Design and construction of an affordable potable water treatment unit for domestic usage

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Abstract: An affordable potable water treatment unit was designed and constructed . The components were coagulation unit, sedimentation unit, slow sand filter unit, utraviolet unit and the storage unit . Filtrate from the chamber was compared with International acceptable standards . The result showed that the treatment chamber proved effective and can produce at least 100 L of portable water per day. The physical and chemical parameters monitored were reduced to the acceptable limit by WHO (World Health Organisation), NAFDAC (National Agency for Food and Drug Administration and Control) Nigeria, Nigerian Standard for Drinking Water Quality (NSDWQ), and NWRI (National Water Research Institute, Nigeria) . However, coliform was not totally removed but the count was reduced by 99.4%.

Keywords: Raw water, filtration, potable water treatment unit, domestic usage, Nigeria,

Citation: Isikwue, O. M., J. A. Ato, and I. T. Ayua. 2015. Design and construction of an affordable potable water treatment unit for domestic usage. Agric Eng Int: CIGR Journal, 17(3):1-9.

1 Introduction

Water is a wonder of the Nature. "No life without water'' is a common saying depending upon the fact that water is one of the naturally occurring essential requirements of all life-supporting activities. Any change in the natural quality may disturb the equilibrium system and it would become unfit for designated uses. The availability of water through surface and groundwater resources has become critical today. Only 1% is available on land for drinking, agriculture, domestic power generation, industrial consummation, transportation and waste disposal (Punmia et al., 2004) . The WHO(2004), estimates that 94% of diarrheal cases are preventable through modifications of the environment, including access to potable water. Simple techniques for treating water at home, such as chlorination, filtration, solar disinfection, and storing it in safe containers could save a huge number of lives each year.

Received date: 2014-03-29 **Accepted date:** 2015-08-01

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Impurities in water are classified as; suspended, dissolved and colloidal. Suspended impurities are microscopic and normally remain in suspension, making the water turbid. Dissolved impurities are not visible, but cause bad taste, hardness and alkalinity. Colloidal impurities are electrically charged particles, usually very small in size that remain in constant motion and do not settle. One of the simplest ways to remove the small-sized particles is by filtration.

The common sources of water are; rain water, surface water, groundwater, and water obtained from reclamation . Flanagan(1992) reported that the usual physical and chemical parameters of groundwater include: Temperature (T), pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), total alkalinity (TA), total hardness (TH), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+),potassium (K^+), chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), sulphate (SO_4^{2-}) and chemical oxygen demand (COD), odor, taste, color, turbidity, pathogenic organisms, and salinity . The quality parameters of importance as far as domestic water is concerned are its physical, chemical and bacteriological properties. Haas (1999) argued that irrespective of water sources, some soluble salts are always dissolved in it . Among the soluble constituents of prime importance in determining the quality of water and its suitability for domestic use are calcium, magnesium, sodium, chloride and sulphate . All surface waters and some groundwater require treatment prior to consumption to ensure that they do not constitute health risk to the users .

Quality and quantity of water to be produced are two criteria that are considered in the design and construction of water treatment unit (Linsley and Franzini, 1979) . It is necessary to consider the population of the area under study, the daily consumption rate and expansion because of population growth rate .

The treatment unit constructed utilizes the principle of slow sand filtration system . A slow sand filter (SSF) is a type of water treatment system suitable for domestic use or in small rural communities . It removes sediment and pathogenic organisms from contaminated water in a single treatment process . The advantages of SSF include (1) it can be constructed by local people, it does not require high technical skill (2) it can be built with local available material (3) it can be operated and maintained manually, it does not require machinery (4) It produces a microbiologically clean water which does not require disinfection.

According to Thames Water and University of Surrey (2005), the purpose of filtration is to remove the particulates suspended in water by passing the water through a layer of porous media. Basically, filtration process is a combination of physical (filtration, sedimentation, and adsorption) biochemical and biological processes . A number of complex forces (transport, attachment, and purification) contribute to each of these stages. SSF is more suitable to treat raw water with low to moderate turbidity and moderate to high dissolved oxygen concentration . Some transport mechanisms involved include laminar/turbulent flow, interception, straining, sedimentation, gravity, inertial and centrifugal forces, diffusion, mass attraction, advection, motility, hydrodynamic forces, and electro-static and electro-kinetic forces .

