 3.50	-	4	5	1	0.8 - 28.0	18.1 ± 7.17
Samreboi (ME-S)	46.2 - 58.3	52.4 ± 4.54	-	4	3	3	7.8 - 27.5	17.3 ± 5.81
Anwona (SD-AN)	45.0 - 57.8	52.2 ± 3.88	-	5	3	2	2.1 - 23.0	15.1 ± 6.14
Banso (W-BA)	41.5 - 61.0	52.1 ± 5.75	1	5	1	3	2.3 - 35.8	17.3 ± 9.57
Sefwi Bodi (ME-SB)	44.0 - 56.9	51.7 ± 4.34	1	3	5	1	3.3 - 26.0	14.8 ± 6.33
Fenaso (SD-F)	48.4 - 55.0	51.2 ± 2.41	-	6	2	-	15.5 - 28.5	19.9 ± 3.98
Adansi Akrofuom (SD-AA)	31.3 - 59.0	49.9 ± 8.38	2	3	3	2	6.0 - 27.5	15.2 ± 7.24
Nzema Akropong (W-NA)	36.0 - 59.3	49.4 ± 7.27	2	3	3	1	2.5 - 16.5	11.3 ± 4.73
Afosu (SD-AF)	39.0 - 55.8	47.3 ± 5.65	3	5	2	-	1.3 - 23.3	9.5 ± 8.53
New Edubease (SD-NE)	40.0 - 60.0	46.0 ± 6.03	5	4	-	1	0.2 - 26.8	11.7 ± 7.79

*Note: Kernel oil yield categories (%): Very High (VH) = 56.0 - 62.9: High (H) = 52.

Table 3. Percentage seed oil yields of bulked *Allanblackia parviflora* seeds from sixteen (16) communities within three (3) ecological zones with different temperature-moisture conditions.

T (˚C)	Moisture Content (%)														
	5.6	7.0	9.0	11.0	13.0	15.0	17.0	19.0	21.0	23.0	25.0	27.0	29.0	31.0	33.0
	Seed Oil Yield (%)														
90	15.5	16.0	17.3	18.5	19.3	19.8	22.8	23.3	27.0	29.9	34.0	36.0	36.8	41.0	41.5
100	17.8	18.8	19.0	19.5	19.8	20.3	23.0	25.8	29.8	**31.5**	33.5	37.3	39.0	41.5	46.3
110	15.0	16.0	18.8	19.3	19.5	18.5	22.9	25.1	27.3	29.3	29.5	33.5	37.0	40.8	45.5

data was analysed further.

Estimated ages of trees relationship with kernel oil yield (KOY)

A histogram of kernel oil yield (KOY) frequencies across 157 trees (Figure 1) showed a skewed distribution, and points to two interesting elements; the distribution has a conspicuously longer tail at the low yield end, and a truncated distribution at the very high yield end. By plotting percentage KOY against farmers' estimated age of trees (Figure 2) it can be seen that trees below 10 years old produced medium KOY, and it was the trees of 30 years old plus which yielded low KOY; the remaining tress, which consisted of most of the trees (>10 to 29 years) produced medium to very high KOY. Limited information is available on tree age and oil yield; however, in a study by Bouchaala et al. (2014) evaluating the effect of olive tree age on oil content, they reported that young olive trees produced higher amounts of oil when compared to adult olive trees. In another study by Darmawan et al. (2016), fresh fruits of oil palm revealed that yield increases to a peak limit with tree maturity and decreases as oil palm trees ages.

An explanation for a potential threshold maximum oil yield was investigated by seeking to establish whether there are patterns or predictors for kernel oil yield (KOY), particularly those in the very high yield category. Eighteen low (<45%) and medium (45 to 51.9%) kernel oil yielding trees were excluded from this analysis phase, namely those with ages below 10 years (3 trees) and

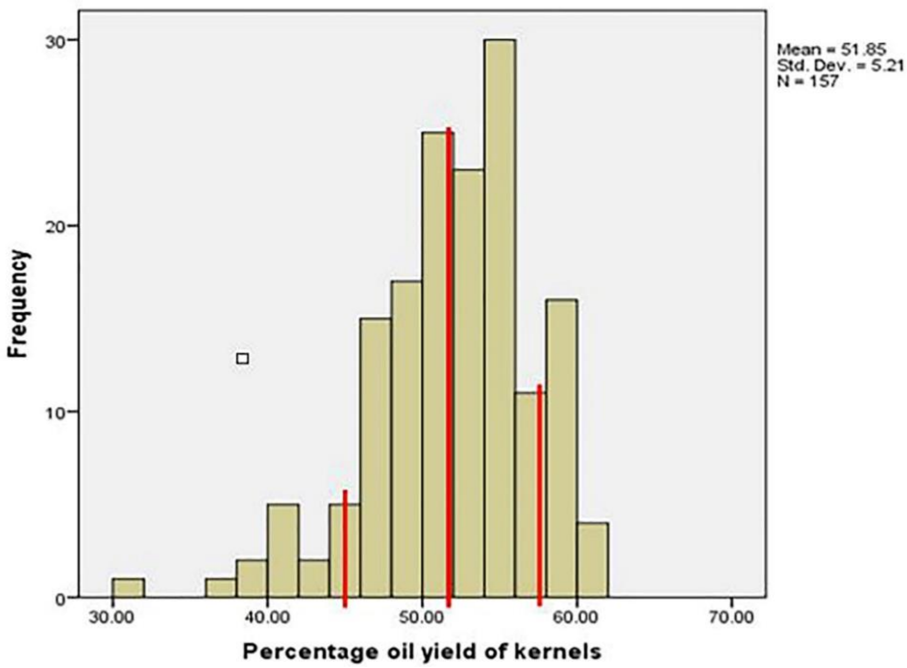

Figure 1. Histogram showing the frequencies of percentage kernel oil yields for 157 *Allanblackia parviflora* trees from sixteen (16) communities with Low (30.0 - 44.9), Medium (45.0 - 51.9), High (52.0 - 55.9) and Very High (56.0 - 62.9) kernel oil yield categories.

