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Design and Development of Laboratory-Scale Water Treatment Unit using Sand and Shea Nut Shell Activated Carbon as Renewable Resources

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ABSTRACT: *The increasing demand for clean and safe water necessitates the exploration of innovative and sustainable solution. Hence, the study aims to design and develop an engineering innovation of a simple laboratory-scale water treatment unit for practical purposes. The research concept was based on sedimentation-filtration-adsorption treatment system. The design assumed unit capacity of 50 litres in batches with assumed retention time of 30 minutes. The unit is driven by gravity with the calculated flow rate of 0.1 m^3/hr. For effective gravity settling of flocs, the active sedimentation zone was assigned 75% of the total volume capacity and sludge sump storage volume of 15%, while the remaining 10% were allocated for freeboard. The media elements were slow sand and shea nut shell activated carbon (SNSAC) materials carefully selected based on the objective of the unit. The hydraulic loading rate of 0.35 m/hr was used, and the surface area of 0.0059 m^2 was evaluated. Also, the media depth of 0.25 m was considered producing headloss of 0.004 m. In calculating for the empty bed contact time (EBCT), the volume of SNSAC was calculated and 6 minutes was obtained. The design produced an active sedimentation tank and a sludge sump with appropriate dimension, parameters and specification. In conclusion, the study is in agreement with the basis of geometric, kinematic, and residence time similarities, a physical process that governed and dominated by internal flow routing, low velocity, gravity-driven flow and possible media interaction. And then recommended the workshop production development of the unit.*

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I. INTRODUCTION

Water pollution is a pressing global issue, threatening human health, economic development, and environmental sustainability. The increasing demand for clean water, coupled with the limitations of convectional water treatment methods, necessitates the exploration of innovative and sustainable solutions. According to the World Health Organization (WHO) (2011) a total of population of about 780 million people worldwide lack access to clean water. Furthermore, the people living in low-income countries especially in Africa suffer more from lack of access to clean and safe drinking water due to the geographic, economic, engineering capacity and social differences (Ahmed, 2019) despite with water availability in the sea, rivers and oceans.

The increase of human activities such as agricultural land development, the use of chemical fertilizer and pesticides/insecticides, coupled with increase in population, and industrial sites has negatively impacted the environment, due to the large quantities of toxic materials generated and released in forms of solid, liquid and gaseous (Kra *et al*., 2019) that have contaminated the open water bodies. This constitutes a great consequence that occurred on surface water bodies, living species and the environment.

The pollutants and impurities present in water need to be identified and removed using engineering concept that probably may start from laboratory model to prototype scale. The water treatment widely employed include physical, biological or chemical processes which effectively remove pollutants from polluted water and wastewater. The chain methods include coagulation-flocculation, biological treatments (biodegradable pollutants), electrochemical methods, membrane processes, and adsorption as well (Sakr, *et al.,* 2015). The last treatment process mentioned (adsorption) employed the use of activated carbon (AC) in large quantities.

AC incorporated with simple engineering unit has proven to be an effective water filtration technique for removing contaminants from drinking water and wastewater in most rural setup because it provides a large surface area on which the contaminant chemicals can adhere (Baruth, 2005). According to Evwierhoma, *et al.,* (2018), AC has been widely used in gas purification, gold purification, metal extraction, water purification, medicine, sewage treatment, air filters in gas masks and respirators, filters in compressed air and many other applications. In another context, having realizes the AC role in scheme of water and wastewater treatments and decontamination (Soonmin and Kabbashi, 2021), the extensive use of the AC in water and wastewater cleansing remains relevant to its comparatively extreme adsorption presentation. The urge for the possible use as a possible replacement to the traditional and innovative water and wastewater treatment lead to the conduct of the research knowledges (Liu, *et al*., 2020). The improved knowledges are not only randomly circulated globally, however also related through elevated working, conservation, and sustained costs (Palansooriya, *et al.,* 2020).