There are four basic components of slow sand filter system: (1) Raw (supernatant) water reservoir – to make maintain a constant head of water above the filter medium, the head provides the pressure that carries the water through the filter . (2) A bed of filter medium (sand) upon which various purification processes take place . (3) Under-drainage system which serves the purpose of supporting the filter medium and presenting minimum obstruction to the treated water as it emerges from the filter bed . (4) Control valves to regulate the velocity of flow through the bed to prevent the level in the raw water reservoir from dropping to minimum during operation.

The objectives of the study include;

1. To design and construct an affordable water treatment unit for domestic use.

2. To produce water of high level of purity that will conform to the acceptable standards from the unit constructed.

3. To eliminate the use of chlorine as its excess results to harmful by-products.

2 Materials and method

2.1 Study area

The University of Agriculture, Makurdi, Nigeria is the study area . It lies between **Latitude**7 ° 43' 32" North and **Longitude** 8 ° 33' 51"East . It is located within the flood plain of lower Benue River valley with physiographic characteristics spanning between 73m – 167m above sea level. Makurdi is tranversed by Benue River (second largest river in Nigeria) . Temperatures are generally high throughout the year due to constancy of insolation with the mean maximum of 32^0C and mean minimum of 26^0C . The hottest months are March and April . The rainfall here is convective, and occurs mostly between the months of April and October and is derived from the moist and unstable southwest trade wind . Despite the big river the rural dwellers lack access to potable water for their domestic and sanitation purposes which has severally led to outbreak of diseases like cholera and diarrhea (Ato and Ayua, 2013).

2.2 Components of the potable water treatment unit

2.2.1 Raw water/ Coagulation tank

The raw water/coagulation tank was a cylindrical plastic container measuring 0.90m deep. The top and bottom diameters are 0.50m and 0.4m respectively. Also incorporated on the tank is a coarse cylindrical strainer to help reduce algal and plankton effect and to trap undesirable particles from entering the sedimentary tank.

2.2.2 Sedimentation tank

The sedimentation tank consists of cylindrical plastic container with equal dimensions as that of raw water tank. Here, the raw water is allowed to settle for some minutes. The sedimentation tank was built to allow the upward flow of the settled water.

2.2.3 Filtration chamber (slow sand filter)

This consists of plastic container, filter media (sand and gravel) and under drain pipe.

Gravel materials were meant to provided support for the sand bed, and act as filter which prevents sand particles from blocking the under drain system (outlet) . It was first introduced into the container to a depth of 15cm (0.15 m) as recommended by Stevenson (1994) that filters used in water filtration for domestic purposes should range from 0.15m to 0.30m in thickness . Then, the fine and coarse aggregates (sand) followed up as the first and middle layers of the media at a depth of 30cm (0.30 m) and 10cm (0.10 m) respectively (VanDijk and Oomen, 1978). The sand was light brown in colour and comprises of different grain sizes . It is completely free from clay, loam and organic matter . The material is common and abundant in the locality.

2.2.4 Micro filters

Microfiltration membranes (adsorbent) have pore sizes that vary from 0.5 to 5 microns . This is to separate suspended solids, bacteria, cysts and many other parasites whose diameter are larger than the pore size of the membrane . The adsorbent materials used was activated carbon because of its availability and affordability . According to Agunwamba (2001), adsorption is a process in which molecules leave the solution and are held in a surface by chemical and physical bonding . The absorbed material is called the adsorbate while the absorbing face is the adsorbent . The bonding is physical if it is reversible and chemical if it is irreversible . Adsorbent usually have large surface areas inside the particles (e.g. silica gel and activated carbon). Adsorption removes organics, taste, colour, turbidity etc.

2.2.5 Ultraviolet light (UVL)

The ultraviolet light chamber is used to generate ultraviolet wavelength with the desired germicidal properties and for delivery of the light to microbial pathogens, which is used for disinfecting the water . When properly connected and powered with electricity, it generates wavelengths of 200 – 300 nm, which inactivates most microorganisms, with the greatest amount of inactivation occurring around 260 nm.

2.2.6 Storage tank

This stores the treated clean water which is ready for human consumption. It is well covered to avoid recontamination of the water.

