TECHNICAL AND BIOLOGICAL PERFORMANCE OF THE ARTI COMPACT BIOGAS PLANT FOR KITCHEN WASTE - CASE STUDY FROM TANZANIA

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SUMMARY: This paper evaluates the suitability of a small-scale biogas system as a decentralised treatment option for the organic fraction of market and household solid waste in Dar es Salaam, Tanzania. A research plant was installed and operated for five months to evaluate its performance when fed with food and market solid waste. The system proved to be effective in terms of the reduction of waste volume and organic load. Performance of the digester regarding gas production was found to be good. The plant design may be improved for enhancing its performance. Reliable operation and maintenance were also found to be crucial to ensure long-term and sustainable use of biogas systems. However, for a wider dissemination of this promising solid waste treatment method, the cost of installation has to come down considerably.

1. INTRODUCTION

Solid waste management in economically developing countries is gaining importance as some of the most important threats to public health and environmental quality are related to inefficient waste management (Diaz et al., 2007). To a great extent, the composition of household waste consists of biodegradable material. This is also the case in Dar es Salaam, where organic matter accounts for around 67% of the total amount of municipal solid waste generated (Mbuligwe & Kassenga, 2004). As the most common practice is to dispose of the waste indiscriminately in the streets or in open dumps, this leads to pollution of ground- and surface water and contributes to the breeding of insects and rodent vector and the spread of diseases (Zurbrügg, 2002).

When dealing with the organic fraction of municipal solid waste (OFMSW), anaerobic digestion is increasingly considered as an alternative to composting.

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Biomethanation at a decentralized level is an ideal option as it minimizes transport costs and provides renewable energy and organic fertilizer.

Nevertheless, in developing countries, anaerobic digestion of OFMSW is mostly inexistent and information about the performance of operating biogas plants is scarce. However, in India, different biogas plants treating various types of organic solid waste have been implemented in recent years (Voegeli & Zurbrügg, 2008).

The Indian organisation known as Appropriate Rural Technology Institute (ARTI) developed in 2003 a small-scale biogas system designed for household level use. About 2500 of these biogas plants are currently in use in Maharashtra (Müller, 2007).

The design and development of the system, which uses organic solid waste rather than manure as feedstock has won the 'Ashden Award for Sustainable Energy 2006' in the Food Security category (www.ashdenaward.org). This compact biogas system (CBS) is now being promoted in Tanzania and Uganda by local NGOs and has been adapted on a wider scale for institutions such as schools and restaurants.

Although biogas technology has been known in Africa for decades for the treatment of animal manure, its application for organic household waste has only been introduced recently. There is no scientific data on the performance of the ARTI system in Africa.

To fill this gap, a detailed monitoring study was conducted by Eawag and ZHAW of Switzerland in collaboration with the Ardhi University of Dar es Salaam, Tanzania from July to December 2008.

The overall objective of this study was to assess the suitability of the ARTI compact biogas plant as a treatment option for organic solid waste at household level in urban areas of developing countries.

2. DESIGN AND TECHNOLOGY

The ARTI compact biogas system is made from two cut-down standard high-density polyethylene water tanks and standard plumber piping.

The larger tank acts as the container containing the waste material while the smaller one is inverted and telescoped into this larger one.

This smaller inverted tank is the floating gas chamber, whose rise is proportional to the produced gas and acts as a storage space for the gas.

The gas can then be used directly for cooking on an adjustable gas stove and the liquid effluent from the digester can be applied as fertilizer in gardens or agriculture.

By specification of ARTI, the CBS of approximate 1 m^3 capacity is designed for treating 1-2 kg (dry weight) of kitchen waste per day (www.howtopedia.org).

Space of about 2 m^2 and 2.5 m height is needed for a CBS of 1000 l (see Figure 1).

The effective volume of the digester is approximately 850 l, given by the dimension of the 1000 l water tank (inner radius: 51.5 cm) and the position of the overflow-pipe (1.04 m above ground level). Roughly 0.6 m^2 (78%) of the total surface area of the digester (0.83 m^2) is covered by the gasholder. In other words, the gas released through 22% of the digester surface is lost to the atmosphere without being utilized.

The usable gas volume of the 750 l-gasholder is 400 l.

