Environmental Health Engineering and Management Journal 2023, 10(3), 273–279
http://ehemj.com
doi 10.34172/EHEM.2023.31
Environmental Health Engineering and Management Journal
Original Article
Open Access Publish Free

Development of microbial fuel cell for wastewater treatment and electricity generation using domestic wastes

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Abstract

Background: The energy crisis is a growing problem around the world, requiring the creation of alternative energy sources that can generate less carbon dioxide and benefit the ecosystem. Re-utilization of wastewater is becoming the emerging energy solution. Wastewater contains a large amount of organic matter that can be oxidized in microbial fuel cells (MFCs) to produce electricity. MFCs use biodegradable materials to create energy in the presence of microorganisms.

Methods: Purposive sampling technique was employed to collect samples from critical polluting sources. The samples were certainly maintained in a refrigerator at 4°C. Several mixes for sample were prepared and tested analytically- for physio-chemical and bacteriological characterizations of each substrate status at pre- and post-treatment stages. Electricity generating capacity of MFCs that employing different substrates was investigated experimentally using batch reactors. The cross-sectional methodology was employed to study possible power generation.

Results: The maximum voltage output of 118.93, 144.84, and 89.76 mV were produced keeping the resistance unlimited for MFC1 (urine substrate), MFC2 (blackwater substrate), and MFC3 (graywater substrate), respectively. MFC that utilized graywater as a substrate brought the tiniest quantity of electricity; however, it stood the most stable. The highest COD reduction (65.83%) in the process was reported in urine substrate and the highest BOD_5 removal (69.18%) was reported in black water substrate.

Conclusion: The experimental results provided a promising indication of MFCs viability, providing hope for future power generation and alternative wastewater treatment option in developing countries.

Keywords: Domestic wastes, Electricity generation, Microbial fuel cell, Substrate, Water purification

Citation: Kifle T, Alemayehu E, Kitila CD. Development of microbial fuel cell for wastewater treatment and electricity generation using domestic wastes . Environmental Health Engineering and Management Journal 2023; 10(3): 273–279. doi: 10.34172/EHEM.2023.31.

Article History:
Received: 30 August 2022
Accepted: 14 January 2023
ePublished: 30 June 2023

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Introduction

A microbial fuel cell (MFC) is a bio-electrochemical system that produces electricity via natural breakdown+s of microbes (1). It is a promising system that turns chemical energy into electricity and eliminates contaminants from wastewater using microorganisms' catalytic action (2,3). Selective microorganisms can biologically breakdown organic wastes and nutrients via simulating natural system change (4). Specifically, bacteria can generates electricity in MFCs while also biodegrading organic materials (5,6).

Biological treatment might take place in either an aerobic or anaerobic setting (7). Microorganisms devour dissolved and colloidal organic materials in wastewater in both conditions (8). The operation of single chamber MFC involves anaerobic and aerobic conditions at electrodes, respectively (Figure 1).

MFC technology has been a quickly rising, sustainable and green technology in recent years. MFC is regarded as a promising viable technology for meeting increasing energy and environmental requirements principally while wastewaters are used as substrates. MFCs produce useful electricity and beside purify wastewater effluents that potentially offsetting the operational costs of wastewater treatment plants (5,6).

It has been proved that MFCs have the potential to generate electricity (10-12). The present study investigated the potential for MFCs to generate electricity from domestic wastes effluent particular to institutional setting and examining their potential to treat domestic waste effluent discharged in developing country, Ethiopia.

Materials and Methods

Materials

Plastic bottles

Plastic bottles are low-cost, lightweight, and long-lasting materials that may be easily molded into a number of products for a variety of uses. In the present study, plastic bottle that holds 2000 mL of wastewater samples were employed in each chamber of the MFCs.

Electrode

Electrodes are crucial components in electrochemical systems (13). Metals and their alloys are electrode materials usually in use. Aluminum and stainless-steel electrodes have been used for this study.

Salt bridge

Salt bridge is a key element in MFC. It keeps separately the anode and cathode electrodes. Water in the cathode contains dissolved oxygen and it needs to keep separate the anode anaerobic. Furthermore, it must allow for spontaneous proton migration from the anode to the cathode.

Copper wire

Copper was utilized as outside circuit that interfaces the cathode and anode. On both electrode sides, the copper wires were attached along with electric tape.