2.3 Assemble of the water treatment unit

The four plastic containers which served as a separate chamber (tank) for raw water/coagulation, sedimentation, slow sand filter and storage processes respectively were fitted with pvc pipes to the outlets interconnecting them . They were connected through the orifices that were drilled on each tank . The area of contact between each pipe and each container was sealed with sealing material (PVC glue) to prevent leakages . The entire system was arranged in varying elevations to allow free flow by gravity . The slow sand filter media was linked to the four micro filters to further improve the quality of the filtrate . The micro filters were connected to the ultraviolet light chamber using 2.54cm PVC pipe to ensure that the filtrate was sterilized . The ultra violet light was connected to the storage tank . Figure 1 shows the design sketch and arrangementof the treatment unit.

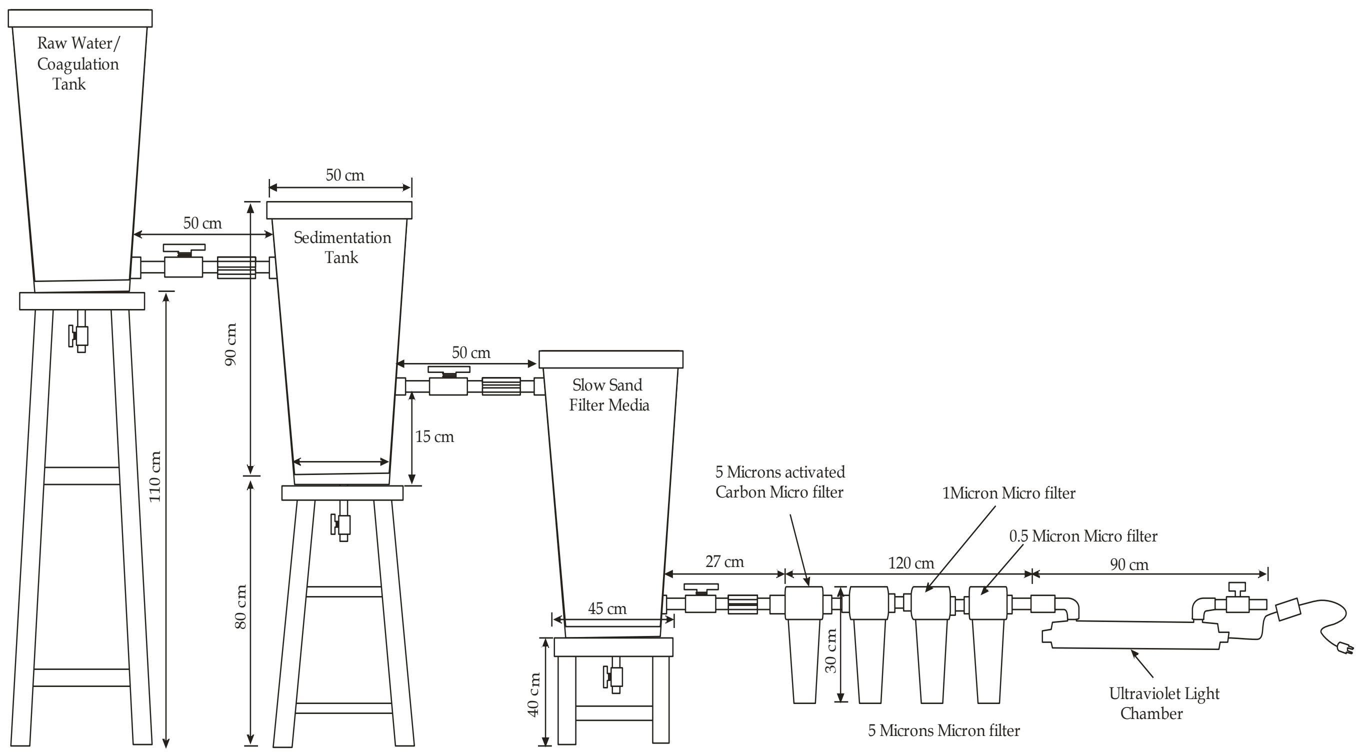

Figure 1 Assemble of the water Treatment Unit

2.4 Collection and treatment of mineral river materials.

The mineral river materials were scooped from the bottom of River Benue . The sand (fine and coarse) and the gravel materials were separately washed manually with water repeatedly . The washed sand and gravel materials were disinfected by soaking in a solution of chlorine and concentrated hydrochloric acid for 24 h to unbind the organisms attached to them . The sand and gravel materials were later washed in distilled water, to reduce their pH.

