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To cite this article: Yusuf Kola Ahmed , Morufu Olusola Ibitoye , Abdul Rasak Zubair , Janet Mosunmola Oladejo , Suleiman Abimbola Yahaya , Saheed Olayinka Abdulsalam & Ridwan Oladipupo Ajibola (2020) Low-cost biofuel-powered autoclaving machine for use in rural health care centres, Journal of Medical Engineering & Technology, 44:8, 489-497, DOI: [10.1080/03091902.2020.1825847](https://doi.org/10.1080/03091902.2020.1825847)

To link to this article: <https://doi.org/10.1080/03091902.2020.1825847>



Published online: 29 Oct 2020.



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INNOVATION



Low-cost biofuel-powered autoclaving machine for use in rural health care centres

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ABSTRACT

Surgical site infections (SSIs) in developing countries have been linked to inadequate availability of sterilising equipment. Existing autoclaves are mostly unaffordable by rural healthcare practitioners, and when they managed to procure them, the electricity supply to power the autoclaves is epileptic. The solar-powered autoclave alternatives are too bulky with a very high initial cost. Hence, low-cost biofuel-powered autoclave becomes an attractive option, and this study sought to present the design, development and clinical evaluation of the device performance. With the global drive for the adoption of green energy, biofuel will not only reduce greenhouse gas emission but also provide revenue for local producers and reduce biomass associated health complications. The theoretical energy requirement for the sterilisation process was calculated. The standard pressure and temperature needed for sterilisation were tested to be 121 °C and 15 psi. The device was also clinically tested with *Staphylococcus aureus* bacteria obtained from the Department of Medical Microbiology and Parasitology, University of Ilorin Teaching Hospital using Brain heart Infusion Broth, MacConkey and Blood agar as cultured media. No bacteria growth was observed when the samples containing the bacteria colony were autoclaved by the designed autoclave and incubated at 37 °C for 2 d. Hence, the device met the mechanical and biological validation standards for effective sterilisation.

ARTICLE HISTORY

Received 23 July 2020
Accepted 6 September 2020

KEYWORDS

Surgical site infection; sterilisation; rural health care centres; biofuel; autoclave

1. Introduction

Sterilisation is an integral part of regular activities in any functional health care centre either to ensure safe disposal of some medical wastes or decontamination of reusable medical devices. Effective sterilisation of medical devices is necessary to prevent healthcare-associated infections (HAI) such as nosocomial infection and surgical site infection (SSI) [1,2]. SSI(s) are infections acquired by patients within 30 d or more after an operative procedure [1]. In 2011, World Health Organisation (WHO) submitted that HAI is a significant burden in developed countries as about 15% of patients in regular wards and over 50% patients in intensive care units (ICU) were affected [2,3]. For example, an average of 500,000 cases of SSI is recorded annually in the United States alone [4]. Although there are few statistics available from developing countries about HAI as resources and expertise needed for such records are limited, the available data

indicated that their cases of HAI are higher [2]. The WHO's report established that about 23.6% of procedures are affected by SSI in developing countries, while only 5.2% of procedures are affected in developed nations [1]. Nigeria, being a prominent country in Africa, is reported to have 30.9% of her paediatric hospital procedures affected by SSI [5]. Another study conducted in a Nigerian teaching hospital by Olowokere et al. [6] reported 27.6% of hospital procedures being affected by SSI in 2018.

Economic implications of SSI often result in higher health care cost, prolonged clinic stays, induced stress on the patient and their families [2,7]. It also financially burdens the healthcare system, creates additional workload for the healthcare workers, precipitates extended disabilities and sometimes death [1,2,8]. To check this trend, it is evident from a study by Fehr et al. [9] that the presence of adequate quantities of working autoclaves can reduce the occurrence of SSI immensely. In their comparative study, a 4%

Table 1. Materials used and their comparative advantage.