The Hydraulic Retention Time (HRT) suggested by ARTI-TZ, which is the ratio of the reactor volume (0.85 m^3) to the flow rate of the inflow substrate (0.02 m^3/day), is 42.5 days. The rather long HRT was designed to compensate for incomplete mixing.

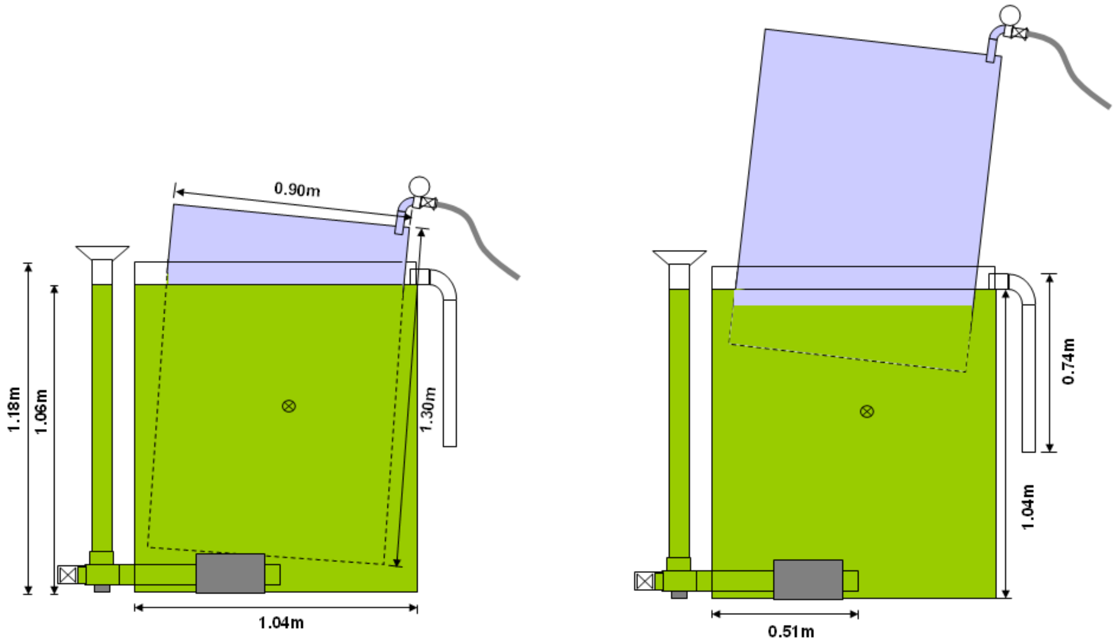

Figure 1. ARTI compact biogas plant scheme (left: with empty gasholder; right: with full gasholder) (Source: Lohri, 2009)

3. METHODOLOGY

To conduct a detailed monitoring of the ARTI compact biogas system, one plant was installed and operated in the campus of Ardhi University. This "full scale plant" however experimentally operated, allowed flexibility in terms of changes in feedstock and on-site measurements of physical and chemical parameters of interest as well as gas production and composition.

During the start-up period, the biogas plant was inoculated with 60 kg of dried cow dung mixed with water and 300 l effluent from an existing biogas plant. Thereafter, the plant was left without further feeding for 10 days, in which only changes in gas production and composition were monitored (Phase 1). The biogas plant was then fed with 2 kg/d canteen waste for four weeks and subsequently, with 2 kg/d market waste for another four weeks (phase 2). The feeding rate of 2 kg per day was chosen because on one hand it represents a realistic quantity of organic waste produced by an average household in Dar es Salaam (Mbuligwe & Kassenga, 2004) and on the other hand it conforms to the reactor specifications. After a break of one week without feeding, the rate of feeding of both substrates (canteen waste and market waste) was increased from 2to 5 kg/day. The purpose was to assess the effects of increasing substrate feeding rates on the performance of the digester and to determine if the operational, as well as process specific biological, chemical and physical limits of the digester can be reached (Phase 3).

All waste materials were chopped and mixed with water before they were fed to the digester . Mixing was achieved by putting the daily waste amount into a 20-l bucket and adding water up to the 10 l mark. To minimise the risk of blocking the inlet pipe, the feedstock was first stirred to to best homogenise the slurry. Then digester effluent (20-30 l taken from the overflow) was recirculated and poured into the inlet two to three times. Main objective was to flush the inlet pipe and at the same time ensure good mixing of bacteria available in the effluent with the new feedstock.

