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Evaluation of Expanded Black Cotton Soil as a Hydroponics Medium

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Abstract The traditional system of producing crops using soil (geoponics) is currently facing major challenges resulting in food deficits. An alternative is the adoption of soil-less culture (hydroponics) which is regarded as key in increasing production of vegetables, herbs and ornamentals. The study aimed at preparing a hydroponic medium from black cotton soil and rice husks. This involved moulding, firing and size reduction. The aggregates were evaluated based on dry bulk density and saturated hydraulic conductivity. The optimal conditions for preparing the medium was found to be at 750°C, 30 minutes and 9:1 for firing temperature, time and ratio of black cotton soil to rice husk (on a weight basis). This process resulted in 33% reduction in bulk density from 1.43 g cm^{-3} to 0.954 g cm^{-3} while the saturated hydraulic conductivity improved from $0.333*10^{-5}$ cm s^{-1} to 0.00385 cm s^{-1}, a value that lies between the ranges of Sandy Loam and Loamy Sand. The process improved black cotton soil into a light weight aggregate medium with reduced bulk density, loose and friable aggregates, easy to drain and having moderate permeability to permit water and nutrient movement. The medium is therefore better suited to grow potted plants under indoor or outdoor conditions.

Keywords: *hydroponics, aggregate medium, bulk density, saturated hydraulic conductivity*

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1. Introduction

The term hydroponics is derived from two Greek words; *hydro* meaning water and *ponos* meaning working, thus literally meaning 'water working'. In practical use, it means growing plants in a water and nutrient solution without soil or 'soil-less culture'. Soil has simply been the holder of plant nutrients, a place where plant roots traditionally live and a base of support for the plant structure. If the nutrients are availed to plants in other ways, then soil would not necessarily be required thereby limiting its accompanying negative characteristics such as unfavourable compaction, poor drainage, degradation [1].

The technology can be traced back to 1936 when the word 'Hydroponics' was coined by Dr. W.F. Gericke [2]. Commercially, the technology is currently adopted in most countries (mainly in the Western world) to grow vegetables, herbs and ornamentals. Among the leading countries in adoption of the technology are Israel, England, Australia, Netherlands, Spain and Canada [2,3]. In Africa, it has been adopted in countries such as South Africa and Kenya.

1.1 Advantages and Limitations of Hydroponics

The following are some of the reasons for the preference towards hydroponics [1,3,7]:

1. Plants grow up to 50% faster than in soil because they have easy access to nutrients and water;
2. Plants become 'vacation proof' and 'neglect resistant';
3. Nutrients are directly available to plants and do not get bound up;
4. Little or no pesticides are necessary because plants start from disease free medium;
5. Smaller containers can be used because roots can grow without being root bound;
6. Gardening is possible where it would not be normally e.g. rocky areas;
7. Less labour is required because there is no digging or weeding;
8. Better quality products and higher yield due to increased control over growing conditions.

However, the technology also experiences some limitations. These include:

1. High initial capital expenditure especially when combined with controlled environment agriculture;
2. It requires considerable degree of management skills;
3. Because of the costs involved, it is appropriate for high value crops;
4. Yields may reduce when the temperature of the solution increases.

1.2. Hydroponic Systems

Common hydroponic systems include aquaculture or aquaponics, aggregate culture and aeroponics. Most

aquaponic systems combine aquaculture (fish farming) with crop production. In aquaponics, the crops are supported so that their roots hang in a nutrient solution. This system is considered to offer increased water use efficiency. However, Roe and Modmore [4] argued against the viability of most aquaponic or aquaculture systems noting that there is still lack of sufficient aquaponic data which meet the scientific standards for modelling under a variety of biotic and abiotic conditions. Most aquaponic investors are also not sufficiently skilled on the dynamics involved. Of major concern is that 1kg of water can only hold 8 mg of air no matter whether aerators are used or not. This means that only certain species of plants can survive for so long before being waterlogged.

In **aeroponics**, the roots of plants are kept in an environment saturated with fine drops of nutrient solution. This system has the major advantage of excellent aeration and wide range of crops that can be grown. It also uses relatively less water. Although its commercial viability has been argued for, it has not been commonly adopted.