S/N	Material	Advantage
1	Mild steel sheet	It has high ductility, elasticity, mechanical strength; it is affordable and readily available
2	Dual gauge	It provides both pressure and temperature reading concurrently, easy to monitor and portable
3	Pressure release valve	It controls the intensity of pressure in the autoclave. It is heat resistant and easy to install
4	Perforated stainless sheet	It is light in weight, easy to clean, and has good ductility and tensile strength
5	Lock-nut	It has good thermal resistivity, hardness and firm grip
6	Rubber gasket	It is stable to heat. It has good expansivity and high strength

deep tissue and 2% organ space SSI was recorded in an environment with many functional autoclaves while 62% and 10% of deep tissue layer and organ space associated SSI, respectively, were recorded in a similar environment without sufficient functional autoclave [9]. Local development and manufacturing of autoclaves and other biomedical devices in Africa will improve the availability of adequate quantities of these devices and hence improve healthcare delivery system in Africa [10]. COVID 19 lockdown of nations has made it necessary for each country to have adequate healthcare facilities.

According to Spaulding's classification, SSI is often associated with critical medical devices such as a scalpel, implants and transfer forceps, among others [11,12]. There are several sterilisation methods for different purposes [11,13]. A performance evaluation of the latest sterilisation methods such as ethylene oxide, dry heat, Anderson system, steam autoclave and gamma rays was carried out by Mubarak et al. [11] using fuzzy PROMETHEE method. Steam sterilisation is found to be the best based on factors such as cost, cycle time, temperature, volume capacity and penetration power [11]. WHO and the US Centre for Disease Control (CDC) also rate steam autoclaving as the best autoclaving method [8,12,14].

In the literature, there have been several steam autoclave design interventions to reduce infection but the persistent power outage and unstable mains supply in African rural and urban areas constitute limitations of the applications of the autoclave designs. Furthermore, the autoclaves are costly and require a relatively high level of skill to operate and repair [15,16]. Solar-powered autoclave alternative is also very expensive, weather-dependent and bulky [15]. For sustainability in a low resource setting, a biofuel-powered autoclave design is proposed in this study. Going by the global drive to go green and reduce, if not eliminate, greenhouse gas (GHG) emission, a bio-fuel power source is a suitable alternative. This bio-energy source is inexpensive as it is produced from readily available plant materials called biomass. It hardly pollutes the air with little or no mass deposit [17]. Thus, it has a very high efficiency. The autoclave

in this study is designed such that it is easy to operate by nursing assistants with minimal training.

2. Materials and methods

2.1. Materials

This design sought to meet not only the technical specification but also minimal cost of production without compromising standards in order to ensure a robust and sustainable design. Materials selection was made based on availability, durability, purpose, point of use and strength of materials. Ease of fabrication and thermal stability were also put into consideration during material selection [18]. Table 1 shows the list of selected materials with their comparative advantages while Table 2 presents the cost summary.

2.2. Medical device requirements

Sterilisation decontaminates a surface by killing the microorganisms present on it in order to prevent potential infection due to such surface or substance [19,20]. Sterility assurance level (SAL) is the probability of one microorganism surviving on an object [15]. According to the US CDC, SAL of 10^{-6} is recommended for critical medical devices such as invasive medical instruments [21]. For steam autoclave, US CDC also recommends 30 min minimum exposure time for linen-wrapped critical instruments at 121°C and 203 kPa pressure in order to achieve SAL of 10^{-6} [22]. Due to the differences in microbial thermal resistance properties (D , Z) and initial quantity of microbe on a sample P_0 called bio-burden, different heating time and temperature are required to meet SAL of 10^{-6} as shown in Equations (1, 2) [15].

$$P(t, P_0) = P_0 10^{-t/D} \quad (1)$$

$$D(T) = D_{121^{\circ}\text{C}} 10^{(121^{\circ}\text{C}-T)/Z} \quad (2)$$

Microbial final population and initial population P and P_0 , respectively, are measured in colony forming unit (CFU). In Equation (1), t is the exposure time, while D is the population reduction time scale; $P(t, P_0)$ is the microbial survival probability or SAL. The D -value is calculated using different individual microbes

Table 2. Design cost overview.