Laboratory analyses were conducted for determining various parameters of the feedstock (TS, VS, COD_{total}, $COD_{dissolved}$, N_{total}, NH_4-N, and P_{tot}) and effluent (TS, VS, COD_{total}, $COD_{dissolved}$, N_{total}, NH_4-N, P_{tot}, PO_4, Pb, Cu, Cd) in the Laboratory of Environmental Engineering at Ardhi

University in Dar es Salaam. Temperature, pH and Redox-Potential of the effluent were also measured on a daily basis.

The ratio of Volatile Fatty Acids to Total Inorganic Carbon (A/TIC-ratio) was measured twice per week according to the Nordmann-Titration (during Phase 2) and Kapp-Titration (during Phase 3). Used as an indicator of the process stability inside the digester, A/TIC-ratio expresses the ratio between Volatile Fatty Acids and buffer capacity (alkalinity), or in other words the amount of Acids (A) compared to Total Inorganic Carbon (TIC).

The Dräger X-am 7000 sensor was used to measure the volumetric percentage of methane (CH_4), carbon dioxide (CO_2) and oxygen (O_2) in the biogas. Integrated sensors were used for determining concentrations of hydrogen sulphide (H_2S) in the range of 0 – 100 ppm and of ammonia (NH_3) in the range of between 0 and 200 ppm. The gas composition was measured on a daily basis in the afternoon (before feeding) when the gas was released.

To measure the gas production, scaling of the gasholder was done. Initially, the biogas produced was allowed to accumulate in the closed gasholder until the drum was lifted to the maximum height. Controlled by the gas meter, 20 l of gas was released. The tap was then closed and a white line drawn on the gasholder just above the surface of the digester liquid, using a permanent marker pen. This procedure was repeated until all the biogas (400 l) was released. The scaling was related to production rate of biogas by simple calculations.

To get further information on how the installed biogas systems are performing, interviews with users of existing ARTI biogas plants in Dar es Salaam were conducted. This household survey aimed to compare the results from the research plant run under controlled conditions with the performance of plants operating under real conditions in private households.

4. RESULTS AND DISCUSSION

4.1 General technical aspects

A positive aspect regarding the ARTI system is that all the materials necessary for the installation are locally available. A DVD produced by ARTI-India includes a visual “do-it-yourself” instruction and can be ordered directly from ARTI-India. The whole installation including the inoculation of the research plant at Ardhi University was carried out by one person and was completed within 3.5 hours. The digester and gas holding tanks have a 30-year guarantee given by the manufacturer and as such the long service lifetime of these important components of the biogas system is assured.

Blocking of the inlet pipe seems to occur frequently as a result of the rather small diameter of the inlet pipe or the insufficient chopping or dilution of the feedstock. In addition, it was observed that the moistness of the system attracts African Giant Land Snails (*Achatina fulica*), which can also lead to clogging of the inlet pipe. Therefore, the inlet pipe should permanently be covered to avoid entering of such snails.

The most essential technical improvements concern digester tank and respective gasholder tank size. The current design leads to a gas loss of about 22% of the total digester area due to the excessive space between digester and gasholder since these two system components are not designed to fit optimally. Minimising the space between these two system components (tanks) would considerably reduce atmospheric loss of biogas.

4.2 Operational parameters

Climatic conditions in Dar es Salaam are favourable for biomethanation, as average air temperature is optimal for anaerobic process (30-35°C) and the negative influence on process stability and gas production caused by rainfall is minimal.

After the start-up phase, recirculation of effluent and thorough mixing of the digester contents ensured that the anaerobic process quickly reached stable conditions. The average temperature inside the reactor was 28.8°C and the pH stabilized around 6.5. During phase 3, when the daily amount of feed was increased from 2 to 5 kg/d, the slurry inside the reactor did not show any alarming sign of disturbance, with pH only slightly dropping to 6.2. As the average air temperature during this phase increased, so did the average digester temperature (30.9°C).

Since pH changes slowly with changes in the quantity and quality of feedstock, the A/TIC-ratio provides real-time valuable information on the process stability.