Aggregate systems use an inert solid material which has most of the desirable physical properties of soil such as flexibility, being friable, good water holding properties, easily aerated and drained. The growing medium cannot grow anything on its own since it does not supply plant nutrients. The nutrients are supplied to the plants by a nutrient solution. However, many growers are confused or reluctant to use some mediums due to lack of experience, lack of performance information and/or ignorance regarding use of the medium in the short or long term [5].

There are several types of commercially available aggregate mediums which can be grouped as organic or inorganic; natural or artificial [1]. Some of the commonly used aggregate media in hydroponic systems include:

a) Rockwool

This is a popular growing medium produced from volcanic rock and limestone which are melted at temperatures of 2500°C or higher. It has high water holding capacity and can also retain as much as 20% air. It is inorganic, very light when dry, sterile and not degradable.

b) Perlite

This is volcanic rock which when heated in excess of 1000°C, expands into light weight particles. It is often used in potting soil mixes to decrease soil density.

c) Vermiculite

This is a natural mineral which expands on the application of heat. It is formed by hydration of certain basaltic minerals. It holds more water than perlite and has good wicking properties hence suitable for passive systems. It can also be used as a soil conditioner.

d) Crushed Granite

The granite rock is crushed and screened to a particle size of 2 mm. It is totally inert, but has relatively low water retention capacity. However, it can be re-used over longer periods.

e) Expanded Clay Aggregates

Round pellets are formed out of clay in rotary kilns at about 1200°C. This causes the clay to expand and become porous resulting in pellets which are inert, lighter in weight which does not compact over time. The pellets are rounded in shape and fall from the kiln in a grade of approximately 0-32 mm with dry bulk density of between 0.35-0.8 g m^{-3}. Although these pellets are considered re-usable [1], breaking a clay pellet after a crop has grown normally reveals root growth within the medium thereby casting doubt on reusability. Also, compared to other hydroponic media, they are relatively heavy and hence not suitable for certain hydroponic systems. In addition, they have been found to drain out fast because there is much space between each pellet than other hydroponic growing media [6].

Other growing media include coarse, washed river sand; coarse fir saw dust; coco coir and scoria which have different degrees of preference due to their varied characteristics. Safrovitz [5] carried out experimental trials to compare the performance between coco coir (palm pith), perlite, vermiculite, saw dust and also their mixes in different proportions. The trial used tomato crop which was subjected to similar environmental conditions and nutrient feed across the mediums. It was concluded that coco coir and perlite performed best among the mediums used in the trial but noted that results could vary depending on the hydroponic method used. It is noted that the variations in crop performance is not only dependent on the medium used but hydroponic system adopted as well [7].

In general, a good hydroponic medium should posses the following desirable characteristics:

1. It should be of light weight and low density;
2. It should be loose to allow easy root penetration;
3. It should drain easily;
4. It should have good water holding capacity;
5. It should have moderate permeability to allow for easy movement of water and solute (nutrients) through it;
6. It should not compact and should remain friable over a wide range of moisture contents;
7. It should remain inert over at least one crop growing season.

Black cotton soils (BCS) occupy approximately 200 million hectares in the arid and semi arid tropics but their suitability for Agricultural production is limited due to their unfavourable physical properties [8]. Adoption of hydroponic technologies can assist in up scaling food production in these areas both in terms of yield and increased choice of variety. The study aims to use the clay soil as a raw material and incorporate rice husks in the preparation of the expanded clay. It is expected that by using the rice husks, there will be more room to vary porosity and subsequent bulk density of the aggregate. This is achieved by varying the proportion of rice husk during preparation. Since the rice husks are organic in nature, they are easily combustible and therefore the clay expansion process could be achieved at relatively lower temperature using field based kilns thereby reducing the production costs appreciably.

The particle size reduction results in uneven particle sizes with wider distribution. This is expected to result in a wider distribution of pore sizes thereby addressing the low water holding capacity and fast drainage shortcomings of current products. The combustion of organic matter in the soil can result in doubling of temperatures hence a lower firing temperature is expected for the composite material compared to the optimum value of 1200°C used for the commercial expanded clay pellets [9].