S/N	Item	Quantity	Unit price (USD)	Total price (USD)
1	Mild steel (2000 mm × 1000 mm × 4 mm)	1	24.32	24.32
2	Dual measurement pressure gauge	1	8.11	8.11
3	Pressure release valve	1	2.70	2.70
4	Perforated stainless sheet (800 mm × 300 mm × 0.5 mm)	1	8.60	8.60
5	Luck-nut	5	1.89	9.45
6	Rubber gasket	1	12.16	12.16
7	Flat bar (400 mm × 100 mm × 1 mm)	1	2.70	2.70
8	Sheet metal (200 mm × 200 mm × 0.7 mm)	1	2.16	2.16
9	Arc welding electrode	10	0.027	0.27
10	Miscellaneous	–	–	13.51
	Total			83.98

established temperature standards. An autoclave standard operating temperature of 121 °C is adopted in this study. T is the environmental temperature, Z is the temperature change that would give 10 times slower kill rate (1-logD). Hence, the exposure time to reach SAL increases as the steam temperature decreases.

2.3. System design and calculations

The various forms of heat transfer dynamics are calculated from some of the parameters of the autoclave design as tabulated in Table 3.

The initial mass of the autoclave before heating and the final mass of the autoclave after heating are given by Equations (3, 4), respectively. Equation (5) gives the time taken to boil the water. The mass of steam loss is given by Equation (6).

$$\begin{aligned} \text{Mass of autoclave } (m_a) + \text{one litre of water} &= m_{\text{initial}} \\ &= 6225\text{g} \end{aligned} \quad (3)$$

$$m_{\text{final}} = 6025\text{ g} \quad (4)$$

$$t_{\text{boil}} = 30\text{ min} \quad (5)$$

$$m_{\text{steam}} = \frac{(m_{\text{initial}} - m_{\text{final}})}{\Delta t} = 6.67\text{g/min} \quad (6)$$

The power required to heat the steel autoclave and water and 4.2 kg of surgical kit is:

$$P_{a+w+kit} = \frac{m_a c_s \Delta T}{\Delta t} + \frac{m_w c_w \Delta T}{\Delta t} + \frac{m_{\text{kit}} c_s \Delta T}{\Delta t} \quad (7)$$

where c_s is the specific heat capacity of steel ($c_s = 420\text{ KJ/kg}$), c_w is the specific heat capacity of water ($c_w = 4.1855\text{ J/gK}$), ΔT is the change in temperature while Δt here is t_{boil} and m_{kit} is the mass of 13 surgical kits. Specific latent heat of vaporisation is $l_{\text{steam}} = 2260\text{ J/g}$. Therefore, the power required to boil water into high-pressure steam is given as:

$$P_{\text{steam}} = \frac{m_{\text{steam}} l_{\text{steam}}}{\Delta t} \quad (8)$$

An aliquot of 1 L of water is used in the autoclave based on existing literature [23]. An aliquot of 200 mL

of water is assumed to be vaporised over the 30 min period. To maintain a fairly constant internal pressure, exiting steam should be continuously replaced with new steam. The steam energy loss P_{conv} by convection is given by Equation (9). The total area losing heat by convection includes the top, the bottom and the curved surface area of the sterilising cylinder and is given by Equation (10). The radiation heat transfer is given by Equation (11) [23].

$$P_{\text{conv}} = h_c A \Delta T \quad (9)$$

where h_c is the coefficient of heat transfer by convection and is given as $h_c = 10\text{ W/m}^2\text{K}$.

$$A_T = A_{\text{curved}} + 2A_{\text{top/bottom}} \quad (10)$$

$$P_{\text{rad}} = \varepsilon \sigma A_T (T_s^4 - T_{\infty}^4) \quad (11)$$

where ε is emissivity and is taken as $\varepsilon = 0.25$ for a shiny surface at the absolute temperature; σ is radiation Stefan Boltzmann's constant and is given as $\sigma = 5.67 \times 10^{-8}\text{ W/m}^2\text{K}^4$; T_s is surface temperature; and T_{∞} is the temperature of the environment listed in Table 3. The total required energy by the autoclave P_{req} is given by Equation (12). The total power required by the power source is given by Equation (13).

$$P_{\text{req}} = P_{a+w+kit} + P_{\text{steam}} + P_{\text{conv}} + P_{\text{rad}} \quad (12)$$

Using thermal efficiency of 0.43 for the biofuel in other to be conservative [24], the total power requirement from source, the heating source P_{source} becomes:

$$P_{\text{source}} = \frac{P_{\text{req}}}{\mu_s} \quad (13)$$

where μ_s is the thermal efficiency of the fuel. Using Equations (3–13), the different power requirements of the system are calculated and summarised in Table 4.