An increase in acidity (or proportional decrease in carbonate alkalinity concentration) is the first practical measurable indicator that an anaerobic treatment system is stressed. It was observed that after inoculation, the amount of VFA was quite high in the beginning compared to the alkalinity, which resulted in a high A/TIC value.

After day 15, the A/TIC ratio was stabilized around 0.15 (feedstock: 2kg food waste/day). Following the change of feedstock type to 2 kg market waste per day, the A/TIC-ratio was levelled around 0.08.

4.3 Reduction of waste volume and organic load

The daily waste reduction can be quantified by comparing TS concentration of the influent with that of the effluent. During the feeding period with 2 kg/d, the system showed a TS reduction of 84.9% for food waste and 72.8% for market waste. The observed TS removal performance rates indicate that the hydraulic retention time of 42.5 days is appropriate.

To describe the reduction of organic load, one option is to measure the VS of influent and effluent. The average VS concentrations of food waste influent and effluent were 451 and 3 g/d, respectively, which result in a removal of 92.2%. On the other hand, the mean VS of market waste influent was 177 g/d and that of its effluent was 26 g/d, which leads to a reduction of 85.3%.

Another alternative to measure the reduction in organic load is through COD. Although the daily COD of influent and effluent of food waste (average influent 567 g/d, average effluent 96 g/d) and market waste (average influent 152 g/d, average effluent 24 g/d) differed considerably, the COD reduction of the substrates was found to be comparable at approximately 83%.

4.4 Gas production and composition

Figure 2 presents the trend in daily gas production during Phase 3, when daily feeding rate was increased from 2 to 5 kg/d for both market waste (Equivalent to 0.5 kg/d TS) and food waste (Equivalent to 1.2 kg/d TS). Between feeding market waste and food waste, a 3-day feeding break was effected in which the gas production dropped to 70 Nl/d.

The rate of production of gas from food waste was observed to be approximately twice that from market waste. The specific gas production for food waste was 264.4 Nm^3/kg while that of market waste was 42.7 Nm^3/kg.

The average composition of methane in biogas produced from market waste (66.4%) was found to be higher than that from food waste (56.8%).

Assuming that a Tanzanian household produces 1 kg of food leftovers and 1 kg of fruit and vegetable peelings per day, 2 kg of kitchen waste produced may be able to generate about 200 l of biogas, which is equivalent to a 45-minutes of burning period.

This burning period represents about 1/3 of the average cooking time of 2.5 h per day for a household with five members.

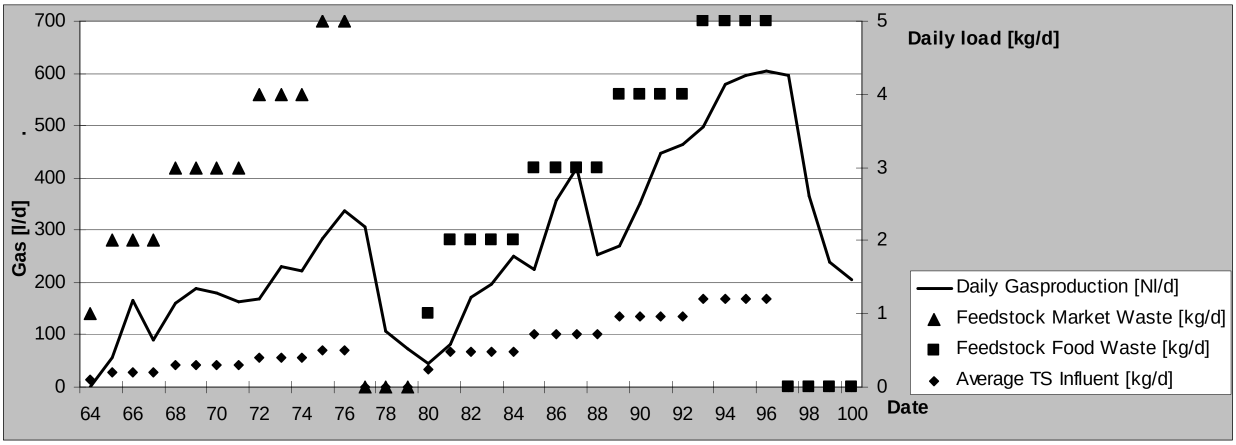

Figure 2. Varying daily feed and resulting gas production (Lohri, 2009)

An average household using 1008 kg of charcoal per year can therefore save one third of the charcoal (336 kg) or an equivalent of TZS 276 000 (Euro 168). As the ARTI system is sold for TZS 850 000 (Euro 507), its amortisation period is estimated to be to roughly three years. However, since the investment costs are rather high, its widespread dissemination is limited. With some additional logistical and operational efforts, the daily feeding rate could gradually be increased from 2 to 5 kg, to produce 670 l/d of gas or 150 minutes of cooking time.