2. Materials and Methods

The black cotton soil was obtained from Kenya Agricultural and Livestock Research Organization (KALRO) Kibos which lies at an altitude of 1173 m above mean sea level, about 8 km from Kisumu City in Kenya. It has heavy black clay soils (vertisols), which are fairly typical of the Kano Plains. The site lies within the Kano plain which is synonymous with the lower course of Nyando River. The plain occupies an area of approximately 430 km^2 sandwiched between the Nandi hills and the Nyabondo plateau. Figure 1 shows the location of the sampling site on the Kenyan map.

The nearest, reliable metereological station is Kisumu which according to Thornwaite's criteria is classed as an 'Equatorial humid' station with an annual mean temperature of 24.5°C, an evaporation rate of 1759 mm per annum and annual rainfall of 1270 mm [10]. The area experiences a high variability in rainfall distribution making agriculture to be a risky undertaking with high incidences of crop failure either due to floods or rain failure. Therefore, the area is a net importer of food. The main crops currently grown in the area are sugarcane, cotton, rice, maize and sorghum [11] but the potential to diversify further the choice of crops is high if the soil related problems are addressed.

The rice husks were obtained from the Lake Basin Development Company (LBDC) Kibos rice mills. This is a waste from the rice milling process and is found in abundance in the area due to the presence of rice irrigation schemes notably the West Kano and Ahero Irrigation Schemes.

The soil was mixed at predetermined ratios with the rice husks on a weight basis as indicated in Table 1. The mixture was moulded after wetting with water into cylindrical blocks. This was accomplished by using a cylindrical galvanized iron mould and wooden extruder. The mould dimensions were 52 mm diameter and 100 mm height. The blocks were then dried in an oven at 105°C for a period of 24 hours.

Higher amounts of rice husk could not permit adequate bonding by the clay and the blocks collapsed when removed from the mould.

Table 1. Clay soil to Rice-husk mix ratios

Black cotton soil (% by weight)	Rice husk (% by weight)
90	10
95	5
97.5	2.5
100	0