2.5 Operation of the treatment plant

The raw water flows from the raw water/coagulation tank into the sedimentation tank and from there it enters slowly into the slow sand filter chamber . The filtrate is passed through micro-filters for more filtration process and then through ultraviolet (UV) light chamber for sterilization. . After the UV light the filtrate (clean water) enters the storage tank . Each stage or process is connected to the other with a valve to regulate the movement of water . With the slow sand filter, water is passed slowly downwards through a bed of sand, where it is treated by a combination of biological, physical and chemical processes . The water passes through the three layers of the slow sand filter media (fine sand, coarse sand, and gravel) . Fine particles in the water are filtered out by the sand, while a population of microorganisms (Schmutzdecke) grow on top of the sand filter and feed on bacteria, viruses and organic matter in the water . The rate of downward movement of water is kept so small that laminar flow conditions may be assumed to prevail throughout the filter bed . The resistance H, offered by the filter as reported by (Huisman and Wood, 1974) is in accordance with Darcy’s law as Equation 1:

$$H = \frac{V_f}{K}.h \qquad (1)$$

where h = the thickness of the filter bed; K = coefficient of permeability (distance per hour); V_f = filtration rate (volume passing per hour divided by the surface area of the bed).

During operation the sand filter is covered with a water depth of 0.3 – 0.35m.

The four micro filters (membrane filtration), operate on the principle of particle separation, based on pore size and pore size distribution . The micro filters further filter the water eliminating colour and odour problems . The first micro filter membrane was incorporated with a 5 microns activated carbon micro filter to trap suspended solids larger than 5 microns, absorb chlorine and many other contaminants and also to improve taste of the filtrate . The second, third and fourth micro filtration membranes had pore sizes of 5 microns, 1 micron and 0.5 micron respectively which trap suspended solids greater than their respective pore sizes . The filtrate then flows into the ultraviolet light chamber . The pathogens in the filtrate were inactivated or sterilized to produce a desired water quality ready for usage, which eliminates the use of chlorine . The stages of operation are as shown in Figure 2.

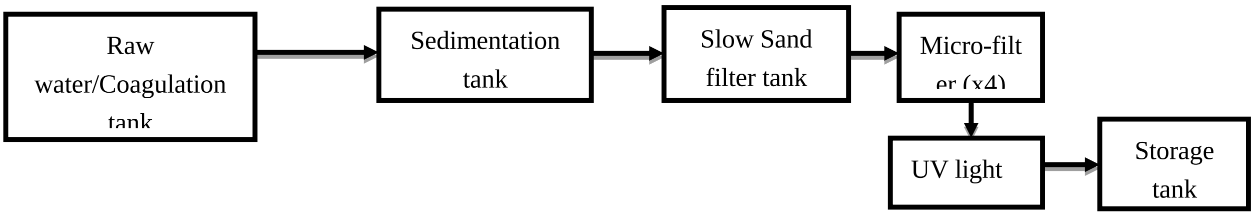

Figure 2 Flow chart of the operation of the treatment unit

2.6 Testing of the treatment plant

The water treatment process was achieved by utilizing a variety of treatment operations/processes, which exploited various physical and chemical phenomena to remove or reduce the undesirable constituents from the water . A coagulant (alum) was added into the raw water/coagulation tank and manually stirred thoroughly to destabilize the colloidal particles **.** After conducting the raw water analysis, the result was used to determine the amount of coagulant (Aluminium sulphate ($Al_2(SO4)_3.14H_2O$)) to be added during the unit process. The alum dosage was determined to be 16mg/L . The reaction results in the formation of larger particles, which gain more strength, and tend to settle at the base of the tank . The aim of adding coagulant is to reduce the amount of suspended particles that may flow into the filter **-** thereby over working the filter media . The raw water was allowed into the sedimentation tank where the water was allowed to settle for about 30 mins before allowed to flow to the slow sand filter and then into the storage tank . One-litre sterilized containers were used to collect water samples in three replications and transported under cold storage to the laboratory for analysis of the water quality.

2.7 Flow rate

The flow rate was controlled by regulating the ball valve . The valve was intermittently adjusted until the required rate of flow was achieved.