However, because of the high cost of imported AC (Kra *et al*., 2019) and constant rising manufacturing demands (Soonmin and Kabbashi, 2021), AC becomes matter of research subject. And its extent of surface area nature which mostly depends on materials (agricultural biomass resources) used for the production, called for the proposal of this work titled design and development of a simple laboratory-scale water purification unit using Shea Nut Shell Activated Carbon (SNSAC). For the purpose of testing the functionality, effectiveness and as well as for practical purposes in water and civil laboratories. These are renewable resources whose utilization has received great attention due to environmental considerations and the increasing demand for energy at worldwide.

II. MATERIALS AND METHODS

The Concept of the Unit

The concept of this work was borne as a result of a proposal to prepare activated carbon from Shea Nut Shell as renewable resource. The development followed the water treatment sedimentation tank concept as shown in Figure 1 in which processed water is settled by gravity in a conventional water treatment plant after the flocculation process. The first assumption is the required water, and determination of the flow rate in the tank. The sediments/flocs materials are settled in sludge tank and disposed of through a drain tap. The system is operated by simple gravity through which processed water move horizontally to the filtration compartments consisting of fine sand and activated carbon (AC) as filter elements. And the filtered water is collected through a trough guided and controlled by an outlet plate on both sides.

Hence, the assumed design capacity of the unit is 50-litres per day of water consumption. The unit was designed for laboratory purpose and gravity-driven hydraulic system as presented in the values of Table 1.

Table 1: Design assumption basis for the unit.

Parameter	Value basis
Design Treatment Capacity	50 litres per batch
Process Type	Sedimentation – Filtration – Adsorption
Operating Mode	Gravity flow
Target Detention Time	30 minutes
Safety Factor	1.3

Process Flow Arrangement

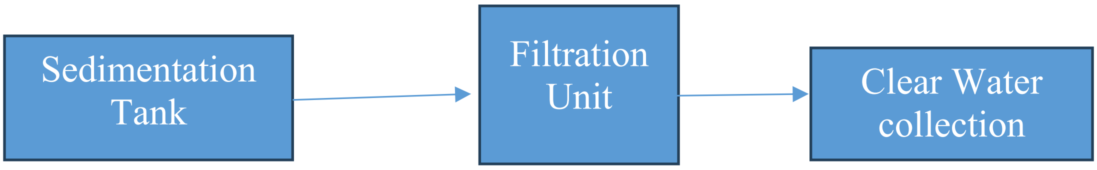

Figure 1: The flow process of the unit

Sedimentation Tank Design

For simplicity the sedimentation tank geometry is rectangular shape. The geometry was chosen because of easy construction and maintenance. The total working volume is 50 litres:

$$V_{total} = 50\ L = 0.05\ m^3$$

This active volume must be divided among the treatment flow system, namely

i. Active sedimentation zone
ii. Sludge storage zone (sump)
iii. Freeboard (for safety and hydraulic stability)

Sedimentation tanks are designed on the basis of detention time, t_d as presented in Equation (1)

$$t_d = \frac{V}{Q} \quad (1)$$

Where, V is the total volume. But intention here is to process 50 litres in batches of about 30 minutes (0.5 hour).

Therefore, the flow rate is given by

$$Q = \frac{0.05}{0.5}$$

$$Q = 0.1\ m^3/hr$$

For effective gravity settling of flocs in small systems, a recommended detection time, t_d is between 20 minutes – 40 minutes. Hence, using average time of 30 minutes is sought, therefore, the total volume is given as Equation (2)

$$V_s = Q \times t_d \quad (2)$$

$$V_s = 0.1 \times 0.5$$

$$V_s = 0.05\ m^3$$

However, the tank also needs space for sludge and freeboard, so the active sedimentation zone is assigned 75 % of total volume

$$V_{sed} = 0.75\ \times 0.05$$

$$V_{sed} = 0.0375\ m^3 = 37.5\ litres$$

This leaves room for sludge accumulation and safe operation.