Each cycle takes an average of 1 h with 30 min heating and 30 min boiling time, thus the energy requirement for a 1 h autoclave cycle [15] is:

Table 3. Dimensions and properties of the autoclave.

Parameter	Dimensions
Mass of autoclave (m_a)	5.22 kg
Mass of steam lost/min (m_{steam})	6.67 g/min
Volume of water boiled off	200 mL
Environmental temperature (T_s)	27 °C
Final temperature (T_{∞})	121 °C
Volume of water in the autoclave	1 L
Total surface area (A_T)	0.5352 m ²
Capacity of autoclave	29 L
Capacity of canister	10.5 L
Diameter of sterilising cylinder	287 mm
Height of sterilising cylinder	450 mm

$$H_{\text{source}} = P_{\text{source}} \Delta t = 2.804 \text{ KWH} \quad (14)$$

Hence, the total energy required for a complete sterilisation cycle is 2.804 KWH which is equivalent to 10.094 MJ of heat. The cellulosic ethanol biofuel has energy content of 30 kJ/g [25]. An aliquot of 1 L of the biofuel is 2.23 kg which makes 66.9 MJ/L. Thus, 1 L of the biofuel could handle several autoclave cycles conveniently.

The strength of the material was tested by obtaining the developed stresses in the sterilising cylinder using Equations (15, 16) [19]. The calculated transverse and longitudinal stress are 0.376 and 0.188 KN/m², respectively.

$$\sigma_T = \frac{PD_m}{2t} \quad (15)$$

$$\sigma_L = \frac{PD_m}{4t} \quad (16)$$

where σ_T is the transvers stress and σ_L is the longitudinal stress. P is the autoclave working pressure of 20.68 N/cm² [19]; D_m is the mean of the internal and external diameter of the sterilising cylinder while t is the thickness of the cylinder. The load applied at yield point on a portion of width 2.32 cm and thickness 0.4 cm of the sterilising cylinder material was tested with a universal testing machine. An average load of 52 KN was found and the yield strength of the material is 56.03 KN/cm² which is far higher than the developed stress in the sterilising cylinder. Thus, the thickness of the cylinder is sufficient for the operation.

2.4. System description

The construction of the biofuel-powered autoclave was divided into two modules: (i) autoclave section and (ii) biofuel stove section. The autoclave body was fabricated with mild steel iron as shown in the isometric view of the design in Figure 1. A five lock and screw system were adopted to ensure air tight closure with an expandable rubber gasket around the tip to prevent leakage as shown in Figure 1. The perforated canister cylinder was designed to hold the medical equipment/substance to be sterilised. A 212 mm stand

Table 4. Calculated theoretical power requirements by the autoclave.

Required power	Variable	Quantity
Power required for autoclave heating	P_a	89.00 W
Power to heat the water	P_w	169.75 W
Estimated Power loss by steam	P_{steam}	251.10 W
Power loss by convection	P_{conv}	503.10 W
Power loss by Radiation	P_{rad}	121.37 W
Power to heat 4.2 kg of medical kits	P_{kit}	71.54 W
Total power required	P_{req}	1205.86 W
Biofuel thermal efficiency	μ_s	0.43
Total power requirement from the source	P_{source}	2.804 KW

supports the canister. The dual gauge measures both the built-up pressure and the corresponding temperature of the steam in the autoclave. The pressure release valve serves two purposes: To expel air out of the autoclave few minutes after the start of the autoclave process to enable quick and adequate pressure build-up for sterilisation by vertical gravity method and to reduces the high pressure and temperature of the autoclave on completion of the sterilisation process. The pressure release valve was incorporated to reduce the temperature and pressure of the autoclave and its content before opening the lid to avoid hazard. Table 5 shows the components of the autoclave and their functions.