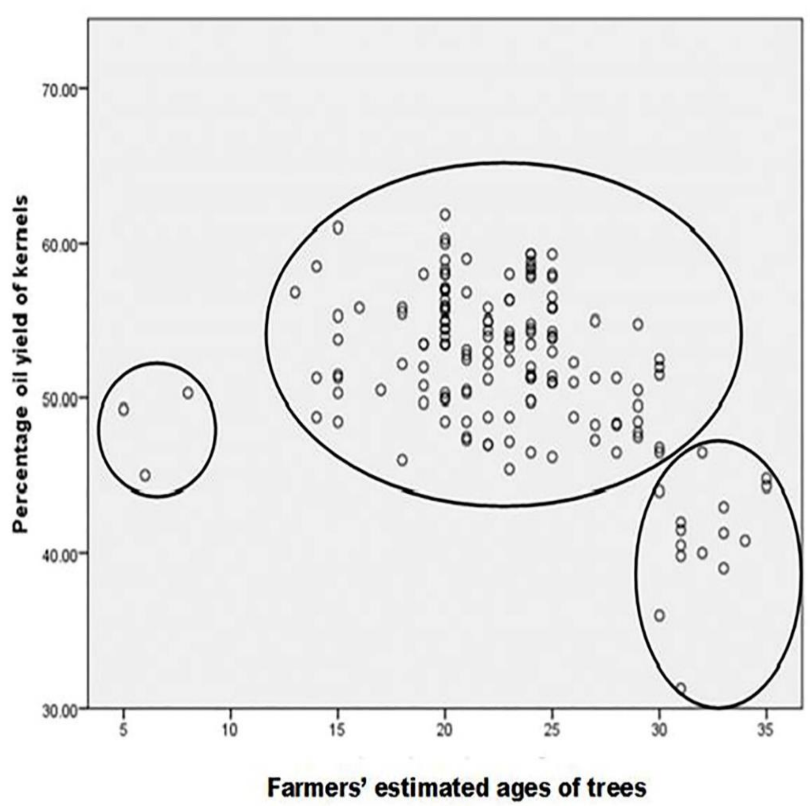

Figure 2. Graph showing percentage kernel oil yield versus farmers' estimated ages of *Allanblackia parviflora* trees (3 trees with ages below 10 years, 15 trees with ages above 30 years and 139 trees with ages between 10 and 30 years).

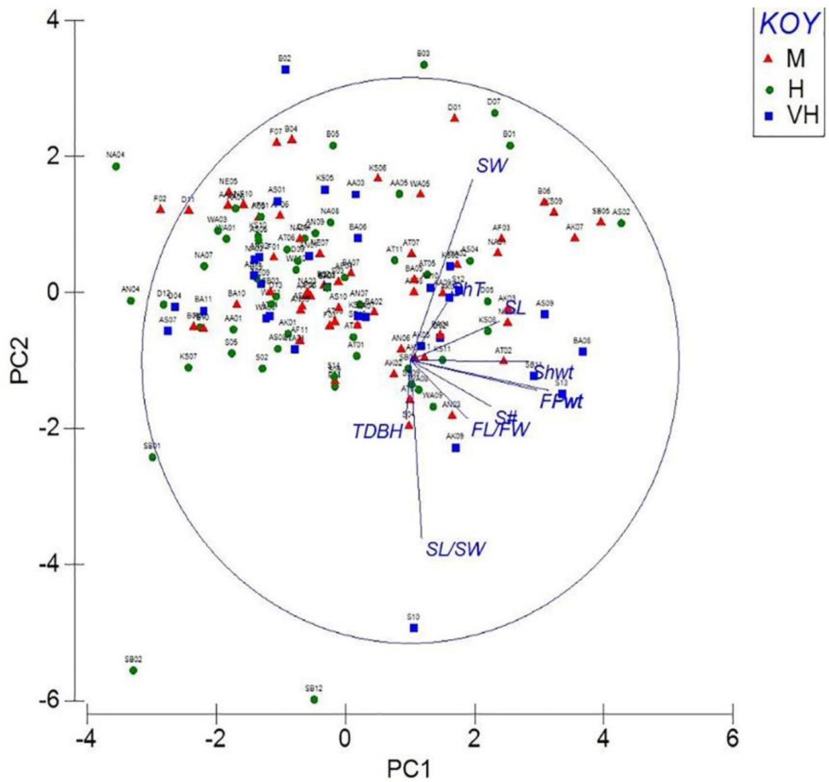

Figure 3. Principal component analysis (PCA) of 139 *Allanblackia parviflora* trees with medium (M), high (H) or very high (VH) kernel oil yield (KOY) due to tree, fruit and seed morphological characteristics.

those with ages 30 years or above (15 trees) circled in Figure 2.

Two separate investigations were undertaken, one to test the hypothesis that tree and fruit morphological characteristics could be used as surrogates for KOY, and two to test the hypothesis that environmental (soil properties) and geographical characteristics (ecological zones) were responsible for variation in the KOY from tree to tree.

Kernel oil yield (KOY) variation due to tree, fruit and seed morphological characteristics

Spatial variation and relationships between the trees' morphological characteristics, kernel moisture content, seed moisture content, kernel weight, shell weight, shell thickness, kernel and seed oil yields were evaluated (see supplementary material Table 5). Significant morphological variation was observed between trees. There was also significant variation among communities for all traits except for fruit pulp weight and shell thickness. However, no significant variation was identified for any of the morphological traits between ecological zones. As reported above, there was a negative strong correlation between SOY and shell thickness. In addition, there were weak but significant correlations between each of fruit weight, fruit pulp weight and shell weight and seed oil yield. For KOY the only morphological parameter to be weakly correlated was fruit dimension, where more squat fruit had higher KOY.