Miscellaneous Materials

The miscellaneous materials utilized in the present study include Glue gun, Para film, variety of glassware, PH meter, digital multi-meter, spectrometer, chemical reagents, digital balance, thermometer, crucibles, oven, and desiccator.

Substrate

Three distinct substrates examined in the present study include urine, black-water, and graywater effluents. All substrates considered were entirely collected from a deep sewage on campus and various areas of the Wolkite University compound, Ethiopia.

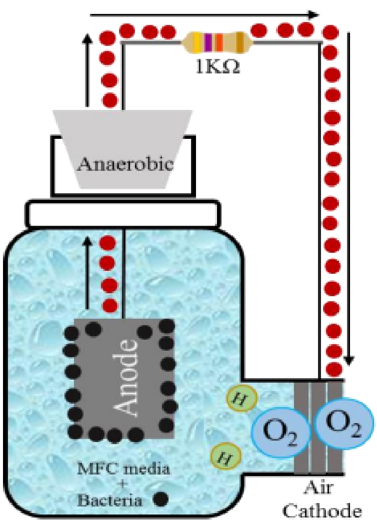

Figure 1. The single-chamber microbial fuel cell (9)

Study design

The MFC is made up of four main parts:

1. Anode: The bacteria and organic debris are kept in an anaerobic condition in the anode chamber.
2. Cathode: Container containing a conductive water solution.
3. Proton-exchange membrane: Salt is a proton-exchange membrane that divides the anode and cathode and allows protons to flow between the two chambers.
4. External circuit: It permits electrons to enter the cathode and serves as a conduit for them to go through when they are extracted out of the anode's solution.

As a part of their digestive process, bacteria in the anode chamber produce protons and electrons by oxidation. MFCs are well-known for their ability to transfer chemical energy from organic substrates into electricity. This is due to the so-called electrogenic bacteria' unique metabolic activity. Anode and cathode are connected by an external circuit and split into compartments by a proton exchange membrane in a conventional MFC (14). MFCs are essentially consisting cathode (aerobic) and anode (anaerobic) electrodes connected by salt bridge (Figure 2).

The electrodes employed in the study have different surface area. Dimensionally 8 cm × 4 cm cathode and anode with aluminum electrodes, giving a total surface area of 32 cm^2. Steel electrodes are 8 cm long and 4 cm wide, with 32 cm^2 surface area. The anodic surface area is used to standardize the unit of power.

Sample size and sampling procedure

Sample size

Samples were collected from three wastewater sources in Wolkite University compound using a purposive sampling technique. Critical polluting sources including waste disposal sites, major sewer lines, and different manhole were considered during sample collection. For all effluents, 2 L and 1 L of samples were collected, and subsequently, examined in laboratory facilities.

Sampling procedure and sample preservation

The wastewater samples were collected for several hours

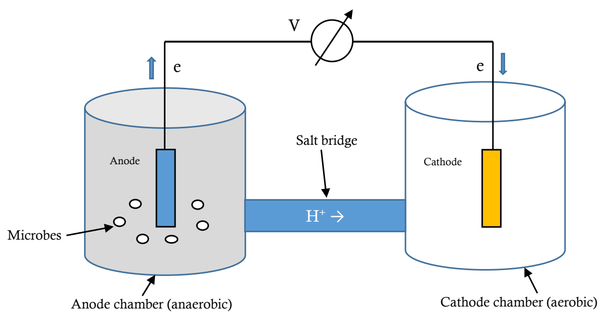

Figure 2. Schematic diagram of MFC setup

in a given day to ensure that the wastewater samples were not greatly disturbed by bacterial growth, which can affect the temperature and total dissolved solids content.

All the plastic bottles were washed with warm soapy water, and then, rinsed three times with distilled water. For microbial analysis, wastewater samples were collected with 1000 mL plastic bottles and stored in a black box to avoid bacterial contamination. The collected samples were maintained in the refrigerator at 4 °C to avoid any changes in the results during the experiment. The samples were put at 4 °C for 2 days in their original water-based suspension.

For the mixed waste analysis, samples were collected for three consecutive days and one-day representative and the next two days representative were prepared using the same procedure. To keep the results consistent, the samples were filtered and stored in the refrigerator.