The biofuel stove unit was designed following the study of Bailis and Hyman [26] as shown in Figure 2(a). The stove housing has a dimension of 287 mm diameter by 100 mm height with a control knob to regulate heat supply to the autoclave. The fuel was developed from cellulosic ethanol made from waste sawdust, water Hyacinth and other agricultural biomass wastes which are very abundant in West Africa [27]. Thus, the bioethanol fuel burns cleanly with little or no GHG [26,27]. Its laboratory pollution study and household tests indicated an average CO/CO₂ ratio of 4% at high power and 5% at low power with negligible particle emission [28]. This alternative energy source is far better than kerosene and biomass fuels including wood and charcoal which are associated with collections of adverse health effects such as pulmonary disorder, lung cancer, cataract, and asthma [29]. The adoption of the ethanol biofuel for autoclave heating as well as other house hold cooking purposes promotes United Nations Sustainable Development Goals (SDGs) [28,30] including economic empowerment through active participation in the bioethanol fuel industry value chain.

Adopting CDC standard [31], the autoclave was designed to achieve sterilisation at a minimum of 121 °C/15 psi for 15 min. However, a 30 min period is encouraged to ensure a near absolute sterilisation depending on the nature of medical equipment,

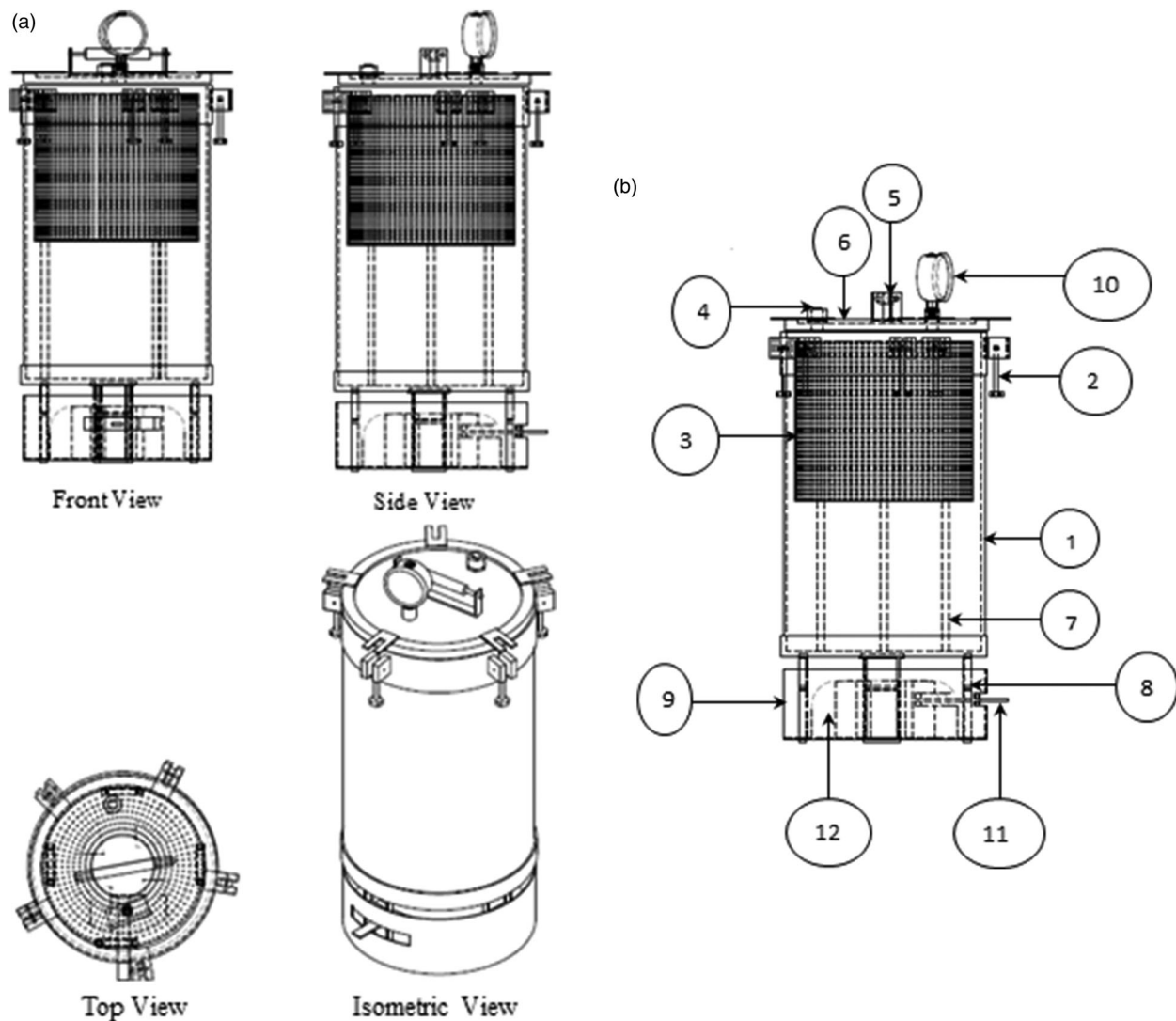


Figure 1. Different views of the designed autoclave. (a) Isometric and autographic views; (b) Labelled side view.

proportion of microbe/bio burden and type of wrap for the equipment/substance to be sterilised [22].

3. Performance evaluation

The performance evaluation of the autoclave was carried out using the recommended standard mechanical and biological tests. All performance evaluation experiments were implemented in the Department of Medical Microbiology and Parasitology Laboratory, University of Ilorin Teaching Hospital. The physical test was done by monitoring and ensuring that the minimum CDC recommended temperature and pressure were attained and maintained for 30 min cycle period as shown in Figure 3(a). While the graph of temperature against time and pressure is presented in Figure 3(b). The experiments were carried out in four trials. The first trial was stopped as steam was leaking from

the paper gasket. This leakage was rectified by changing it to a rubber gasket which performed well. For each of the last three trials, the sterilising temperature ($\geq 121^\circ\text{C}$) was successfully maintained (i.e., by manually regulating the heat supplied using the heat control valve) for 30 min. Also, the indicator tape changed colour and the biological control test showed no bacteria growth.