The morphological parameters considered for the multivariate analysis included tree diameter at breast height (TDBH), fruit weight (Fwt), fruit pulp weight (FPwt), fruit dimension (FL/FW), number of seeds per fruit (S#), seed length (SL), seed width (SW), seed dimension (SL/SW), total shell weight per fruit (Shwt) and shell thickness (ShT).

A principal component analysis defined by the first three axes explains 60.7% cumulative variation of morphological differences. PC1 (28.8%) was mostly driven by Fwt, FPwt, Shwt, S# and SL. PC2 explained 18.1% and was driven by seed dimensions (SW and SL/SW). When trees categorized for KOY are labelled on the plot (Figure 3) no separation into these categories is observed. The graph revealed no clear pattern as most of the KOY variations are not influenced strongly by morphological variables.

A dendrogram obtained after hierarchical cluster analysis (HCA) labelled for individual trees and the

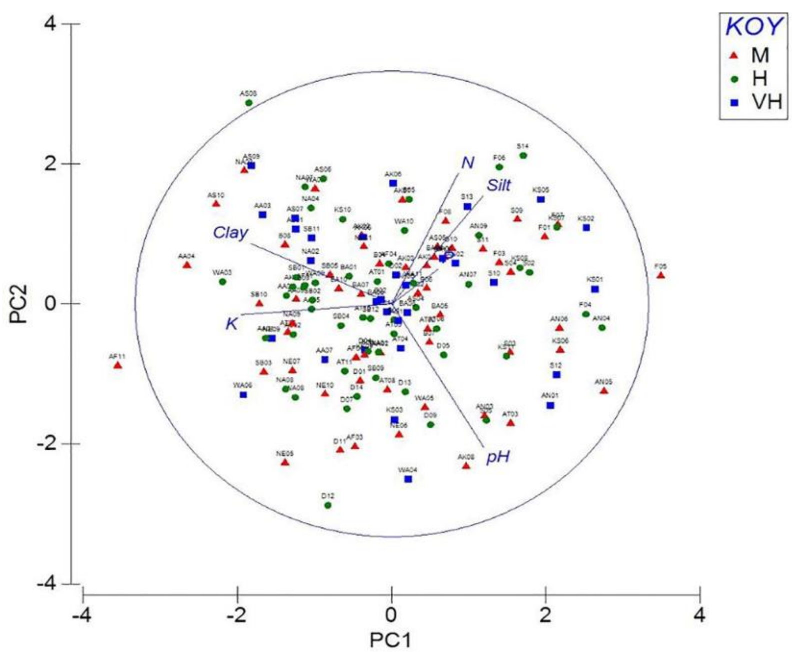

Figure 4. Graph showing the principal component analysis (PCA) of 139 *Allanblackia parviflora* kernel oil yield (KOY) variation (medium, high and very high) due to soil physical and chemical properties

communities they are from, revealed 4 groups (clusters). All three KOY categories were distributed throughout each cluster, although most of the very high kernel oil yielding trees (15) were found in cluster 1. Again, no clear patterns were observed with regard to KOY categories, communities and morphological characteristics (see supplementary material Figure 6).

This finding for *A. parviflora* is similar to that for Neem tree kernel oils where seed oil content was consistently observed not to correlate with morphological parameters of seeds (Kaura et al., 1998; Muñoz-Valenzuela et al., 2007).

Kernel oil yield (KOY) variation due to soil properties

Across all 157 trees, analysis of soil physical (% sand, % clay and % silt) and chemical (% organic matter, % carbon, pH, nitrogen, phosphorus and potassium) properties revealed significant variation between most communities based on pair wise comparisons. No significant correlations between any soil properties and oil yields were found (see supplementary material Table 6).

Multivariate analysis was therefore conducted using pH, nitrogen, phosphorus, potassium, %clay and %silt to determine the relationships between soil parameters and KOY. Percentage sand, organic matter and carbon were excluded to avoid the effect of multicollinearity, as there was strong correlation between these parameters and the other variables used in the statistical analysis. The same categorisations for kernel oil yields (M, H and VH) were used to search for patterns (across 139 trees). A principal component analysis (PCA) of soil properties of individual trees and their relationship with kernel oil yield (KOY) is shown in Figure 4. The PCA for soil properties represented by 3 axes cumulatively explained 64.0% of the variation. PC1 (27.1%) was actively driven by soil acidity (pH), potassium (K), clay and silt. PC2 contributed 19.0% and was driven by pH, nitrogen (N) and silt. There are few discernible patterns in the PCA, although some clustering of very high and high kernel oil yielding (KOY) trees in the upper left-hand area where high clay, high potassium (K) and low pH influenced the plot.

Hierarchical cluster analysis (see supplementary material Figure 7) for the soil properties of individual trees and their relationship with KOY shows seven (7) clusters. Even though cluster 1 had only 14 trees, 4 high and 4 very high kernel oil yield trees were identified, and the trees correspond to the highlighted grouping in Figure 4. Otherwise no clear patterns were identified among kernel oil yield with regard to soil properties.

The multivariate analysis shows only a weak association between some high oil yielding plants and soils with higher clay proportions and potassium. Sawan et al. (2007) showed that potassium (K) applied to the soil can result in a significant increase in oil yields of oilseeds. Contrary to these findings on *Allanblackia* was a study by Adam, Acheampong, and Abdul-Mumeen (2015), who studied the effect of soil variation on yield and quality of