4.5 Effluent quality

The average concentration of total phosphorus in the effluent while feeding food waste was 248 mg/l (6.8% of TS), of which 171 mg/l (69%) was in the form of phosphate. After changing substrate to market waste, the effluent had a concentration of 147 mg/l of phosphate, which accounted for 66% of the total phosphorus concentration of 225 mg/l (8.2% of TS). For comparison purposes, the influent of diluted market waste had a total phosphorus concentration of 162 mg/l.

While average ammonium-nitrogen (NH_4-N) concentration in the influent was found to be 31.6 mg/l for food waste and 27.9 mg/l for market waste, the NH_4-N concentration observed in the effluent was 74.1 mg/l for food waste and 85.5 mg/l for market waste. Therefore, the bacterial activity resulted in an NH_4-N increase of 134.5% for food waste, and 206.5% for market waste.

The quality of the effluent as organic fertilizer can only be judged on the basis of its suitability to support the growth of particular type of plant. Furthermore, the concentration of potassium (K), as well as that of Fe, Ca, Mg and Zn is significant because phosphate builds chelates with these essential trace elements, which potentially can prevent the reception of PO_4.

Comparison with quality standards of compost is also of limited validity. Nevertheless, the concentrations of heavy metals were found to be far below the tolerated values for compost as one would have expected since the wastes came from unlikely sources (canteen and market) of heavy metals.

4.6 Survey of Biogas Systems

The household survey conducted in October 2008 revealed that most of the installed ARTI biogas plants in Dar es Salaam are poorly operated and maintained. Out of 12 biogas plants only 4 were in operation, whereas 8 were not in use due to various reasons, which include:

- Insuffcent operating instructions given by ARTI-TZ, which has led to low understanding on the way the biogas systems should be operated;
- Poor maintenance by the operators, which has resulted into inappropriate operation, poor performance and damage of CBS; and,
- Lack of follow-up services by ARTI-TZ, which has largely been responsible for failures of CBS for unidentified reasons.

The major causes for the breakdown of the 8 ARTI systems include breakage and blockage of inlet pipe, overfeeding, and damage of gas tap. In some cases, the digester was not in use for several months and the real cause of the failure could not be determined. In general, the operators of the CBS did not seem to be well informed in terms of potential feedstock, quantity of water required for dilution of feedstock, recirculation of effluent, correction of defects, etc. Considering the fact that even minor problems can lead to a complete failure of the system (e.g. blockage of the gas pipe due to condensation of water in the pipe), proper training and effective follow-up services are inevitable for the sustainability of the CBSs. Based on these observations, following improvement proposals are given:

- Employment of an additional ARTI technician for fixing all damaged systems. Furthermore, the technician should be responsible for the follow-up services, especially during the first few months after installation of a new CBS until the users are able to operate and do minor maintenance of the systems independently on daily basis.
- Conducting a workshop for the ARTI technicians on how to inspect a CBS systematically using a checklist.
- Preparation of a simple manual in English and Kiswahili for customers, which can be distributed during training on how to operate and maintain the CBS. The manual will be useful in giving handy information on operating the system (notably the feeding procedure) and trouble shooting.
- Encouraging the customers to call ARTI-TZ immediately in case of any difficulties so that a complete restart of the CBS can be avoided.

Following this survey, ARTI-TZ has already made great efforts to improve its services and is currently distributing a manual in English and Kiswahili to customers. During a second survey of the systems in November 2008, all but two biogas plants were functioning thus proving that the services offered by ARTI-TZ following the first survey were successful. Two major issues of concern in all the systems were frequent blockage of gas pipes by condensation of water and long distance (up to 15 m) between digester and burner in two of systems surveyed. It is thus recommended to remove regularly water condensed in the pipes by installing a simple water drain.