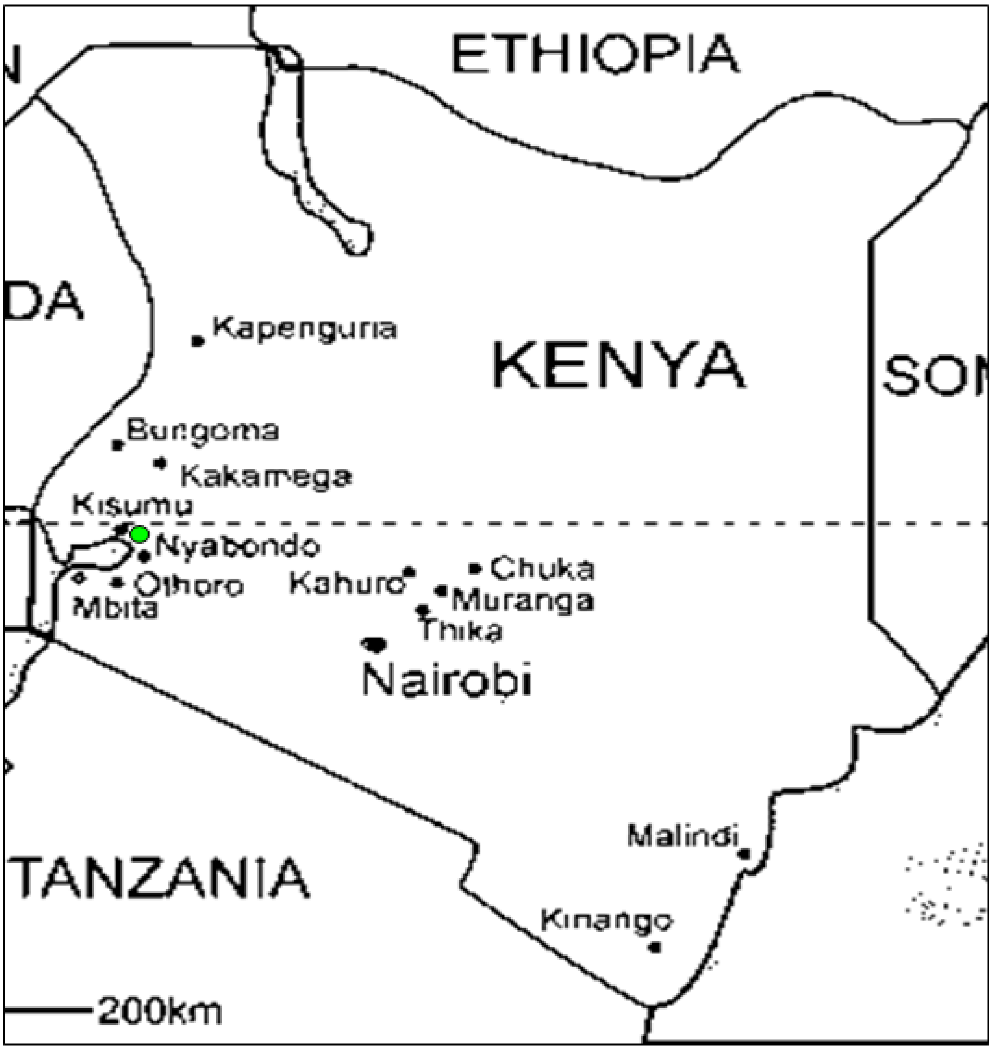

Figure 1. The map of Kenya showing the soil sampling site

The dried blocks were fired under varied but controlled temperatures in an electric furnace. The firing temperature ranged from 700°C to 800°C with steps of 50°C between one firing temperature and the next. The temperature limits were selected because all clay bodies contain some measure of carbon, organic materials, and sulphur which burn off at between 300°C and 800°C after which they fuse together. For each firing temperature, the firing times were 30 minutes, 60 minutes and 90 minutes. This was the time from when the desired temperature was attained to when the furnace was switched off.

Size reduction of the expanded clay blocks was done mechanically to obtain smaller aggregates within the particle size range of soils. These aggregates were passed through a series of soil test sieves. The top sieve was sieve number 4 with an opening size of 4.75 mm followed by sieve numbers 10, 20 and 200 with opening sizes of 2.0 mm, 0.85 mm and 0.075 mm respectively. At the bottom was the pan to collect the fines. Except for sieve number 4, the aggregates retained in each sieve, plus the pan, were mixed proportionately at a predetermined ratio of 1:4:4:1.

The dry bulk density (BD) was determined for the blocks before and after firing. This was the mass of the block divided by the volume of the mould assuming no shrinkage. For the aggregates, a density bottle was used. The bottle filled with aggregates was slightly tapped to enable packing as would result if water was added. The bulk density was obtained from Equation 1 as,

$$\rho_b = \frac{M_{(a+b)} - M_b}{V_b} \quad (1)$$

Where ρ_b = dry bulk density in g cm^{-3}
$M_{(a+b)}$ = mass of aggregates plus bottle in grams
M_b = mass of empty bottle in grams.

The saturated hydraulic conductivity was estimated using the constant head permeameter due to the coarse textured properties of the resulting aggregates when compared with the original black cotton soils. For the constant head method, the saturated hydraulic conductivity, k (cm s^{-1}) was computed using Equation 2 as;

$$k = \frac{qL}{Ah} \quad (2)$$

Where q = discharge in cm^3 s^{-1}
L = length of specimen (cm)
A = cross-sectional area of the specimen (cm^2) and
h = constant head causing flow (cm)

The results were analyzed using the SAS studio n-way factorial ANOVA at 5% level of significance and compared with desired values corresponding to loamy soils. The factors were as summarized in Table 2 resulting in 36 experiments for each property evaluated.

Table 2. Experimental Factors and the Levels used

Factor	Levels I	II	III	IV
Temperature (°C)	700	750	800	-
Time (minutes)	30	60	90	-
Black cotton soil (%)	90	95	97.5	100

3. Results and Discussion

3.1. Bulk Density

The overall mean bulk density was 0.99 g cm^{-3}. The model gave a coefficient of determination (R^2) of 0.973 and a Root Mean Squared Error (RMSE) of 0.0277 g cm^{-3}. The least square mean (LS Mean) of bulk density at different firing temperatures are given in Table 3.