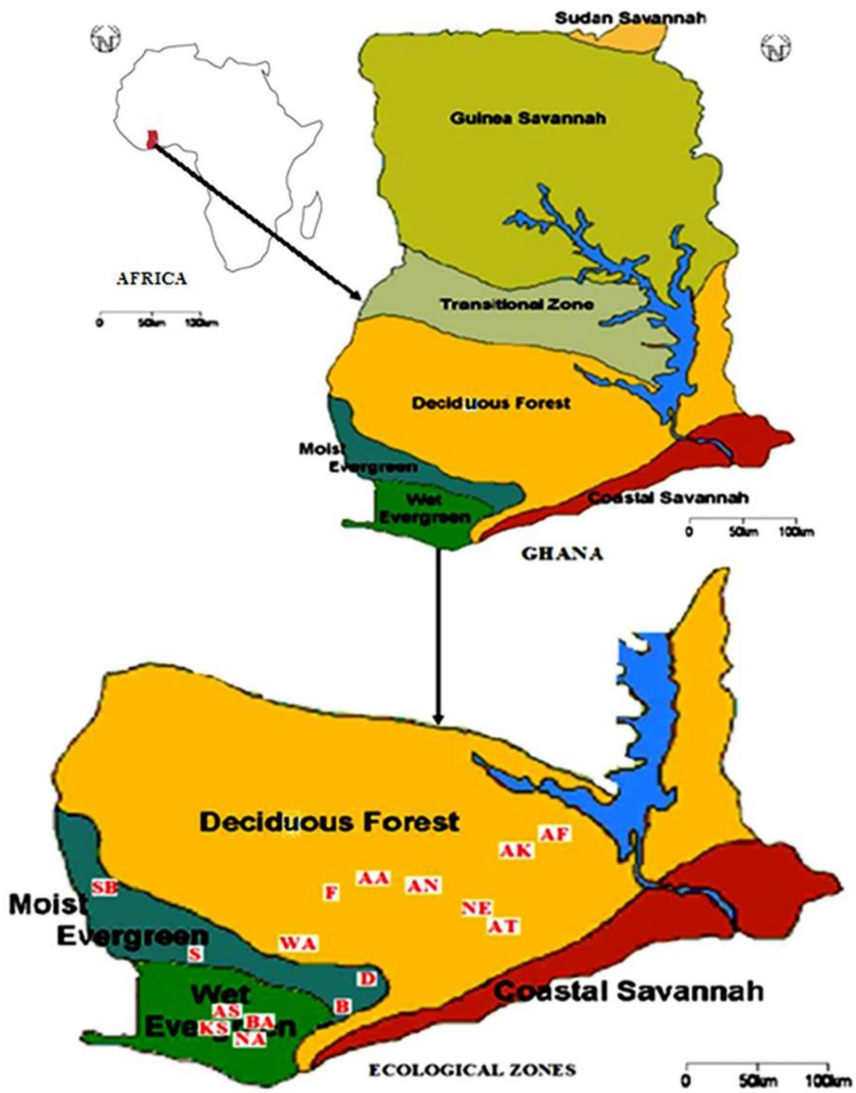

Figure 5. A map of Africa showing the location of Ghana with the seven ecological zones. *Allanblackia parviflora* trees were sampled from three (3) ecological zones noted for abundance of the trees namely; wet evergreen, moist evergreen and deciduous/semi-deciduous forest. Trees were sampled from sixteen (16) communities (Adansi Akrofuom, **AA**; Afosu, **AF**; Akoase, **AK**; Anwona, **AN**; Atwereboana, **AT**; Fenaso, **F**; New Edubease, **NE**; Wassa Akropong, **WA**; Benso, **B**; Daboase, **D**; Samreboi, **S**; Sefwi Bodi, **SB**; Asonti, **AS**; Banso, **BA**; Kwansima, **KS** and Nzema Akropong, **NA**). The ecological map of Ghana was taken from RESPTA (2008).

Shea butter from selected areas in the northern regions of Ghana. They were able to show a significant and positive impact of sandy soil, organic matter, organic carbon and nitrogen on oil extracted from Shea nuts in Ghana.

Kernel oil yield (KOY) variation due to ecological zones influence

Table 4 showed percentages of kernel oil yield categories and absolute numbers (in parenthesis) of trees sampled from the three ecological zones. Out of 78 trees sampled from the semi deciduous (SD) ecological zone, most (54.4%, 44 trees) were of low and medium kernel oil yielding trees respectively. The moist evergreen forest zone (ME) was the most variable ecological zone with 47.5% high KOY trees. Interestingly, from the wet evergreen forest zone (W), the three proportions of (M, H and VH) KOY categories were spread evenly. However, ecological zone W had the highest percentage of very high KOY (30.8%) compared to zones ME and SD. The

