Bryant and Afitiri *Energ Sustain Soc* (2021) 11:16
https://doi.org/10.1186/s13705-021-00293-6

Energy, Sustainability and Society

ORIGINAL ARTICLE

Open Access

Household willingness to adopt a single-stage solar-supported hyper-thermophilic anaerobic biogas digester in Ghana

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Abstract

Background: Sustainability of energy is key for quality life; thus, the use of clean energy at the household level warrants moving from fossil-based energy to modern forms like biogas. However, the joint interactive effect of household income, biogas usage and willingness to adopt a single-stage solar-supported hyper-thermophilic anaerobic biogas digester (SSHTABD) is not known.

Methods: A cross-sectional survey was carried out to assess the willingness of residents of Elmina to adopt the SSHTABD. Stratified and simple random sampling techniques were used to select 219 respondents fitted into a complementary log–log regression model.

Results: Household willingness to adopt the SSHTABD was 86%. Among them are households not willing to use biogas but have high income and households willing to use biogas but have either low or high income are more likely to adopt the technology compared to households not willing to use biogas and have low income. Households not willing to use biogas, but have high income (OR = 1.725, confidence interval [CI] 0.803–3.706) and households willing to use biogas, but have low income (OR = 1.877, CI 1.103–3.188) compared to households willing to use biogas and have high income (OR = 1.725, CI 1.080–3.451) are more likely to adopt the technology as households not willing to use biogas and have low income. Additionally, households employed under the formal government sector, formal and informal private sectors are 40%, 136% and 103%, respectively, more likely to adopt the technology than those unemployed.

Conclusion: The high willingness of households to adopt the technology calls for government to support households to own biogas digesters thus requires policy interventions and interdisciplinary research.

Keywords: Energy, Biogas, Willingness, Hyper-thermophilic, Anaerobic, Ghana

Introduction

Over the years, the development and harnessing of clean energy have been termed "the golden thread" by the International Energy Agency and World Bank, linking economic growth, social equity and environmental sustainability of a country [1]. Hence, striving for sustainable economic development cannot be achieved without making clean energies accessible to all at the household level. This makes clean energy a topical issue in international development and environmental management [2].

Ghana and many sub-Saharan African (SSA) countries still depend extensively on traditional cooking fuels at the

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household level. The assessment of household access to clean cooking fuels across 31 countries in SSA reveals that just 10% have access while the proportions of access to unclean and clean cooking energy sources in Ghana are 79% and 21%, respectively, as at 2014 [1]. Indoor air pollution stands as a leading cause of premature deaths that occur annually worldwide [3] and about 85% of premature deaths that occur annually worldwide are accounted for biomass combustion [4]. This figure represents approximately 18,000 daily deaths, a mortality rate that exceeds deaths from HIV/AIDS, tuberculosis and road injuries combined [4].

Biomass usage in Ghanaian households is very high. The proportions of households that use firewood and charcoal are 56% and 36%, respectively, which produce a combined prevalence of biomass usage of 92% [5]. Studies have equally shown that Ghana is one of the largest consumers per capita of charcoal in West Africa. 84% and 13% of Ghanaian households are reported to use firewood and charcoal, respectively, as cooking fuels [5, 6]. Although much of firewood harvested comes from deadwood from farms and fallow land, it is estimated that Ghanaians consume 25–28 million tons year^{-1} of raw wood largely due to a lack of alternative fuel sources [6, 7].

Clean cooking energy usage at the household level has immense benefits to human health and the environment [1, 8], and increases the economic and social development of a country [9, 10]. Access to clean cooking energy types that are affordable, reliable and sustainable helps reduce the amount of greenhouse gases (GHG) and other pollutants emitted into the atmosphere [4, 11], reduces poverty, improves human health, preserves ecosystems and promote economic growth [9, 12, 13].

Although households reliance on traditional biomass fuels for cooking is seen as a first-order health threat, a decline in climate change mitigation and the associated environmental effects [6, 14, 15], renewable fuel usage such as biogas combustion with high efficiency in simple devices at the household level comes up with numerous advantages not observed with traditional cooking fuels methods, such as substantial local benefits as well as a reduction of GHG emissions and particulate matter into the atmosphere [9], meeting the energy demands of households [12] and moving towards sustainable development goals [9, 11, 16].