This gave a mean value of 0.99 g cm^{-3}. Increasing the temperature from 750°C to 800°C did not result in a significant difference in the means between the two levels. Thus based on a need to conserve energy during firing and hence reduce the cost of production, the optimum firing temperature would be 750°C resulting in LS Mean bulk density of 0.967 g cm^{-3}.

The LS Means of bulk density based on the time of firing were 0.999, 0.991 and 0.981 g cm^{-3} for 30, 60 and 90 minutes respectively. There was no significant difference in the means across all the levels of time. The least time of 30 minutes was the most cost effective. In a study to determine the influence of firing temperature and time on clay bricks it was observed that prolonged firing time had no significant effects on the physical properties of clay bricks investigated. It was concluded that longer times were unnecessary and needed to be avoided to save time and energy [12]. The lowest LS Means of bulk density based on percent black cotton soil was achieved at 90% giving a value of 0.911 g cm^{-3} as summarized in Table 4 below.

The lowest bulk density was obtained by adding 10% (by weight) rice husk to the black cotton soil (BCS) before firing. A combination of the desired factor levels for the production of the medium was 750°C, 30 minutes and 90% for firing temperature, time and percent black cotton soil, respectively, gave a value of 0.94 g cm^{-3} although the lowest value of 0.83 g cm^{-3} was obtained for a combination of 800°C, 30 minutes and 90% black cotton soil but this would be uneconomical in terms of the energy demand required to raise the temperature from 750 to 800°C. The process at the selected factor levels is therefore able to appreciably reduce the bulk density by 34% from 1.43 g cm^{-3} for the original black cotton soil to 0.94 g cm^{-3}. This results in reduced weight, better root penetration, inertness and increased drainage, hence a better medium. However, the bulk density is still higher than those of commercial expanded clays which range between 0.35 to 0.8 g cm^{-3}. In this study, this could be improved by reducing the amount of fines in the medium. Table 5 gives the corresponding bulk densities for various aggregate size ranges at 750°C, 30 minutes, 90% black cotton soil factor levels.

The effect of the fines (0.0 to 0.075 mm) is to occupy the spaces between the larger aggregates thus increasing its density. A medium devoid of the fines would have lower bulk density but have reduced water holding capacity.

Table 3. LS Means for Bulk Density based on Temperature

TEMPERATURE (°C)	BD LSMEAN (g cm^{-3})
700	1.064
750	0.967
800	0.940

Table 4. LS Means for Bulk Density based on Percent Black Cotton Soil

%BCS	BD LS MEAN (g cm^{-3})
90	0.913
95	0.956
97.5	0.974
100	1.118

Table 5. Bulk Density of Aggregates at various Size Ranges

Size range (mm)	BD (g cm^{-3})
2.00 – 4.75	0.868
0.85 – 2.00	0.835
0.075 – 0.85	0.75

3.2. Saturated Hydraulic Conductivity

From the study, the overall mean of saturated hydraulic conductivity (Ksat) was 0.00446 cm s^{-1} giving 0.986 and 0.000294 for R^2 and RMSE respectively. The LS Mean of saturated hydraulic conductivity nearly doubled from 0.00335 cm s^{-1} to 0.00606 cm s^{-1} for a temperature change from 700°C to 800°C respectively, as shown in Table 6.

Low values hinder drainage and water movement, while high values result in very fast drainage and low water retention. The best soils for agricultural production are the loamy soils which have the following values of saturated hydraulic conductivity estimated by the RETention Curve (RETC) model given in Table 7 below.

From Table 6, it is noted that the value of Ksat corresponding to a firing temperature of 800°C is way above the range for loamy soils. In terms of the firing temperature, the ANOVA gave the results as in Table 8.