Sludge Sump Volume

For small water treatment systems, we typically allocate between 15% – 25% of total volume for sludge. Therefore, 15 % is used as per laboratory-scale, hence

$$V_{sludge} = 0.15\ \times 0.05$$

$$V_{sludge} = 0.0075\ m^3$$

Freeboard Volume

Freeboard provides surge capacity, prevention of overflow and hydraulic stability. In selecting freeboard allowances for small sedimentation tank, standard practices value is between 8% – 12 % of tank volume. For this work, 10 % is assigned and hence,

$$V_{freeboard} = 0.10\ \times 0.05$$

$$V_{freeboard} = 0.005\ m^3$$

Design of Media Elements

Determine the type of media elements to be used in water treatment system require to understand some factors such as the water quality of the proposed abstract source, the treatment goals intend to be achieved, the flow rate and hydraulic loading rate, head loss and energy costs.

The media materials used are slow sand and AC. The hydraulic loading rate (HLR) for slow sand is between 0.1 m/hr – 0.5 m/hr. For this study an

average hydraulic loading rate value of 0.35 m/hr. was used. Hence, the value is converted to m/sec for easy calculation and gives 9.72 x 10^{-5} m/sec.
The next step is to calculate the surface area of the sand element which is given by Equation (3)

$$A = \frac{Q}{HLR} \quad (3)$$

$$A = \frac{5.78 \times 10^{-7}\, m^3/s}{9.72 \text{ x } 10^{-5} \text{ m/sec}}$$

$$A = 0.0059\, m^2$$

For the design of laboratory-scale water treatment unit, the media depth of 0.25 m is considered, therefore, the head loss is checked using the expression Equation (4)

$$h_f = \frac{180\ \mu\, L\, (1-\varepsilon)^2 V}{\rho g \varepsilon^2 d_p^2} \quad (4)$$

Where, h_f is the head loss, m; μ is the dynamic viscosity of water, Pa.s. usually 0.001 Pa.s @ 20°C; L is the media depth, m; ε is the porosity, typically 0.4 – 0.45 for sand; V superficial velocity, m/s (flow rate divide by area); ρ water density, kg/m^3 (1000 kg/m^3); g is 9.81 m/s^2; and d effective particle diameter, m.
Here the solution

$$h_f = \frac{180 \times 0.001 \times 0.25 \times (1-0.4)^2 \times 0.00009794}{1000 \times 9.81 \times 0.4^2 \times 0.0059^2}$$

$$h_f = 0.004\, m$$

Filter Sand Element
The parameters considered in the chosen filter elements include filter depth which is 0.25 m, sand size (diameter) that ranged from 0.3mm – 0.6mm, and also, the filtration rate of 5 m^3/m^2-hr (5 m^3/m^2-hr – 15 m^3/m^2-hr). The value of filtration rate was taken from the slow-to-rapid gravity filtration transition zone that have been optimized for small gravity system that was operated at the lower bound of rapid gravity filtration. It provides a high turbidity removal, long filter runs, low head loss, and no need of high pump energy (Crittenden and Thomas, 1998).
Grain size of between 0.3mm – 0.6mm in diameter satisfies two fundamental criteria: Hydraulic conductivity (not too slow) and particle capture efficiency (not too coarse) (AWWA, 2007). For engineering justification smaller than 0.3 mm results in excessive head loss and clogging, while larger than 0.6 mm gives poor turbidity removal according to Darcy's Law.
For effective gravity filtration design, the recommended values ranged from 0.15m – 0.30m for laboratories application, for small plants 0.30m – 0.60m and for the municipal 0.6m – 1.0m.

Activated Carbon (AC) Filter
Activated carbon performance highly depends on contact time not just the thickness of the elements. The empty bed contact time (EBCT) should be under time range > 12 minutes for organic flocculants removal. The contaminant type and required EBCT is presented in the Table 2.