This realization has compelled several countries to adopt different clean cooking fuels and energies (renewable energy technologies). For instance, Mozambique and South Africa introduced wind pumps and wind generators [10, 17], while Tanzania introduced electric stoves for biomass fuel burning [18]. Similarly, solar crop dryers [19] and biogas lamps for lighting [20] were introduced in Uganda and Kenya, respectively. Additionally, biogas technologies were equally adopted in Nigeria [12]. However, Ghana is yet to develop a major program to promote biogas plants dissemination on a larger scale [7]. The by-product from the biogas digestion process includes carbon dioxide, methane and digestate that can be hygienized for (peri)-urban agriculture. The development and use of a solar-supported high-temperature anaerobic digestion system for BW compared with the normal mesophilic and thermophilic biogas digesters which cannot kill pathogens (such as *Salmonella typhi* and *Salmonella senftenbengensis)* would not only provide biogas to be used for cooking but also a digestate, free of pathogens, for safe use as fertilizer [21]. Most thermophilic systems that have existed rely on the use of electricity or biogas generated from the same digesters for heating the system. Thus, having a biogas digester that relies on the use of solar energy to heat the reactor to a hyper-thermophilic condition to kill all available pathogens is worth noting.

A study by Armah et al. [1] affirms the need to move from traditional biomass fuel and other "dirty" energy to modern forms at the household level to overcome the adverse effects associated with such fuel usage and improve the living standards in SSA.

Several studies have reported many barriers that impede households' willingness to adopt biogas technologies as cooking fuels, giving credence to country-specific barriers such as social, economic, financial and technical constraints [10, 21–24]. Yet, few observational studies have been carried out to explore the role of socio-environmental factors in accepting biogas technologies [2, 20, 25]. Furthermore, our understanding of the interactive effect of households' income and gas usage when available and their joint influence on the willingness of households to accept and adopt a biogas digester is limited. More so, the knowledge of Elmina's residents on a single-stage solar-supported hyper-thermophilic anaerobic biogas digester (SSHTABD) for black water treatment for energy production is very nascent, let alone relevant compositional and socio-environmental factors associated with the adoption of this technology.

Therefore, the aim and objective of this study are to fill this knowledge gap by assessing the willingness to adopt a household biogas digester, more specifically, a single-stage solar-supported hyper-thermophilic anaerobic biogas digester (SSHTABD) constructed for this purpose.

Materials and methods

Study area

This study was conducted in Elmina in the Komenda Edina Eguafo Abirem (K.E.E.A.) Municipality of the Central Region of Ghana (Fig. 1). Elmina lies within latitudes 5°05' North and longitudes 1°20' West and serves as the

Fig. 1 Map of Ghana showing the district map of the study area, Elmina (Source: [21])

administrative capital of the K.E.E.A. Municipality [21]. According to the 2010 population and housing census, Elmina has a total population of approximately 34,000 inhabitants but is projected to increase to 42,366 in 2020 using a growth rate of 2.2%. The town is bordered to the south by the Gulf of Guinea, West by Bantoma, East by Abakam and North by Bronyibima townships [21]. The town is known to be one of the biggest fishing hubs of Ghana and serves as a great tourism community in the country. The inhabitants of Elmina are largely fisher folks, however, the presence of the Brenya lagoon, which stretches and overflows its borders during high tides to Terterkessim slum, has opportunity for salt production in commercial quantities [21]. Annual rainfall of the area ranges between 750 and 1000 mm with generally high average temperatures of 27 °C. Shrubs and grasses are the dominant vegetation cover in the area.

Choice of location

The Terterkessim slum in the Elmina Township is a public health threat to the inhabitants and a hindrance to commercial salt production. The quality and quantity of salt produced by the Elmina Salt Industry (ESI) are negatively affected by black water (BW) from open gutters and open defecation in the community. The public toilet in the community is in a deplorable state, hence households without toilet facilities refuse to use it and resort to open defecation into open gutters, lagoon and around the salt ponds [21]. These make Terterkessim urban slum in Elmina a priority area for engineers, NGO's and policymakers to build technologies to help curb this menace. This, therefore, made it imperative to build one demonstrative household toilet facility connected to a biogas digester for both biogas production and disinfection of the digestate within the Terterkessim urban slum of Elmina (Fig. 2). Consequently, it was ripe to ask residents of Elmina if they were willing to have such a facility in their homes. This initiative sought to bring about positive changes in the economic, energy security and promotion of public health status of residents of Elmina [21].