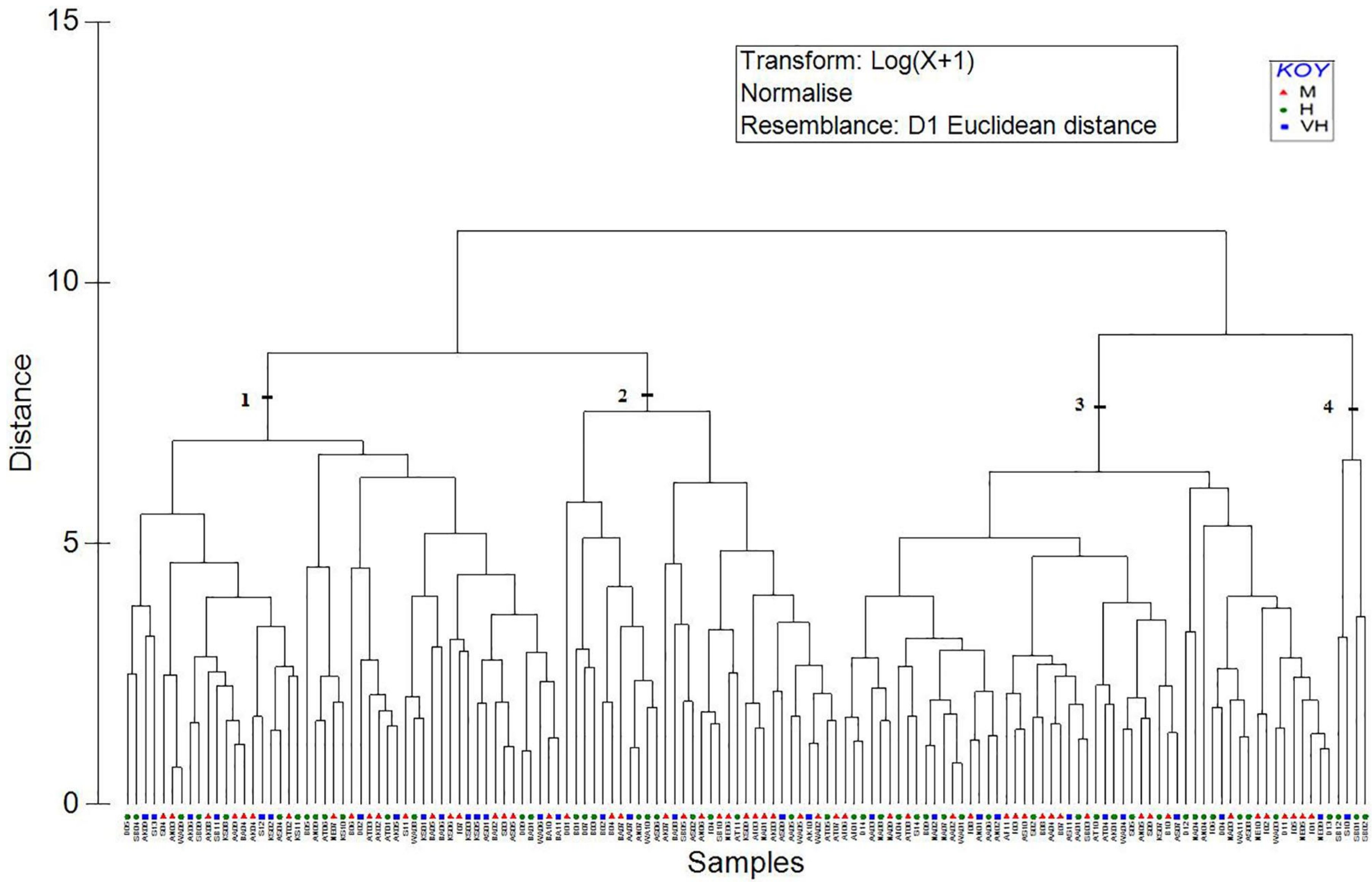

Figure 6. Hierarchical cluster analysis (HCA) of 139 *Allanblackia parviflora* kernel oil yield (KOY) relationship (M, H and VH) due to tree, fruit and seed morphological characteristics, showing the four clusters at Euclidean distance 7.5.

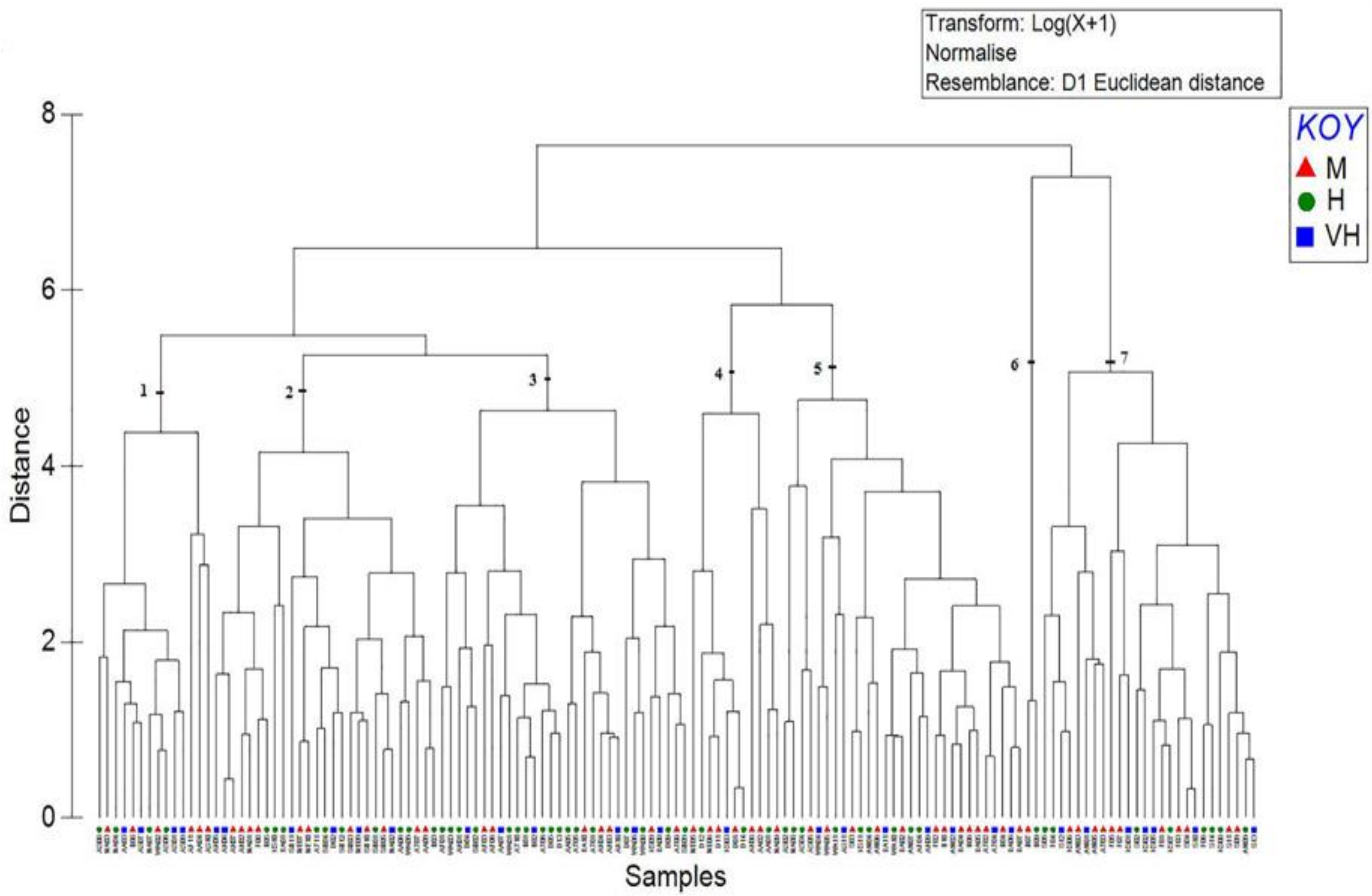

Figure 7. Hierarchical cluster analysis (HCA) of 139 *Allanblackia parviflora* kernel oil yield (KOY) relationship (medium, high and very high) due to soil physical and chemical properties showing 7 clusters at Euclidean distance 5.