Although the research plant at Ardhi University did not experience noticeable problems and was regarded as simple to operate, the inspection tours clearly proved that a proper follow-up service is not optional but absolutely essential. This is especially important during the first 3 months after installation of a CBS, since during this period the basics of operating and maintaining the system are generally yet to be properly grasped by owners.

4.7 Safety Issues

Although a theoretical risk of explosion with biogas exists, such catastrophe is not likely to occur. Danger arises mainly in closed chambers, where a mixture of air and biogas (6-12%) exists. However, no explosion related to biogas utilisation has been reported in Tanzania (Schmitz, 2007), probably because digesters and burners are normally located in open and well-ventilated areas.

Both methane (lighter than air) and carbon dioxide (heavier than air) are toxic gases but are not considered to pose a serious threat to human health because most buildings in Tanzania are well ventilated.

The possibility of creating a breeding place and attraction of disease transmitting insects in the exposed liquid between the digester and gas holder (rim) is relatively low, however it can not be completely neglected. A study conducted by Zoology Department of Dar es Salaam University revealed that:

- 80-90% of the larvae (and pupae) found in the digester were species of the *Psychodidae* family (engl. sewage flies or moth flies), which do not bite and are not transmitters of serious diseases.
- 10-20% of the larvae (and pupae) were *Culex*, which are the most widespread mosquito species in Dar es Salaam. They act as human nuisance and as vector of filarial parasites. By virtue of their physiological attribute, their larvae need to live underneath the liquid surface to suck air through their breathing tube. Any turbulence will disturb this important activity for their survival. As flooding or flushing of breeding place prevent the breeding of mosquito larvae (Cheesbrough, 1987), stirring the rim surface sporadically with a stick can therefore reduce the mosquito population to a certain extent.
- *Anopheles* mosquitoes (transmitter of Malaria parasites) were not found due to the high organic pollution of the digester liquid. According to Marquardt et al. (2000), *Anopheles* larvae occur in a wide range of habitats but most species prefer clean, unpolluted water.

If biogas is continuously produced but not constantly used, the capacity of the gasholder will be exceeded. There is hardly any danger for the dome to topple over, as the gasholder will be slightly lifted by the pressure of the gas. The abundant biogas can thus bubble out through the rim which is comparable to a safety pressure valve.

Although hydrogen sulphide is a toxic gas, desulphurisation of the biogas at household level is not necessary. Since CH_4 and CO_2 are both odourless, the characteristic rotten egg smell of H_2S can be helpful in detecting gas leakages. Simple experiments have been done by installing a simple sulphur trap to the research plant. However, the efficiency of the trap could not be accurately determined due to the low H_2S detection range of the measuring devise (Dräger X-am 7000 sensor).

5. CONCLUSION

The results of the study have revealed that there is a great potential for anaerobic digestion of the organic fraction of municipal solid waste in low and middle-income countries. The ARTI system has proved to be effective in terms of the reduction of waste volume and organic load. Although the performance of the system regarding gas production is good, the design of digester has to be improved. The most essential technical improvements concern digester and gasholder size. The unnecessarily large gap between the digester and gasholder leads to a loss of gas. Minimising the space between these system components (without jeopardising the free movement of the gas holder) would considerably reduce atmospheric loss of biogas. Although there is some room for improvement, the ARTI biogas system has proven to be technically and environmentally viable.

However, reliable operation and maintenance services are needed to ensure long-term and sustainable use of the system.

As there are currently no competing products on the Tanzanian market for anaerobic digestion system of organic solid waste at household level, the market potential of ARTI biogas system may therefore be regarded as good. The most critical market factor is the reliability of the installed systems - as poor performance may cause the owners to complain to potential future customers thus jeopardising the market of the biogas systems.

Consequently, a robust quality control system needs to be put in place to ensure that the installed biogas systems perform to the level, which is expected. To make the ARTI biogas system affordable to a wider public in Tanzania, the cost of installation has to come down considerably.

The ARTI biogas system has a good potential for being scaled up depending in particular on the range in sizes of water tanks available on the market. In view of this, larger generators of organic solid wastes such as schools and restaurants can easily adapt the system to match with the volume of waste they generate. A follow-up project will therefore focus on an ARTI biogas system with three 4000-l digesters, which have been operating in a secondary school in Dar es Salaam since August 2008.

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