Sample measurement and analysis processes

Prior to the trials, sludge samples were gently mixed together and left to adjusted room temperature, before inoculating 2000 mL of sludge in the connected stacks (3 MFCs). For each parameter examined, the maximum holding duration was retained until the beginning of the laboratory measurement processes. All parameters examined must be maintained in case the analysis is not immediately completed. The maximum holding time was kept and performed based on the WHO/UNEP, 1996 standard protocol.

For MFCs, suitable fittings and other measurement devices were prepared initially before collecting samples from each site.

During the experiment—up on preparing the sample, different parameters (pH, conductivity, TS, VS, turbidity, and voltage) were tested and recorded. Several mixes were prepared, and ultimately the experimental results were collected. The pH of the solution (suspension) was adjusted to a standard pH (5-8) within a temperature range of 22-40°C.

Equations in used in the study

Power

Power is literally the product of voltage and current. It is described as:

$$P = V \times I$$

Where P is power output, V is voltage output, and I is current.

Whereas, the following alternate equation is also used to express power in the study.

$$P = \frac{V^2}{R_{ext.}}$$

Where R is the applied external resistance and V is the cell potential.

Alternatively, power can be expressed by the following equation:

$$P = I^2 \times R_{ext}.$$

Power density is expressed as the following equation:

$$P = \frac{V^2}{A_{an} \times R_{ex}}$$

Where A_{an} is surface area for anode, V is electric voltage, and R_{ex} is external resistor.

Internal resistance

The total maximum power is theoretically calculated by the following equation:

$$P = \frac{OCV^2}{R_{int} + R_{ext}}$$

The principles of electric circuits reveal that when $R_{int} = R_{ext}$, the maximum power is recorded. Thus:

$$P_{max} = \frac{OCV^2}{4 * R_{int}}$$

The above equation can be used to obtain internal resistance in the MFC's system.

Columbic efficiency

The columbic efficiency is generally expressed as:

$$C_e = \frac{\text{electron recovered}}{\text{total electron in biomass}}$$

The term "electrons" refers to the charge of an electron in coulombs. In MFCs', the columbic efficiency is expressed as:

$$C_e = \frac{8 \int I \times dt}{F \times Van \times \Delta COD}$$

Where F is Faraday's constant, V_{an} is substrate volume in anode chamber, COD is proportional to substrate concentration, and 8 is constant value.

Results

Characterization of wastewater samples

Physio-chemical and bacteriological characterizations of effluents at pre-treatment stage and effluent status following digestion in MFC at post-treatment stages are presented in Table 1. The actual MFC setup employed to examine various conditions in blackwater substrate is shown in Figure 3.

In Table 1, pH and DO parameters show an increase following the significant reduction of pH and DO depressing-species from wastewater effluents. Whereas, total solids (TS), volatile solids (VS), biochemical oxygen demand (BOD5), chemical oxygen demand (COD), total

Table 1. Physico-chemical and bacteriological characterization of substrates

Parameter	Unit	Substrate characteristics (pre-treatment)			Substrate characteristics (post-treatment)		
		Urine	Blackwater	Gray water	Urine	Blackwater	Gray water
pH	-	6.3	6.7	7.4	6.8	7.1	7.2
TS	mg/L	385	3982	56	156	1256	38.2
VS	mg/L	213	1231	37	78	874	21.6
BOD_5	mg/L	208	902	45	67	278	32
COD	mg/L	600	1600	900	205	693	378
DO	mg/L	3.9	2.56	3.9	4.2	4.8	4.2
TK	mg/L	2740	1112	5564	1231	636	3674
TP	mg/L	1600	500	1352	764	230	589
TN	mg/L	8830	1388	564	3423	879	332
TC	Col/100 ml	$215*10^4$	$513*10^4$	$0.3*10^4$	$134*10^4$	$302*10^4$	$0.13*10^4$
FC	Col/100 ml	$98*10^4$	$317*10^4$	$0.1*10^4$	$54*10^4$	$125*10^4$	$0.04*10^4$
Conductivity	μS/cm	19067	27894	12271	9645	11092	4515

Col = colonies.