Data collection

This study is part of a larger project that evaluated the development of a single-stage solar-supported

Fig. 2 A single-stage solar-supported hyper-thermophilic anaerobic biogas digester constructed in Terterkessim slum, Elmina (Source: [21]). **a** Solar photovoltaic, **b** charge controller, **c** a pure sine wave invertor kept near the toilet seat, **d** single-stage solar-supported biogas digester

hyper-thermophilic anaerobic reactor for biogas production and disinfection of BW in the Terterkessim slum, Elmina-Ghana (Fig. 2). A Household-Based Survey (HBS) was conducted in 2016 to assess the perception of residents in Elmina-Ghana, on their willingness to adopt the SSHTABD in their homes if it was constructed for them.

A cross-sectional survey was carried out to assess the perception and willingness of residents of Elmina to adopt the SSHTABD. With Ghana's population growth rate of 2.2%, the 2020 population size of Elmina was projected to be 42,366. Using a confidence limit of 93% and margin of error of 7% and based on a similar survey carried out in the Northern region of Ghana [26], a minimum sample size of 203 was considered adequate for the study.

The sample size (n) was calculated using a mathematical formula proposed by [26],

$$n = \frac{N}{1 + N(\alpha^2)},$$

where: n = sample size, N = sample population or the total population of the area under study (projected population for the year 2020 is 42,366), α = margin of error, i.e., 0.07, which is the confidence limit of 93%.

Two hundred and nineteen (219) households were selected for the interview by the researchers to minimize errors and assure accuracy. The randomly selected individuals from the 219 households were drawn from the adult population whose ages were 18 years or older. Only one member or individual was drawn from each household. Age 18 years was chosen to be the minimum age because that is a constitutionally accepted age in Ghana for one to be considered an adult. Any individual in a household whose age fell within the inclusion age criteria and was met in a particular household was considered to be part of the guided interview. A preliminary study was conducted in a community in Cape Coast. The community members in the pilot study were closely related to residents of Elmina in terms of culture, ethnicity, dominant religion and age distribution. This was necessary to identify and limit the influence of confounding factors in the study. Before the commencement of the study, a test of content validity, internal consistency, and reliability of the instrument was ascertained. The validity and reliability of the data collection tool used was 0.823. This value exceeds the recommended reliability value of at least 0.6.

The HBS employed stratified sampling and simple random sampling approaches. Fifteen (15) evaluation areas (EAs) in Elmina were stratified based on residential and income strengths. The income strength criteria were called Lower Class Residential Area (LCRA), Middle-Class Residential Area (MCRA) and High-Class Residential Area (HCRA) based on World Bank classification of daily income earned [27]. The LCRA included areas such as Terterkessim slum, New Market Area, Cemetery and Zongo. The MCRA comprised Estate, Police Station, Brofobobaho, Chapel Square, Fishing Harbour Area and Akotobinsin. SSNIT Flats, Elmina Beach Resort Area, Ahomka FM, African Pot and Construction Pioneers (CP) residential areas constituted the HCRA. The second stage of the sampling approach involved random sampling of the 219 respondents from the fifteen evaluation areas in Elmina. The HBS made use of structured interviews approach to collect data. Here, enumerators administered the interview guide by reading the questions from the survey instrument. Four Teaching Assistants of the Department of Environmental Science, University of Cape Coast (UCC) were recruited as research assistants and oriented on how to administer questions ethically to participants. The research assistants were given a one-day orientation on how to administer the interview guide, even though they had previous experiences in collecting data from similar studies. The field survey took place between 1st October and 19th December 2016.

Measures

Response variable

The response or dependent variable for the study was household willingness to adopt the SSHTABD in their homes should the government say he wants to construct one for each household. Household willingness to adopt the SSHTABD was represented as a dichotomous variable where respondents are expected to answer "yes" or "no" with "1" means yes and "0" means no.

Explanatory variables

The selection of the key predictor variable and other variables for this study as well as the sequence of entry of the predictor in the regression model was based on literature, theoretical relevance, parsimony, model fit and practical significance.