Table 4. Percentages of 157 *Allanblackia* kernel oil yield (KOY) categories and absolute numbers (in parenthesis) of trees sampled from three ecological zones.

Ecological zone	Kernel oil yield (KOY) category				
	Low (L)	**Medium (M)**	**High (H)**	**Very high (VH)**	**Total number of trees sampled from eco-zones**
Semi-deciduous (SD) forest zone	12.8% (10)	43.6% (34)	28.2% (22)	15.4% (12)	78
Moist evergreen (ME) forest zone	2.5% (1)	32.5% (13)	47.5% (19)	17.5% (7)	40
Wet evergreen (W) forest zone	7.7% (3)	30.8% (12)	30.8% (12)	30.8% (12)	39
Number of trees in KOY category	14	59	53	31	157

Table 5. Minimum, maximum (ranges) and mean tree, fruit morphological characteristics of trees with their significant pair-wise comparison between communities in relation to kernel and seed oil yields (SD = Standard deviation; n = 157; p – values in parenthesis).

Parameter	Tree ranges	Tree means ± SD	Community variations (Significant differences)	Correlations	
				Kernel oil yield	**Seed oil yield**
Tree height (m)	7.4 - 42.0	27 .0 ± 8.43	AK > AN, B, BA, WA B, WA < AK, S S > WA, B	0.06 **(0.44)**	-0.06 **(0.45)**
Tree DBH (cm)	12.7 - 102.8	47.6 ± 13.37	BA < AT, NE, S NE > AA, AF, AS, B, BA, F, WA	-0.02 **(0.80)**	-0.10 **(0.22)**
Fruit weight (kg)	0.79 - 3.1	1.9 ± 0.54	F < AA, AF, AK, AS, AT, BA, KS, S, SB, WA KS > AN, B, F, NA	-0.09 **(0.26)**	-0.18 **(0.03)****
Fruit pulp weight (kg)	0.63 - 2.8	1.7 ± 0.49	No Significant differences	-0.11 **(0.18)**	-0.19 **(0.02)****
Fruit length (cm)	18.4 - 49.5	29.3 ± 5.30	AK > AA, AF, AN, AS, AT, B, BA, D, F, NE, NA, S, SB, WA AN < AK, AT, KS, SB B, BA, WA < AK, KS KS > AN, B, BA, WA SB < AK, AN	-0.13 **(0.10)**	-0.08 **(0.31)**
Fruit width (cm)	9.3 - 19.8	12.7 ± 1.61	AK > NE, F F < AK, BA, KS, S KS > AT, AS, B, F, NE, S NE < AK, KS	0.02 **(0.82)**	-0.09 **(0.25)**
Fruit length/fruit width (Fruit dimension)	1.5 - 3.5	2.3 ± 0.36	AK > AN, BA	-0.16 **(0.04)****	-0.02 **(0.81)**
Number of seeds/fruit	11.0 - 71	29.0 ± 9.70	AA, AN > D, KS, NE, NA	0.02	0.06

Table 5. Contd.

			AF > NE, SB AK > D, F, KS, NE, NA AS, S > NE < SB D < AA, AK, AN, SB F < AK, SB KS, NA < AA, AK, AN, SB NE < AA, AF, AK, AN, AS, S, SB SB > AF, AS, AT, B, BA, D, F, KS, NA, NE, S, WA	**(0.78)**	**(0.42)**
Seed weight /fruit (kg)	0.07 - 0.67	0.2 ± 0.10	NA < AK, SB	0.06 **(0.47)**	0.01 **(0.90)**
Seed length (mm)	21.5 - 48.7	33.8 ± 4.18	AK > AA, AF, AN, AS, F, NA, SB, WA AN < AK, AT, B, BA AS, WA < AK > SB AT, B, BA > AN, NA, SB F < AK, SB KS, NE, S > NA, SB NA < AK, AS, AT, B, BA, KS, NE, S SB < AK, AS, AT, B, BA, D, F, KS, NE, S, WA	-0.07 **(0.36)**	-0.14 **(0.08)**
Seed width (mm)	9.7 - 28.8	20.0 ± 2.78	AA, AF, AK, AS, KS, NE < B > S, SB AN, AT, BA, NA < B > SB B > AA, AF, AK, AN, AS, AT, BA, F, KS, NA, NE, S, SB, WA D, F > S, SB S < AA, AF, AK, AS, B, D, NE, KS SB < AA, AF, AK, AN, AS, AT, B, BA, D, F, KS, NA, NE, WA WA < B, SB	-0.03 **(0.70)**	-0.09 **(0.28)**
Seed length/seed width (Seed dimension)	1.2 - 2.7	1.7 ± 0.23	S > AA, AF, B, NA	-0.04**(0.64)**	-0.04**(0.61)**
Kernel moisture content (%)	1.6 - 6.0	3.2 ± 0.57	AA > AK, AS, AT, BA, D, KS, WA AF > AN, AK, AS, AT, BA, D, KS, WA AK < AA, AF, NA, NE, S, SB AN < AF > D < NA AS < AA, AF, NE, S, SB AT < AA > D < SB < NA B, F > BA, D BA < AA,AF, B, F, NE, S, SB D < AA, AF, AN, AT, B, F, KS, NA, NE, S, SB	-0.42 **(0.00)****	-0.17 **(0.04)****

Table 5. Contd.