The mechanical test was carried out by placing a temperature-sensitive adhesive chemical indicator tape (plain) on the body of the sample bottle to be sterilised before sterilisation. After sterilisation, the chemical indicator changed from plain to black striped tape as shown in Figure 4 indicating that a temperature of 121°C or higher was attained. The biological validation was implemented using two samples of aseptically collected cornea scrapings from bacteria keratitis patients which yielded isolates of *Staphylococcus*

Table 5. Summary description of autoclave parts and function.

Part list				
Part no	Quantity	Part name	Description	Material
1	1	Pressurised sterilising cylinder	It is the sterilising cylinder with internal diameter 287 mm and height 450 mm and thickness 4 mm	Mild steel
2	5	Screw fastener	It is used for tight locking of autoclave lid	Mild steel
3	1	Canister	Internal diameter 250 mm, height 225 mm with thickness 0.5 mm. It is used for carrying the materials to be sterilised during autoclaving	Stainless steel
4	1	Pressure release valve	It is located on top of the autoclave for reducing the temperature and pressure in the autoclave on completion of the sterilisation process	
5	1	Handle	It is made of poor conductive substance	Thermoplastic
6	1	Lid	The lid (295 mm diameter) covers the autoclave air-tightly to ensure pressure build up in it	Mild steel
7	3	Canister stand	The canister is supported by 3 mm diameter, 212 mm height supporting stand	Mild steel
8	4	Autoclave supporting legs	These legs are seated on the space provide in the cook stove compartment with a gap between them to allow air in for fuel combustion	Mild steel
9	1	stove	This is the heat source for autoclaving	Mild steel
10	1	Dual gauge	It is a specially made pressure and temperature gauge.	
11	1	Heat control valve	It is a manual control valve for regulating heat supply to the sterilising cylinder	Mild steel
12	1	Fuel tank	The reservoir of the biofuel	Mild steel

aureus obtained from the Department of Medical Microbiology and Parasitology, University of Ilorin Teaching Hospital.

The samples (with loosen caps) were wrapped in linen material and placed in the canister of the autoclave and sterilised for 30 min at 121 °C. The growth media used includes Brain Heart Infusion Broth (BHI-Oxoid®), MacConkey Agar (MAC-MAST®) and Blood based agar (Oxoid®).