The volumetric flow rate, $\emptyset$ (as Equation 2) was then estimated from measurement of filtrate volume and duration of flow through the filter medium by using a stopwatch.

$$\emptyset = \frac{Volume\ of\ filtrate}{Time\ Taken}\ (litre/second) \qquad (2)$$

A volume of one liter was measured to have flown into the filtrate container during an estimated time of 14 min and 24 s (864 s). Applying Equation (2), the flow rate was

$\emptyset = \frac{1L}{864} = 1.16 \times 10^{-3}$ L/s or 4.18 L/h . This was the flow rate achieved for the testing . Based on this, the total volume of water expected to be produced in a day was calculated.

2.8 Water sampling

Raw water samples were collected at a depth of 15 cm from River Benue in one-litre sterilized containers, kept in darkness at 4℃ until microbiological processing are completed . Weights and rope were tied to the mouths of the containers to help lower them to the required depth (15 cm). The samples were collected in three replications across the width of the river (the two banks and the centre) by using a small canoe . It was collected in the morning hours (8.00 am) and transported under cold storage to the laboratory for analysis of the water quality.

Treated water samples were collected in one-litre sterilized containers in three replications and transported under cold storage to the laboratory for analysis . The essence of the cold storage was to keep the samples in stable condition.

2.9 Filtrate quality

The water samples (collected filtrate) were analyzed at Benue State Water Board Makurdi in order to assess the physico-chemical and microbiological quality . The parameters analyzed with the methods used are presented in Table 1.

Table 1 Parameters analyzed with their method of analysis

S/No	Parameter	Method of Analysis
1	Turbidity (mg/L)	Turbidity meter
2	pH	pH meter
3	Appearance	Visualizing with the Eye
4	Taste	Tongue
5	Colour	Photometer
6	Electrical Conductivity (μs/cm)	Electrical Conductivity meter
7	TDS (mg/L)	TDS meter
8	Nitrates (mg/L)	Colorimetry
9	Fe (mg/L)	Atomic Adsorption Spectrum (AAS)
10	PO_4 (mg/L)	Colorimetry
11	SO_4 (mg/Ll)	Colorimetry
12	Total hardness (mg/L)	Colorimetry
13	Ca (mg/L)	Titrimetry
14	Mg (mg/L)	AAS
15	DO_2 (mg/L)	DO meter
16	Total Coliform count (cfu/L)	Multiple-tube fermentation (Bacterial count using Most probable number, MPN)

Note: Source: Agunwamba (2008).

The results of the analyses were compared with WHO and NAFDAC, Nigeria standards for potable water.

2.10 Cost estimation

The cost of designed and constructed unit was estimated at the rate of ₦80, 000.00 (Eighty thousand Nigerian Naira) only (i.e US$ 471 at exchange rate of ₦170/$) .

3 Results and discussion

3.1 Physical parameters

The results of physical analysis are presented in Tables 2 . These values were compared with the WHO (2004), NAFDAC (2004), NSDWQ (2013) and National Water Research Institute (NWRI, 2013) standards of potable water.

Table 2 Physical characteristics of raw water, treated water and standard reference values.

S/No.	Parameters	Raw water Control	Treated water	WHO standards	NAFDAC standards	NSDWQ/ NWRI
1	Turbidity (mg/L)	39.00	3.00	5.00	-	5 NTU
2	pH	7.40	6.80	6.8 – 8.4	6.5 – 8.5	6.5 – 8.5
3	Appearance	Brownish	U	U	U	Clear
4	Taste	Objectionable	U	U	U	-
5	Colour	82.00	5.00	5.00	-	-
6	Electrical Conduct. μs/cm	78.40	60.80	100	-	-
7	TDS mg/L	34.70	29.60	100	500	500

Note: KEY: U = Unobjectionable,

There was a considerable reduction in the value of turbidity from 39 mg/L to 3 mg/L which is within the acceptable limit of WHO . Evidently, the filter media in conjunction with the micro filtration membranes had drastically reduced the turbidity of the raw water through filtration, implying high retention capacity of the filters . This shows the efficiency of the filter materials and their arrangement . That is gravel was laid in layers commencing with larger size at the bottom, and reducing in size progressively to the top followed by sand grains.

The pH value of the treated water (6.8) is within the range of WHO and NAFDAC's acceptable standard for drinking water, which is satisfactory for usage . This indicates that the coagulate dosage (16 mg/L) was okay.