			KS < AA, AF, D, NA, SB S > AK, AS, BA, D NA > AN, AK, AS, AT, BA, D, KS, WA NE > AK, AS, BA, D, WA SB > AK, AS, AT, BA, D, KS, WA WA < AA, AF, NA, NE, SB		
Seed moisture content (%)	1.8 - 6.6	4.8 ± 0.71	AA > AT, BA, NA AF > AN, AS, AT, BA, NA AK, B > BA, NA AN > BA < AF, KS, SB AS < AF, BA, KS, S AT < AA, AF, KS, S, SB BA < AA, AF, AK, AN, AS, B, D, F, NE, KS, S, SB, WA D, F > BA < KS > NA < S KS > AN, AS, AT, BA, D, F, NA, NE, WA NA < AA, AF, AK, AS, B, D, F, NE, KS, S, SB, WA NE > BA < KS > NA < SB S > AS, AT, BA, D, F, NA, WA SB > AN, AT, BA, NA, NE WA < BA, KS, NA, S	-0.12 **(0.13)**	-0.33 **(0.00)****
Kernel weight per fruit (kg)	0.04 - 0.5	0.13 ± 0.06	NA < AK, S, SB	0.10 **(0.20)**	0.15 **(0.06)**
Shell weight per fruit (kg)	0.01 - 0.3	0.09 ± 0.05	No Significant differences	-0.004 **(0.961)**	-0.18 **(0.03)****
Shell thickness (mm)	1.0 - 2.7	1.7 ± 0.33	AA, AK, AN, AT, NA, WA < AF, NE AF > AA, AK, AN, AS, AT, B, BA, D, NA, S, SB, WA AS, B, S, SB < AF, F, NE BA < AF, F, KS, NE F > AS, BA, B, S, SB KS > B, BA, NE, S NE > AA, AN, AK, AS, AT, B, BA, D, KS, NA, S, SB, WA	-0.205 **(0.01)****	-0.56 **(0.00)****

***Note: > or <** means the variable under consideration between communities is greater (>) or less (<) and significant.
KOY = kernel oil yield; **SOY** = seed oil yield; **DBH** = diameter at breast height.
AA = Adansi Akrofuom; **AF** = Afosu; **AK** = Akoase; **AN** = Anwona; **AT** = Atwereboana; **F** = Fenaso; **NE** = New Edubease; **WA** = Wassa Akropong; **B** = Benso; **D** = Daboase; **S** = Samreboi; **SB** = Sefwi Bodi; **AS** = Asonti; **BA** = Banso; **KS** = Kwansima and **NA** = Nzema Akropong.

Table 6. Minimum, maximum (ranges) and mean soil properties of individual trees with their significant pair-wise comparison within communities in relation to kernel and seed oil yields (SD = Standard deviation; n = 157; p – values in parenthesis).

Parameter	Tree ranges	Tree means ± SD	Community variations (Significant differences)	Correlations	
				Kernel oil yield	Seed oil yield
Organic carbon (%)	0.05 - 4.28	1.9 ± 0.91	AA, AF > AK, AN, AS, B, BA, D, F, KS, NA, NE, S, SB	0.05	0.00
			AK, AN, AS, B, BA > AA, AF, AT, WA	**(0.51)**	**(0.99)**
			AT > AK, AN, AS, B, BA, F, KS, NE, S, SB		
			D > AA, AF, F, KS, NE, S, SB		
			F, KS, NE, S, SB > AA, AF, AT, D, WA		
			NA > AA, AF, WA		
			WA > AK, AN, AS, B, BA, F, KS, NA, NE, S, SB		
Organic matter (%)	0.09 - 7.38	3.1 ± 1.40	AA, AF > AK, AN, AS, AT, B, BA, D, F, KS, NA, NE, S, SB	0.07	0.06
			AK, AN, AT, B, NE > AA, AF, WA	**(0.38)**	**(0.44)**
			AS, BA, F, KS, S, SB > AA, AF, D, WA		
			D > AA, AF, AS, BA, F, KS, S, SB		
			NA > AA, AF, D		
			WA > AK, AN, AS, AT, B, BA, F, KS, NA, NE, S, SB		
pH	3.32 - 6.00	4.3 ± 0.43	AA > AF, AN, AS, D, F, NE	-0.03	0.06
			AF > AA, AK, AS, NA	**(0.73)**	**(0.45)**
			AK > AF, AN, AS, D		
			AN > AA, AK, AS, AT, B, BA, NA, SB, WA		
			AS > AA, AF, AK, AN, AT, B, BA, D, F, KS, NE, S, SB, WA		
			AT, BA < AN > AS		
			D > AA, AK, AS, NA, SB, WA		
			F > AA, AS, NA, WA		
			NA < AN, AF, D, F, NE, KS, S		
			NE > AA, AS, NA, SB, WA		
			KS, S > AS, NA		
			SB < AN, D, NE		
			WA > AN, AS, D, F, NE		
Nitrogen (mg/kg)	0.01 - 0.37	0.2 ± 0.08	AA, AT > AK, AN, AS, B, BA, F, KS, NE, S, SB	0.08	0.03
			AF > AK, AN, AS, B, BA, D, F, KS, NA, NE, S, SB	**(0.32)**	**(0.70)**
			AK, AN, AS, B, BA > AA, AF, AT, WA		
			D > AF, F, KS, NE, S, SB		

Table 6. Contd.