The key explanatory variable- "GasWealth" was derived from the interactive effect of Household willingness to use gas when available (no, yes) (hereafter gas use) and Household income status. Household income status was measured as a continuous variable, however, for parsimony and to establish sufficient cases in each sub-group, the continuous variable—household income was grouped using the World Bank criteria [27] to get two distinct categories—low income (earn < 1.9 USD a day), high income (earn > 1.9 USD a day).

The composite variable gave four mutually exclusive groups—households with no interest to use biogas and have low income, households with no interest to use biogas but with high income, households willing to use biogas but with low income and rich households willing to use biogas.

It is extensively documented that household willingness to adopt biogas systematically varies within compositional factors (biosocial and socio-cultural factors) and socio-environmental factors [10, 20, 22, 24, 25]. Compositional and socio-environmental factors were controlled for by including them in the regression models. The compositional factors included the gender of the respondent (male, female), the age of respondent (young adult: less than 35 years, middle-aged adult: 35–55 years, old aged adult: more than 55 years), the education attainment (no formal education, primary, secondary, higher), the employment status of respondent (unemployed, formal government sector, formal private sector, informal private sector) and the household size (small: 1–5, medium: 6–10, large: above 10). The socio-environmental factors included the access to toilet facility (no, yes), and the type of cooking fuel (clean, unclean).

Data analysis

Descriptive and multivariate statistical techniques were employed in data analysis to examine relationships and proportions between factors that would influence a households willingness to adopt the SSHTABD while controlling the theoretically relevant compositional, and socio-environmental factors using a Statistical Package for Social Sciences (IBM SPSS version 22) software and Stata 13 (StataCorp, College Station, TX, USA) SE software.

Descriptive analysis

Descriptive analysis of predictors of household willingness to adopt the SSHTABD was operationalized by cross-tabulation. This was done to assess the proportions of the differences observed among predictors of the response variable (willingness to adopt the SSHTABD). The descriptive results output was presented as a contingency table.

Multivariate analysis

The relationship between willingness to adopt the SSHTABD and joint effect of gas use and income status of households were determined using generalized linear models (GLMs). Armah et al. [28] asserted that the use of GLMs simplifies the regression by relating the response variable to a linear model through a link function and makes the magnitude of the variance of each measurement to be a function of its predicted value. Several probable options exist for a binary response (no = 0, yes = 1) to the willingness to adopt the SSHTABD such as the complementary log–log model, negative log–log model, probit model and logit model depending on the link function of the GLM [6].

A complementary log–log regression model is appropriate when the responses to a dichotomous response variable are asymmetric in the [0, 1] interval for which the affirmative is more than 55% as in the case of the response variable in this study [29, 30]. The negative log–log regression model is also adopted when the response to the outcome variable is asymmetric with more than 55% non-affirmation. The probit and logit models have the same link functions [28] and are appropriate when the responses to the outcome variable are symmetric with 50% affirmative and 50% non-affirmative [29, 30].

Eighty-six percent of respondents responded "yes" to adopt the SSHTABD in their homes. The complementary log–log model, which takes into account the fact that affirmative responses are more likely, gives a better representation and is used for the analysis of the relationship between the odds of willingness to adopt the SSHTABD and theoretically relevant variables. The likelihood willingness to adopt the SSHTABD was estimated using exponential coefficients-odds ratios (ORs). An OR = 1 signifies that the higher value of the predictor does not affect the odds of willingness to adopt the SSHTABD; OR > 1 means that the higher values of the predictor are associated with higher odds of willingness to adopt the SSHTABD; and OR < 1 implies that higher values of the predictor are associated with lower odds of willingness to adopt the SSHTABD.

The cross-sectional survey was found to have a hierarchical structure with respondents nested within the survey cluster. This could potentially bias the standard errors (SE). The study, therefore, accounted for clustering of observations in units of households by imposing on the models a "cluster" variable, and thus, the identification numbers of respondents at the cluster level. This adjusted the SE producing statistically robust parameter estimates. The study employed a statistical significance level set at 0.07 and a confidence interval (CI) of 93% based on a similar approach used by [26] in Northern Ghana.

Three models were run at the multivariate level. Model 1 included the joint effect of gas use and income status. Biosocial factors and socio-cultural factors constituted model 2 while model 3 comprised socio-environmental factors.

Results

Descriptive analysis

Household willingness to adopt the SSHTABD was 86%. The joint effect of household gas use and income status and their influence on household's willingness to adopt the SSHTABD is shown in Fig. 3.