There was no significant effect on Ksat by raising the time from 60 to 90 minutes. However, the means at 60 and 90 minutes are above those of loamy soils. A firing time of 30 minutes is therefore not only sufficient but also the most economical. The least square means for saturated hydraulic conductivity reduced with a decline in percent rice husk as shown in Table 9.

Table 6. LS Means of Hydraulic Conductivity for Temperature

Temperature (°C)	Ksat (cm s^{-1})
700	0.00335
750	0.00396
800	0.00606

Table 7. Estimated Ksat Values for Selected Soils

Soil Texture	Ksat (cm s^{-1})
Clay Loam	$0.722 * 10^{-5}$
Silt Loam	0.000125
Loam	0.000289
Sandy Loam	0.001228
Loamy Sand	0.004053

Table 8. LS Means of Saturated Hydraulic Conductivity for Time

Time (min)	Ksat LS Mean (cm s^{-1})
30	0.00393
60	0.00470
90	0.00473

Table 9. LS Means of Saturated Hydraulic Conductivity for % BCS

% BCS	Ksat (cm s^{-1})
90	0.00521
95	0.00486
97.5	0.00434
100	0.00342

Higher percent clay soil content means more compact aggregates, hence the reduced hydraulic conductivity. From this analysis, it shows that 100% black cotton soil gives the lowest hydraulic conductivity but these results when compared with those of bulk density contrast.

In order to obtain the best set of preparation conditions, both the results on bulk density and saturated hydraulic conductivity were considered simultaneously together with the economics involved. A temperature rise from 750°C to 800°C did not result in significant change in mean bulk density but raises the hydraulic conductivity by 53%. Hence the higher temperature of 800°C is undesirable and uneconomical. The lower temperature of 700°C is also undesirable because it results in the highest bulk density which could mean incomplete combustion of the organic content. This would mean that aggregates prepared at this temperature may not be fully inert.

A firing time of 30 minutes was selected because it was the most economical as well as it gave acceptable results both in terms of bulk density and hydraulic conductivity. However the challenge was in deciding on the best percent black cotton soil. Since the optimum temperature and time has been selected as 750°C and 30 minutes respectively, they were treated as constants and the results for corresponding bulk density and saturated hydraulic conductivity expressed as in Table 10.

By trading saturated hydraulic conductivity for lowest bulk density, 90% black cotton soil was selected giving a Ksat value of 0.00385 cm s^{-1} which is although highest within the range of loamy soils. To further justify the choice of these conditions, the water retention was assessed. Table 11 gives the water retention at various tensions for the medium.

The water retained is consistently higher for 90% black cotton soil. This is an important parameter that affects water availability to crops and the medium's storage capacity.

Table 10. Hydraulic Conductivity and Bulk Density (at 750°C, 30 minutes)

% BCS	Ksat (cm s^{-1})	BD (g cm^{-3})
100	0.002475	1.327
97.5	0.003422	1.113
95	0.003604	1.076
90	0.003854	0.954

Table 11. Water Retention

% BCS	Moisture content (% wt)			
	10 bar	5 bar	1 bar	1/3 bar
100	12.01	12.92	13.11	34.73
90	13.58	15.79	15.65	49.62

4. Conclusions

Black cotton soils can be converted into an aggregate hydroponic media by improving on its physical characteristics to make it light weight with low bulk density, remain loose and friable over wide ranges of moisture contents, drain easily and have moderate permeability to permit water and nutrient movement through it.

In preparing the medium, optimal conditions of firing temperature, time and percent black cotton soil of 750°C, 30 minutes and 90% respectively, were selected and gave a mean bulk density of 0.954 g/cm^3, an appreciable reduction compared to 1.43 g cm^{-3} for the original clay soil. The corresponding saturated hydraulic conductivity obtained was 0.00385 cm s^{-1}, an improvement from $3.333*10^{-5}$ cm s^{-1} for the soil (estimated by RETC model based on the texture of the soil being sandy clay). Compared to commercial expanded clay aggregates fired at 1100-1200°C, the bulk density is slightly higher than average of between 0.35 to 0.8 g cm^{-3} but there is considerable savings on energy. In addition, the materials are available locally and special kilns could be designed to use the extra rice husk for firing reducing the cost of production further.

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