3.1. Media fertility and sterility tests

All the media were tested for fertility and sterility to certify the media to be of high quality and fit for the experiments so as to avoid error in the results obtained. The scrapings were inoculated into brain heart infusion broth (BHIB) to make a concentration at 0.5 McFarland standards and incubated for 24 h at 37 °C. After the incubation, they were sub-cultured unto MacConkey and Blood agar plates and incubated at 37 °C for 24 h. The culture was examined at every-day interval and growth of the bacteria was confirmed as depicted in Table 6. For sterility test, a portion of both media containing the microbe was sterilised immediately after constitution in an autoclave at 121 °C for 15 min. They were then incubated for 7 d with routine check every day. No microbial growth was observed. Hence, from Table 6, the media MacConkey and Blood agar can be said to be high

quality media suitable for the sterility testing sampling.

Samples of the Microbial colony shown in Figure 4(a) were then sterilised using the designed biofuel-powered autoclave at 121 °C for 30 min. Portions of the autoclaved microbial sample were then cultured in the tested MacConkey and Blood agar medium and immediately incubated for 48 h at 37 °C along with control media (Unsterilized). The samples were observed after the incubation period and there was no microbial growth; a clear culture was obtained while there was observed growth in the control media. This indicated the successful elimination of the microbes by the designed autoclave.

4. Discussion

The design, development and clinical evaluation of a biofuel-powered autoclave for healthcare centres in low resource settings have been presented. This device has been shown to decontaminate medical waste samples and devices effectively and reliably. Thus, it can replace the not readily available and expensive conventional high-end autoclaves which often require electricity in rural healthcare centres. The modular nature of the design allows for detachment of the biofuel stove such that the autoclave alone can be used on alternative power sources such as electrical heating element, cooking gas and kerosene energy source in African rural areas when the need



Figure 2. Images of the main parts of the designed autoclave. (a) Cook stove; (b) Autoclave; (c) Canister.

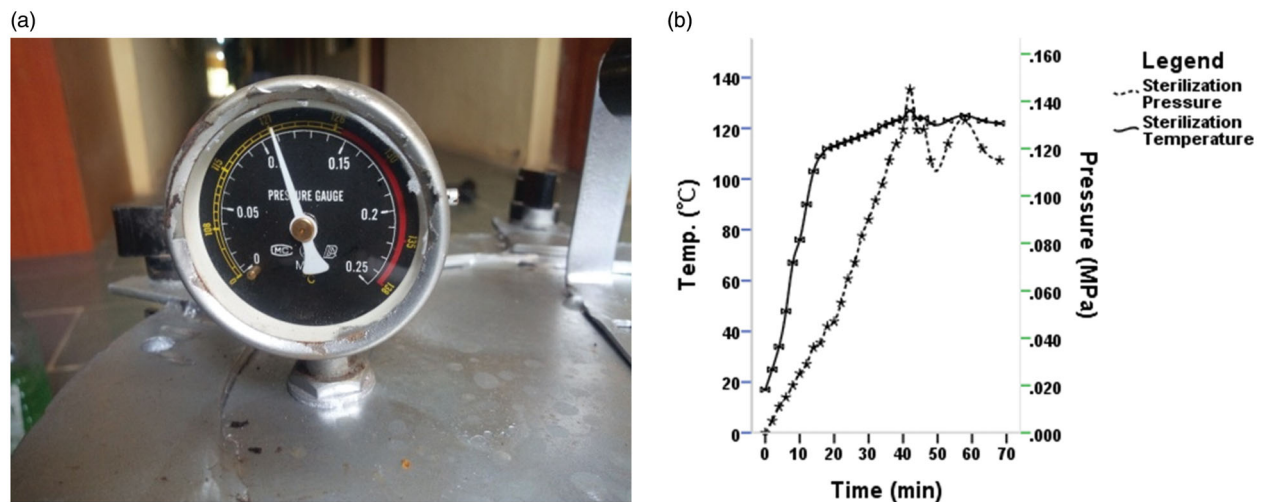


Figure 3. Performance test results. (a) Dual gauge at 121 °C; (b) Graph of temperature with time and pressure.

arises. Hence, this design is robust and flexible unlike the solar-powered design by Birhanu and Mulu [23] which is bulky and has a high implementation cost. Although low-cost autoclave designed by Tao [15] is automated, its operation is rather complex and would always require technical assistance which may not be available in rural areas.