Willingness to adopt the SSHTABD was higher in all the categories observed in the study. From Table 1, 73% of respondents belonging to the no biogas use and low-income category were willing to adopt the SSHTABD. Households that were not willing to use biogas if available but have high-income status, as well as those that are willing to use biogas but have low income had both an 88% of willingness to adopt the SSHTABD. Households that earn a higher income and were willing to use biogas when available showed an 89% proportion to adopt the SSHTABD.

Males' and females' proportions of willingness to adopt the SSHTABD were 87% and 86%, respectively. The descriptive statistics revealed that households that have

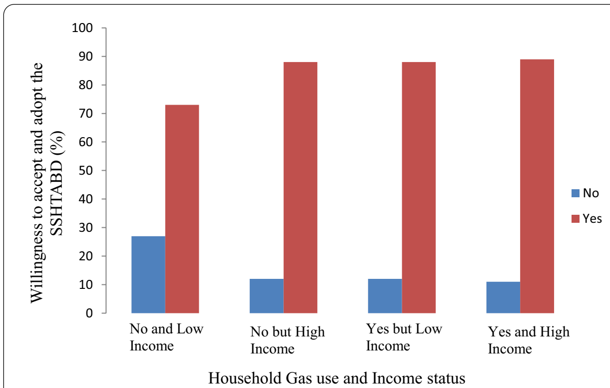

Fig. 3 Gas use–income status heterogeneities in willingness to adopt the SSHTABD

Table 1 Percentage distribution of household willingness to adopt the SSHTABD by predictor values

Variable	Willingness to adopt the SSHTABD	
	No (%)	Yes (%)
Gas use and income status		
No, low income	27	73
No, high income	12	88
Yes, low income	12	88
Yes, high income	11	89
Age (years)		
Young adult (below 35 years)	14	86
Middle-aged adult (35–55 years)	11	89
Old-aged adult (above 55 years)	19	81
Highest educational level		
No education	23	77
Primary	10	90
Secondary	11	89
Higher	16	84
Employment status		
Unemployed	24	76
Formal government sector	14	86
Formal private sector	7	93
Informal private sector	11	89
Household size		
Small (1–5 members)	13	87
Medium (6–10 members)	14	86
Large (above 10 members)	14	86
Availability of toilet facility		
No	16	84
Yes	12	88
Source of cooking fuel		
Unclean	15	85
Clean	12	88
N	219	

access to a toilet facility and use clean cooking fuel both reported 88% willingness to adopt the SSHTABD.

Multivariate analysis

To establish the context-specific disparities in predictor variables to a household willingness to adopt the SSHTABD, disaggregated data analysis was carried out. Disaggregated data analysis has been reported to have the ability to ascertain the context-specific disparities in the predictor variables [31]. Three models were ran at the multivariate level: combined effect of gas use and income status and biosocial (model 1); socio-cultural variables (model 2); and socio-environmental variables (model 3); to assess their relationship with household willingness to adopt the SSHTABD. Table 2 indicates the OR, robust standard errors, probability values, and CIs in the models. In model 1, the categories of the combined effects of biogas use and income level status were evaluated. Households which were not willing to use biogas if available but have high income were 66% more likely to adopt the SSHTABD than households not willing to use biogas if available and have low income. Those that were willing to use biogas but have low income were 65% more likely to adopt the SSHTABD than households not willing to use biogas if available and have low income. Those that were willing to use biogas and have high income were 68% more likely to adopt the SSHTABD than households not willing to use biogas if available and have low income. The relationship between the combined effect of biogas use and income status and household willingness to adopt the SSHTABD in model 1 became more robust while accounting for socio-cultural and socio-environmental factors. The model output revealed that females (OR = 0.928, CI 0.658–1.311) were less likely to adopt the SSHTABD compared to males. Middle-aged adult households (OR = 1.094, CI 0.753–1.591) were more likely to adopt the SSHTABD compared to young adult households while the old-aged adult (OR = 0.848, CI 0.515–1.398) were less likely to adopt the SSHTABD compared to the young adults' households.