Figure 3. MFC setup for blackwater substrate

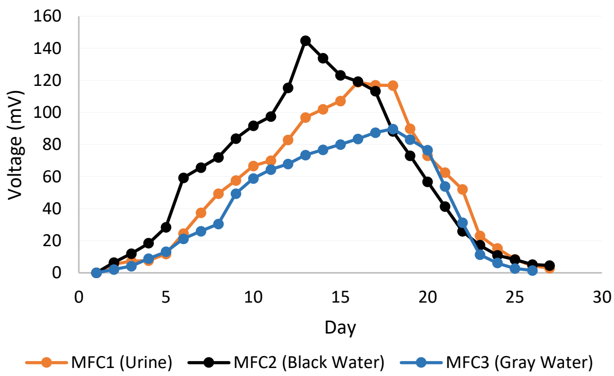

Figure 4. Diurnal voltage outputs for different substrates

potassium (TK), total nitrogen (TN), total coliform (TC), Fecal coliform (FC) and conductivity show an increase due to metabolic breakdown and decomposition by microorganism involved in the process.

Electric voltage production

Three sets of MFCs (urine, blackwater, and graywater) were distinctly examined for the maximum voltage output potential at ambient temperatures ranging from 22 to 10 °C. For all three sets, the voltage outputs were carefully measured using a calibrated multimeter (Model No 8NF6R) across a 1000-ohm resistor at regular intervals of 24 hours until the output voltage dropped to zero, which essentially took a period of one month.

Blackwater substrate produced the maximum voltage output while all three substrates run under the similar environmental conditions (Figure 4). The voltage output change within days of incubation for blackwater substrate is more significant than other substrates. For black water substrate, electricity generation gradually reduced just after 13 days. It also took much less time than both urine and graywater substrates to generate the maximum voltage. The MFC that utilized graywater as a substrate generated the minimum quantity of voltage of the three substrates; nevertheless, it was the utmost stable one.

Discussion

Substrates characteristics

Graywater, blackwater, and urine are extremely different substrates in terms of composition and overall physical quality. Urine has the highest nutritional concentration, and its isolation allows for recovery from a much less volume of urine. Despite that graywater makes up the bulk of domestic trash, it is rather clean, and hence, appropriate for reuse. Light graywater that does not include kitchen wastewater has very low particle, organic content, and nutritional levels. Blackwater that contains organic matter making it ideal for energy recovery.

In this research, blackwater is defined as wastewater from kitchen sinks and feces. Blackwater (feces and kitchen wastewater) contains high levels of organic and nutritional content, as well as sediments, bacteria, and pharmaceutical/hormone residues.

Greywater has the lowest pollution among the three

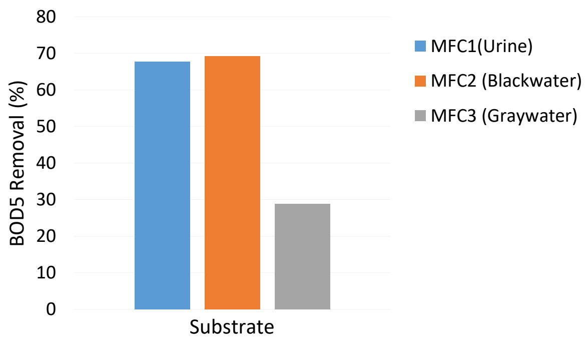

Figure 5. BOD_5 reduction for different substrates

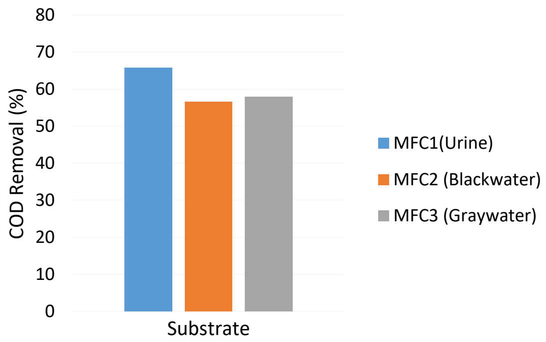

Figure 6. COD reduction for different substrates

streams yet contributes the most to total volume. The most detergents and personal care items are found in light graywater, which is also low in nutrients and pathogens. Graywater is also low in organic content.