The Colour of the raw water was 82 units, which was reduced to 5 units, hence corresponding to the WHO and NAFDAC acceptable standard for drinking/domestic water (5units) indicating that the colour of the treated water was clear and colourless . In addition, the filtrate sample was tasteless and had an unobjectionable smell . This made the water safe and palatable for its desired usage. The TDS of the raw water was 34.7mg/L and after treatment it reduced to 29.60mg/L, which was also within the range of WHO . Total hardness of the raw water sample, which was 100 units reduced considerably to 80 units after treatment . Other parameters also reduced at various proportions like electrical conductivity 78.40 to 60.80 µs/cm, temperature 25.5^{o}C to 25.0^{o}C.

3.2 Chemical parameters

Table 3 presents the result of the chemical parameters as analysed in the laboratory.

Table 3 Chemical characteristics of raw water, treated water and standard reference values.

S/No	Parameters (mg/L)	Raw water	Treated water	WHO	NAFDAC	NSDWQ/ NWRI
1	Nitrates	19.20	7.20	-	-	-
2	Fe	1.42	0.22	0.3 – 0.5	<200	0.3
3	PO_4	0.98	0.58	-	-	-
4	SO_4	28.00	18.00	200	-	100
5	Total hardness	100	80.00	500	200	100
6	Ca	60.00	60.00	50.00	200	-
7	Mg	40.00	20.00	50.00	75	-
8	DO_2	5.70	6.00	-	-	-

There was significant reduction in nitrates (NO_3), iron (Fe), phosphate (PO_4), sulphate (SO_4), magnesium (Mg) etc . This indicated that, the treatment unit is capable of reducing even toxic substances in water . Excess of these chemical parameters have adverse effects. For example, Isikwue and Chikezie (2014), highlighted that excess amount of nitrates in water causes an increase in algal growth and if in drinking water can be toxic to humans . Sources of nitrates may include human and animal wastes, industrial pollutants and non-point source, runoff from heavily fertilized croplands and lawns . High levels of nitrates in drinking water have been linked to serious illness and even death in infants.

3.3 Bacteriological Parameters

The result of the bacteriological test carried out on the raw and treated water is shown in Table 4.

Table 4 Bacteriological characteristics of raw water, treated water and standard reference values.

S/No	Parameter	Raw water	Treated water (filtrate)	WHO	NAFDAC	NSDWQ/ NWRI
1	Coliform count MPN/100 mL	900	5.00	0	-	0

From the Table, it is easily evident that the raw water value of 900 MPN/100 ml reduce d 5 MPN/100 ml after treatment. The presence of bacteria is an important indicator of water quality (Kegley and Andrew, 1998) . Even though this is above the WHO,NSDWQ and NWRI values of 0 MPN/100 ml, however the 99.4 % reduction is a very significant achievement . Based upon the above values, it could be said that the water treatment unit designed and constructed is capable of trapping, retaining, sterilizing and eliminating coliform from the raw water . Most bacterial and virus removed could be attributed to the action of the slow sand filter bed, micro filtration and the ultraviolent light wavelength.

The quality of water delivered depends on (1) the quality of raw water (2) the climatic condition particularly (3) the filtration rate and (4) the composition of the filter medium . It was observed that, high flow velocities allowed the passage of water through the filter bed with least resistance and consequently results in low filtrate quality. Also the lower the flow rate the higher was the filtration efficiency - hence the more acceptable water quality . Flow rate and turbidity should be paramount in the design and need to be carefully controlled in the filtration process.

The estimated cost of ₦80,000.00 (Eighty thousand Nigerian Naira) or US$ 471 only is believed to be considerably affordable and cheap as compared to the disastrous effect of non - potable water usage or other higher water treatment technology.

With the estimated flow rate of 4.18 L/h the unit gave an estimated approximate production capacity of about 100 L/d . According to USAID (1982), it is estimated that each person will need a minimum of 20 – 50 L of water a day for drinking, cooking, laundry, and personal hygiene.

4 Conclusions

A potable water treatment unit was designed and constructed with a capacity of about 100l/day. The filtrate and raw water samples were collected and analyzed. The results met the desired specifications and standards set by WHO and NAFDAC for potable water usage. However, coliform was not completely eliminated but there was reduction to 99.4%.

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