The odds further increased from what was observed in model 1 for categories of biogas used and income status in model 2. The output in model 2 revealed that households that are willing to use biogas but have low income (OR = 1.915, $p < 0.05$) are more likely to adopt the SSHTABD compared to their other counterparts in the reference group. Similarly, households that are willing to use biogas and have high income are 204% more likely to adopt the SSHTABD than those that are not willing to use biogas and have low income. Model 2 output (Table 2) equally revealed that primary (OR = 1.990, CI 0.922–4.294), secondary (OR = 1.857, CI 0.970–3.555) and higher (OR = 1.637, CI 0.726–3.688) educated individuals of a household were more likely to adopt the SSHTABD compared to no formal education individuals of a household. With respect to employment status, formal government (OR = 1.355, CI 0.743–2.470) employees were more likely to adopt the SSHTABD compared to the unemployed group. Formal private sector and informal private sector employees were 140% and 97% more likely to adopt the SSHTABD than the unemployed group.

Regarding household size, medium household size (OR = 1.014, CI 0.637–1.614) was more likely to adopt the SSHTABD compared to small household size while the large household sizes (OR = 0.868, CI 0.555–1.357) are less likely to adopt the SSHTABD compared to small household sizes.

Table 2 Complementary log–log regression model showing the relationship between household characteristics and willingness to adopt the SSHTABD

Variable	Gas use and income status + Biosocial factors					Socio-cultural factors					Socio-environmental factors				
	OR	SE	*P* value	Conf	Interval	OR	SE	*P* value	Conf	Interval	OR	SE	*P* value	Conf	Interval
	Model 1					Model 2					MODEL 3				
Gas use and income status (ref: No poor)															
No rich	1.657	0.554	0.130	0.861	3.190	1.794	0.690	0.129	0.844	3.812	1.725	0.673	0.162	0.803	3.706
Yes low income	1.645	0.422	**0.052**	0.995	2.718	1.915	0.523	**0.017**	1.122	3.270	1.877	0.507	**0.020**	1.105	3.188
Yes high income	1.676	0.457	0.058	0.982	2.860	2.039	0.611	**0.017**	1.133	3.670	1.930	0.572	**0.027**	1.080	3.451
Sex (ref: Male)															
Female	0.928	0.163	0.673	0.658	1.311	0.890	0.164	0.527	0.621	1.276	0.868	0.159	0.438	0.606	1.243
Age (years) (ref: Young adult (below 35 years))															
Middle-aged adult (35–55)	1.094	0.209	0.637	0.753	1.591	0.950	0.205	0.813	0.622	1.451	0.911	0.192	0.658	0.602	1.377
Old-aged adult (above 55)	0.848	0.216	0.519	0.515	1.398	0.700	0.196	0.204	0.404	1.213	0.697	0.199	0.206	0.398	1.219
Highest educational level (ref: No education)															
Primary						1.990	0.781	0.080	0.922	4.294	1.959	0.760	0.083	0.916	4.190
Secondary						1.857	0.615	0.062	0.970	3.555	1.735	0.561	0.089	0.920	3.271
Higher						1.637	0.678	0.235	0.726	3.688	1.380	0.577	0.441	0.608	3.131
Employment status (ref: Unemployed)															
Formal government sector						1.355	0.415	0.322	0.743	2.470	1.398	0.431	0.278	0.764	2.558
Formal private sector						2.398	0.879	**0.017**	1.169	4.919	2.362	0.864	**0.019**	1.152	4.839
Informal private sector						1.974	0.560	**0.017**	1.132	3.442	2.029	0.580	**0.013**	1.159	3.553
Household size (ref: Small (1–5 members))															
Medium (6–10 members)						1.014	0.241	0.955	0.637	1.614	1.050	0.246	0.835	0.663	1.663
Large (above 10 members)						0.868	0.198	0.534	0.555	1.357	0.911	0.210	0.687	0.579	1.432
Availability of toilet facility (ref: No)															
Yes											1.171	0.237	0.436	0.788	1.741
Source of cooking fuel(ref: Unclean)															
Clean											1.112	0.224	0.598	0.749	1.650
N	218					218					218				