			F, KS, NE, S, SB > AA, AF, AT, D, WA NA > AF, WA WA > AK, AN, AS, B, BA, F, KS, NA, NE, S, SB		
Phosphorus (mg/kg)	0.32 - 37.15	12.6 ± 6.49	AA, AN > B, BA AF > AT, B, BA, NE, SB AS, F, NA, S > B, BA, NE B > AA, AF, AN, AS, F, KS, NA, S BA > AA, AF, AN, AS, F, NA, S NE > AF, AS, F, NA, S	-0.11 **(0.17)**	-0.07 **(0.38)**
Potassium (mg/kg)	8.53 - 307.42	53.7 ± 47.68	AA, AF > AK, AN, AS, AT, BA, D, F, KS, S AK, AN > AA, AF, AS, B, BA, D, NA, NE, SB, WA AS > AA, AF, AK, AN, AT, B, BA, D, F, KS, S, WA AT > AA, AF, AS, B, NA, NE, S, SB, WA B > AK, AN, AS, AT, F, KS, NA, NE, S, SB BA > AA, AF, AK, AN, AS, F, NA, NE, S, SB D > AA, AF, AK, AN, AS, AT, NA, NE, S, SB F > AA, AF, AS, B, BA, D, NA, NE, SB, WA KS > AA, AF, AS, B, BA, NA, NE, S, SB, WA NA, NE > AK, AN, AT, B, BA, D, F, KS, S, WA S > AA, AF, AS, AT, B, BA, D, KS, NA, NE, SB, WA SB > AK, AN, AT, B, BA, D, F, KS, S, WA WA > AK, AN, AS, AT, F, KS, NA, NE, S, SB	-0.13 **(0.11)**	-0.06 **(0.43)**
Sand (%)	24.86 - 80.43	55.5 ± 13.43	AA, AF, F > AT, D, KS, NE, S, SB AK > D, KS, NE, S, SB AN > D, KS, NE, SB AS < AT, D, KS, NE, S, SB AT > AA, AF, AS, B, F, NA B < AT, D, KS, NE, S, SB, WA BA < D, NE, SB D > AA, AF, AK, AN, AS, B, BA, F, NA KS > AA, AF, AK, AN, AS, B, F, NA NA < AT, D, KS, NE, S, SB, WA	0.05 **(0.56)**	0.01 **(0.94)**

Table 6. Contd.

			NE > AA, AF, AK, AN, AS, B, BA, F, NA, WA		
			S > AA, AF, AK, AS, B, F, NA		
			SB > AA, AF, AK, AN, AS, B, BA, F, NA		
			WA > B, NA, NE		
Clay (%)	6.56 - 52.13	19.4 ± 9.65	AA, AK, NA > AN, AS, AT, BA, D, F, KS, NE, S, WA	-0.06	-0.08
			AF > AN, D, F, KS, NE, S, WA	**(0.46)**	**(0.32)**
			AN, S > AA, AF, AK, B, NA, SB		
			AS, BA < AA, AK, > KS < NA		
			AT > AA, AK, KS, NA		
			B, SB > AN, KS, S		
			D, NE, WA > AA, AF, AK, KS, NA		
			F > AA, AF, AK, NA		
			KS > AA, AF, AK, AS, AT, B, BA, D, NA, NE, SB, WA		
Silt (%)	5.4 - 51.18	26.1 ± 9.99	AA, AF, AT > AN, B, BA, D, F, NE, SB	0.09	0.10
			AK > AN, D, F, NE, SB	**(0.25)**	**(0.23)**
			AN > AA, AF, AK, AS, AT, D, KS, NA, NE, S, SB, WA		
			AS < AN > D < F, NE > SB, WA		
			B, BA > AA, AF, AT, D, NE, SB, WA		
			D > AA, AF, AN, AS, AT, B, BA, F, KS, S, NA, WA		
			F > AA, AF, AK, AS, AT, D, KS, NA, NE, S, SB, WA		
			KS, NA, S < AN > D < F > NE, SB		
			NE > AA, AF, AK, AN, AS, AT, B, BA, F, KS, NA, S, SB, WA		
			SB > AA, AF, AK, AN, AS, AT, B, BA, KS, NA, NE, S		
			WA > AN, AS, B, BA, D, F, NE		

***Note: > or <** means the variable under consideration between communities is greater (>) or less (<) and significant.
*Abbreviations meaning: **KOY** = kernel oil yield and **SOY** = seed oil yield.
AA = Adansi Akrofuom; **AF** = Afosu; **AK** = Akoase; **AN** = Anwona; **AT** = Atwereboana; **F** = Fenaso; **NE** = New Edubease; **WA** = Wassa Akropong; **B** = Benso; **D** = Daboase; **S** = Samreboi; **SB** = Sefwi Bodi; **AS** = Asonti; **BA** = Banso; **KS** = Kwansima and **NA** = Nzema Akropong.

results from this work suggest more low and medium kernel oil yielding trees in SD ecological zone and more very high kernel oil yielding trees in W ecological zone. Ecological zone might therefore be seen as a somewhat reliable predictor of KOY, in that the proportion of very high kernel oil yielding trees increases from semi-deciduous zone to the wet evergreen zone.

Since classification of ecological zones is done by their geology, topography, soils, vegetation, climate conditions, living species, habitats, water resources, and sometimes also anthropogenic factors it is difficult to know which of these factors, or all of them together, are influencing KOY. Wen et al. (2012) have reported a significant positive effect of climate factors (mean annual temperature, sunshine and evaporation) on Jatropha seed weight and oil content.

Conclusion

The *A. parviflora* (tallow tree) kernel oil yields (KOY) were high with less variability compared to intact seed oil yield (SOY) for the trees sampled across 16 communities and 3 ecological zones. Seed oil yield was influenced mainly by shell thickness, moisture and temperature. Low kernel oil yield was attributable to very young or very old trees. No tree, fruit or seed morphological variable could reliably predict kernel oil yield. Measured soil parameters were similarly not good predictors for kernel oil yield although there is a suggestion that at least some trees in some communities have oil yields that respond to more clay-based soils. Otherwise, very high oil yielding trees were most likely to come from wet evergreen forest zone, where distinctive climate, geology and soils prevail. Based on these results we conclude that kernel oil yield is at least partially environmental. Therefore, selection of trees for domestication could be based on individual tree phenotypic expression and also growing the trees in environmental condition similar to the wet evergreen forest zone for very high kernel oil yield production.

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CONFLICT OF INTERESTS

The authors have not declared any conflict of interest.

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