Although the autoclave designed by Oyawale and Olaoeye [19] is economical, it, however, uses electricity which is epileptic in low resource settings. Their design also has a control module which requires high technical skill to repair, and such skills are lacking in rural areas. Thus, the device designed, fabricated and presented here offers a better and cheaper alternative

to decontaminate medical devices and wastes by autoclave method. It is also user friendly. However, the ease of operation of this device can be enhanced with the incorporation of a simple control system to achieve automation which will eliminate monitoring time. Further validation can be done using thermal resistive *G.Stearothermophilus* spores to support the efficacy of the autoclave in the future.

5. Conclusion

This study has presented a locally designed and manufactured biofuel-powered autoclave for use in health care centres in low-income communities. The device

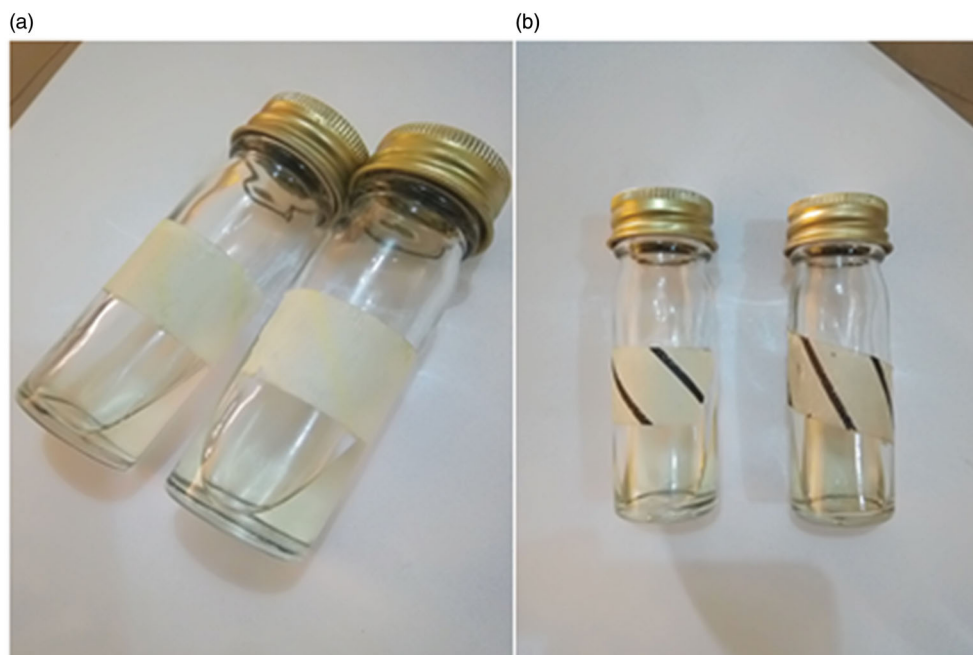


Figure 4. Changes in Chemical indicator tape affixed to the sample bottle. (a) Plain stripe tape before sterilization; (b) Plain stripped tape turned black stripped after sterilization.

Table 6. Media Suitability Tests.

Observation/day	Fertility test		Sterility test	
	MacConkey medium	Blood medium	MacConkey Medium	Blood Medium
1	+	+	—	—
2	+	+	—	—
3	+	+	—	—
4	+	+	—	—
5	+	+	—	—
6	+	+	—	—
7	+	+	—	—

Description: (+) = microbial growth; (—) = no microbial growth.

can sterilise surgical equipment, medical wastes and reusable laboratory equipment. The modular design enables the use of bioethanol fuel as well as other arrays of energy sources such that the device would always be readily available for use even if biofuel is not available. The per-unit cost of the device is approximately 84 USD. This is affordable compared with the exorbitant prices of similar devices in the market. It is, therefore, recommended for mass production to reduce the risk of HAI in such centres particularly SSI.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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