Table 2: Contaminant type and required empty bed contact time (EBCT)

Contaminant Type	Required EBCT (minutes)
Taste-Odor	5 – 8
Color-Organics	8 – 15
Micropollutants	15 – 25

(Source: Bansal and Goyal, 2005)

The major objective of this study is to target turbidity polishing, color, odor, and organic removal, hence the EBCT given by Equation (5)

$$EBCT = \frac{V_{carbon}}{Q} \quad (5)$$

Where, V_{carbon} is the volume of the carbon elements while Q is the discharge through. Therefore, by the rectangular shape of the volume where carbon element takes 40 % of the thickness, the equation (6) was used.

$$V_{carbon} = Area \times thickness \quad (6)$$

$$V_{carbon} = 0.0059 \times (25\ \%\ 0f\ 0.14)$$

$$V_{carbon} = 0.000207\, m^3$$

The discharge, Q, through the system has been calculated and given as $5.78 \times 10^{-7}\, m^3/s$, hence the EBCT estimation is given by

$$EBCT = \frac{0.000207}{5.78 \times 10^{-7}\, m^3/s}$$

$$EBCT = 5.78 \times 10^{-7}\, m^3/s$$

$$= 357.27\, s = 5.95\, mins. \approx 6\, mins.$$

III. RESULTS AND DISCUSSION

Design Specification
The logical summary allocation processes is presented in Table 3 below:

Table 3: Summary of the unit processes allocation

Component	% of Total	Volume m^3 (Litre)
Sedimentation Tank	75	0.0375 (37.5)
Sludge Sump	15	0.0075 (7.5)
Freeboard	10	0.005 (5)
Total	100	0.050 (50)

The tank is rectangular in geometry given 0.0375 m^3 volume capacity, therefore the dimensions to the parts is presented in Table 4.

Table 4: Dimension of the Sedimentation Tank

Parameter	Dimension (m)
Length	0.50
Width	0.28
Depth	0.25
Freeboard	0.07
Total Depth	0.32

The parameter specification for the filtration unit is presented in Table 5.

Table 5: Design Parameters and Specifications

Parameter	Specification
Type of unit	Gravity-fed Adsorption Column
Construction material	Galvanized iron sheet
Design Flow Rate	0.1 m^3/hr.
Contact Time EBCT	6 minutes
Treatment Capacity	0.050 m^3 (50 litres)
Sludge Sump Capacity	0.0075 m^3

Treatment Unit Components

The unit components consist of the following parts and section as displayed in Figure 3 and labelled as A – E.

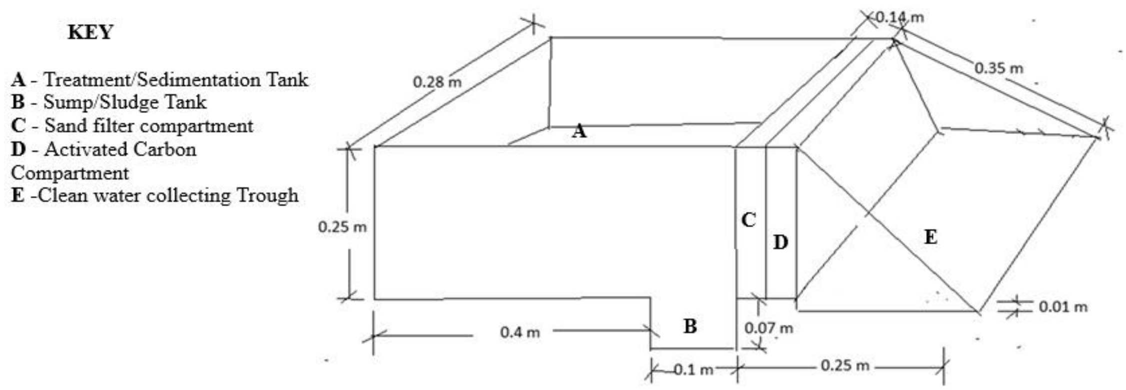

Figure 2: The components of the treatment unit.