The wastewater from non-kitchen sinks, laundry, and showers is usually termed graywater. It is also known as "mild graywater" in the scientific community. When compared to other graywater sources, "dark graywater", which comprises kitchen sinks, is the most polluting source. Pollution loads up to 40-60% is mainly contributed by kitchen wastewater (VS, COD, BOD, total oil, and active substances). According to the experiment results, graywater's physical and chemical quality varies for different sources. The quality of cleaning and bathing products, the number of people in a household, and other sink disposal procedures and personal behaviors all have an impact on graywater's physical and chemical characteristics.

On average, an adult produces 0.8-1.5 L of urine each day, whereas a toddler produces around half that amount. Water makes up 95% of the mixture, with dissolved salts accounting for 5%. Food determines the quality of urine output per capita, yet scientifically established design values have emerged. While urine makes up only 1% of total residential wastewater, it contains 50-80% of total nutrients (75-80% nitrogen, 50-55% phosphorus, and 70% potassium), as well as the majority of pharmaceuticals and their metabolites. Adults are principally responsible for the elimination of macronutrients (nitrogen, potassium, phosphorus, and sulfur).

BOD_5 and COD removal efficiency

BOD_5 reduction of substrates urine, blackwater, and graywater are 67.79%, 69.18%, and 28.89%, respectively (Figure 5). The maximum BOD_5 removal was occurred in blackwater substrate and the lowest one occurred in graywater substrate. Thus, BOD_5 removal with all examined substrates were found moderate.

COD reduction for all MFC is below 80% (Figure 6). The maximum COD removal was in urine waste (roughly 65.83%), while matched to 56.69% and 58% for blackwater and graywater substrate, respectively. Thus, COD reduction with all developed MFCs and examined substrates were also found moderate.

Electrochemical analysis

Power and power density curve

MFCs operate in the same way as traditional electricity generators. They slightly generate a current and a certain cell potential.

To determine the optimal current and potential for maximizing power, a variety of external resistors having various values were employed.

Blackwater substrate produced the maximum power output. In fact, all substrates in the investigation were operated within similar environmental settings. The power change exhibited for blackwater substrate is very significant compared to other substrates (Figure 7). Power output gradually reduced just after 13 days for black water substrate, which took much less time than both urine and graywater substrates to generate the maximum power.

MFC2 produced the highest power compared to MFC1 and MFC3, with a value of 655 $\mu W/cm^2$ equating to 453 $\mu A/cm^2$ of current. Whereas MFC1 produced 442 $\mu W/cm^2$ corresponding to current value of 372 $\mu A/cm^2$. MFC3 produced the lowest power (442 $\mu W/cm^2$), corresponding to current value of 281 $\mu A/cm^2$. Hence, the best system in terms of the maximum power generation is the one that stacks MFC2 in series (blackwater), followed by MFC1 (Figure 8). In MFC1, at both anode and cathode side, aluminum electrodes had been used. MFC3, which had steel at the anode and aluminum at the cathode with graywater substrate, produced a low power density.

All MFC1, MFC2, and MFC3 were activated under the same conditions; with the only difference in the substrate source. In the present research, MFC that employed black water substrate outperformed urine and graywater substrates. As the electrode combination used in MFC3 were slightly different, reduced power density was exhibited in the case of gray water substrate.