Discussion

The study assumed a design capacity of 50 litres in batches at half an hour retention time of which the design calculation produced a flow rate of 0.1 m^3/hr and a retention volume of 0.05 m^3. In interpretation, this is a very small control volume suitable for the objective of this research work, laboratory-scale water treatment unit, and can be suitable for pilot filtration water treatment.

From the concept to produce effective water treatment unit as produced, presented and indicated in Figure 2, the unit was divided into three (3) zones, the active sedimentation zone (**A**), sludge storage zone (**B**), and freeboard for safety and hydraulic stability. The active sedimentation zone was assigned 75% of total volume capacity to leaves room for sludge accumulation and safe operation. A rectangular geometric sedimentation tank was chosen for its simplicity in construction and maintenance.

The sludge storage sump-type was assigned 15% of the total volume capacity as done for sedimentation tank because the standard followed the allocation specification of the value between 15% – 25%. Therefore, for laboratory-scale 15% of volume capacity was assigned given the calculated value of 0.0075 m^3 as presented in Table 3.

The freeboard provides surge capacity, overflow regulations and hydraulic stability. The standard practices in chosen freeboard value ranged from 8% – 12% of tank volume and 10% was assigned in this work to ease the gravity flow. The moderate volume value of 0.005 m^3 was produced.

In designing for filtration media elements, slow sand and SNSAC were chosen. The hydraulic loading rate for slow sand of 0.35 m/hr was adopted and used to evaluate its surface area of 0.0059 m^2 of which observed to be adequate for laboratory-scale water treatment unit according to previous study. At media depth of 0.25m, the head loss was estimated as 0.004m. In operation, lower bound of rapid gravity filtration to provides for high turbidity removal, and of no energy pumping.

The SNSAC performance is heavily depends on contact time and according to the objective of this study (removing turbidity, color, odor, and organic materials), the EBCT 6 minutes was estimated. This is acceptable and sufficient for laboratory scale water treatment unit according to WHO (2011) of which the effective sufficient is guarantee by filter elements.

The design value for the sedimentation tank specified 0.0375 m^3 of rectangular geometric form providing the dimensions of 0.5 m length, 0.28 m width, 0.25 m depth, and 0.07 m freeboard. The design parameters and specification indicated gravity-fed adsorption column unit type, design flow rate of 0.1 m^3/hr, EBCT of 6 minutes and production capacity of 0.05 m^3. The concept unit from the design produced the components drawing that can be put to prototype for further development as shown in Figure 2.

IV. CONCLUSION

The objective of the study was to produce a design laboratory-scale water treatment unit suitable for laboratory study/testing of water quality for any purpose such as water abstraction from sources, the achievable treatment goals, flow rate and hydraulic loading rate desired with low gravity flow. The study designed a physical process that governed by system dominated by internal flow routing, low velocity, gravity-driven flow, no inertia turbulence and possible media interaction. In action, the system is dominated by gravity, low-velocity, retention time, non-pressurized and laminar to weakly transitional.

It can be concluded that, the design follows the basis of geometric, kinematic and residence time similarities, implicitly keeping the flow laminar and transitional. These conditions will be suitable and possible to produce the unit prototype and commence further study on the research objectives.

V. RECOMMENDATION

The study recommends as follow:

i. The workshop production development of the design water treatment unit can be commenced.

ii. The conduct of future hydraulic and similarity frame-work analysis of the design unit could be proposed.

iii. The study on the efficiency of the unit in term of water production, treatment and functional capacity is opened.

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CONFLICT OF INTEREST

The research was a participatory effort by all the authors listed herein, all decisions were agreed upon by the authors, therefore no conflict of interest of whatsoever.

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