Internal resistance

Internal resistance is an important element that can affect

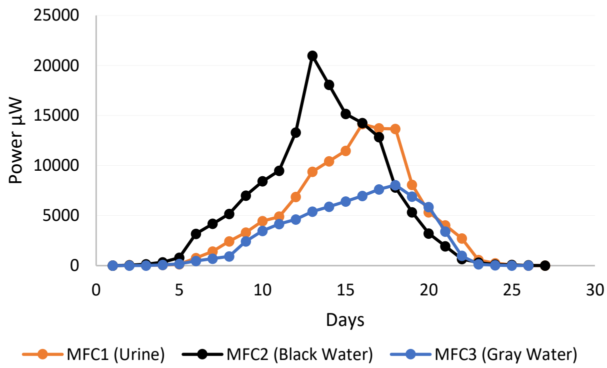

Figure 7. Diurnal power outputs for substrates

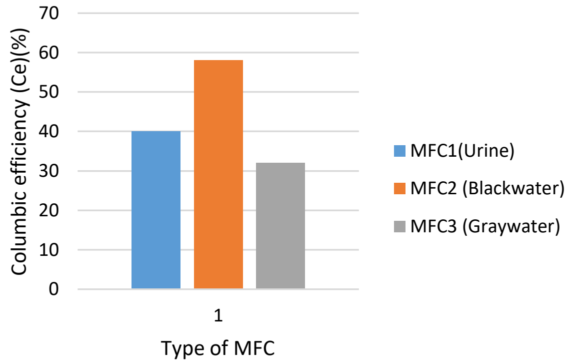

Figure 9. Columbic efficiencies of the examined substrates

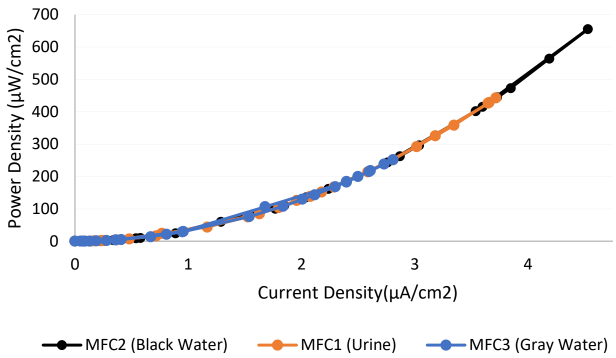

Figure 8. The power density curve for MFCs

the performance of the MFC. In other words, some MFCs may have the same reactor volume and even the same amount of substrate, but produce different currents.

In early experiments, the power density curves were developed using variety of external resistances. The internal resistance of each MFC was determined by recording the maximum output power and comparing it to the external resistance. The internal resistances of MFCs (1-2-3) in the present study were entirely 1 kΩ.

Columbic efficiency

The columbic efficiency is an important parameter to consider while evaluating the MFC's performance. The bacteria and the system as a whole are more active and efficient when the columbic efficiency is high.

It is critical to determine the COD before estimating the columbic efficiency of the fuel cells. The average COD in urine, blackwater, and graywater was considered to compute columbic efficiencies for each MFCs.

The instantaneous current value after 24-hour operation was used to calculate the columbic efficiency of the examined MFCs. MFC2 exhibited the maximum columbic efficiency (Figure 9). Because, blackwater was the major substrate and both electrode chambers were aluminum.

Conclusion

In the present research, technical feasibility of MFCs as an energy source along with domestic waste treatment capacity of MFCs in Ethiopia was investigated. The amount of electricity produced from wastewater effluents and corresponding treatment achieved were measured using appropriate techniques and instruments.

The MFCs potential for removal of BOD_5 and COD from substrates blackwater, urine, and graywater is only moderate. TC and FC removal with MFCs are also moderate. The MFCs potential for electric power generation is highly variable with duration given. The MFC using gray water as a substrate produced the least electricity but proved to be the most stable MFC. Wastewater treatment and electricity generation potential with MFCs for substrates are blackwater > urine > graywater. The experimental results provide a moderate indication of MFCs viability with substrates blackwater, urine, and graywater.

Further research is required to examine the possibility of enhanced wastewater treatment and electricity generation with blended substrates along with boosted microbial activities in MFCs. In addition, future research will investigate the MFCs potential for effluent flow conditions apart from batch flow.

Acknowledgements

The authors would like to express their profound gratitude to Jimma University for financial assistance of this research and Mr. Seifu Kebede, Environmental Engineering Chair holder at Jimma University, Jimma Institute of Technology, for technical assistance of this research. In addition, special thanks to Mr. Yared Temesgen and Amsayawu Genet (Hydraulic and Water Resource Engineering Department of Wolkite University) who gave us technical assistance up to the end of this research.

Authors' contribution

Conceptualization: Esayas Alemayehu.
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Formal analysis: Chali Dereje Kitila.
Funding acquisition: Tensay Kifle.
Investigation: Tensay Kifle.

Methodology: Esayas Alemayehu.
Project administration: Chali Dereje Kitila.
Resources: Chali Dereje Kitila.
Software: Chali Dereje Kitila.
Supervision: Esayas Alemayehu.
Validation: Chali Dereje Kitila.
Visualization: Chali Dereje Kitila.
Writing–original draft: Tensay Kifle.
Writing–review & editing: Chali Dereje Kitila.

Competing interests

The authors declare that there are no conflicts of interests.

Ethical issues

The authors hereby certify that all data collected in the field of study were described in the manuscript and no data from the study have been or will be published separately elsewhere.

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