In the socio-environmental model, households not willing to use biogas and have high income were 73% more likely to adopt the SSHTABD compared to those that were not willing to use biogas and have less income. In addition, households willing to use biogas but have less income were 88% more likely to adopt the SSHTABD compared to those that were not willing to use biogas and have less income. Furthermore, households willing to use biogas and have high income were 93% more likely to adopt the SSHTABD compared to those that were not willing to use biogas and have less income. These proportions, however, have decreased from what was observed in model 2. The model output equally revealed that females were less likely to adopt the SSHTABD compared to males (OR = 0.869 CI 0.606–1.243). The odds of the categories under respondents' age decreased from the socio-cultural model. The middle-aged adults (OR = 0.911 CI 0.602–1.377) and the old aged-adults (OR = 0.697 CI 0.398–1.219) had lower odds compared to the young adults' category. Regarding the educational status of respondents, those with primary, secondary or higher educational attainment had higher odds of willingness to adopt the SSHTABD compared to those without formal education (OR = 1.959 CI 0.9166–4.190; OR = 1.735 CI 0.920–3.271; OR = 1.380 CI 0.608–3.131), respectively. Formal government sector (40%), formal private sector and informal private sector employees were 136% and 103% more likely to adopt the SSHTABD compared to the unemployed group. These proportions indicated an increase in the odds of willingness to adopt the SSHTABD from the socio-cultural model. Considering the household size, medium household size was more likely to adopt the SSHTABD (OR = 1.050, CI 0.663–1.663). Large household size (OR = 0.911 CI 0.579–1.432) was less likely to adopt the SSHTABD compared to the small household size.

With regards to access to toilet facility, households with toilet facility (OR = 1.171, CI 0.788–1.741) were more likely to adopt the SSHTABD compared to those without toilet facility. Also, households with clean source of cooking fuel (OR = 1.112, CI 0.749–1.650) were more likely to adopt the SSHTABD compared to those with unclean cooking fuel.

Discussion

The goal of this study was to assess the interactive effect of biogas use and income status of households willing to adopt the SSHTABD in Elmina (should it be constructed for them) as well as the contribution of biosocial, socio-cultural and socio-environmental factors. In this study, a pooled disaggregated data analysis was carried out to evaluate household-level factors that determine willingness to adopt the SSHTABD in Elmina. Unlike previous studies that focused on biosocial, socio-cultural or socio-environmental determinants of willingness to adopt biogas separately [10, 22–24], the current study examined the interactive effect of biogas use–income status while controlling the compositional and socio-environmental factors for households in Elmina.

Based on the results, household willingness to adopt the SSHTABD was 86%. This proportion of households' willingness to adopt the SSHTABD is similar but a little higher than reported in the study by Jan et al. [10] who found that 77.5% of the total respondents of rural communities were willing to adopt biogas systems in Pakistan.

Several studies have established a relationship between income status and willingness to install a biogas system as well as biogas use. However, these studies treated income status and biogas use as separate determinants. High income earning households are reported to have the financial ability to install biogas digesters while low income earning households and developing nations are unable to adopt biogas digesters due to financial constraints and limited eternal financial sources [20].

The findings of this study indicate enormous discrepancies among household's biogas use and income status categories in willingness to adopt the SSHTABD and serve as key predictors of the willingness to adopt the SSHTABD in households in Elmina. Households not willing to use biogas and have high income, households willing to use biogas but have less income, as well as households willing to use biogas and have higher income, have higher odds to adopt the SSHTABD. The categorical differences could be attributed to the ability to finance and maintain the technology. These findings support other studies that established that high income earning households tend to use clean energies and adopted them to install biogas technologies in their homes [24, 32]. Clean cooking fuels are chosen over unclean cooking fuels by households with high-income earnings while the inability of households that have low income to afford clean cooking fuels may opt for other fuel types regarded as unclean cooking fuels [1].

The results equally revealed that females are less likely to adopt the SSHTABD compared to males. Households headed by females fall within the low-income earning class of society which limits their access to clean cooking fuels [1, 33]. This affects their willingness to adopt the SSHTABD compared to their male counterpart.

The middle-aged adults and the old-aged adults have lower odds compared to the young adult category. This finding can be attributed to what pertains in the Ghanaian cultures where younger adults are expected to cook at the household level while middle-aged adults and old-aged adults look on. In the literature, age has often been taken as a proxy for experience and increased risk-taking [10]. Hence, young adults will take more risk to the installation and maintenance of a biogas digester than older adults. Older household members are known to be more traditional and dogmatic, hence lower odds were found more likely for their willingness to adopt the SSHTABD compared to the young adult category. This is similar to other studies presented in [32] and [10].

Regarding the educational status of respondents, those with primary, secondary or higher educational attainment have higher odds of willingness to adopt the SSHTABD compared to those without formal education. This is consistent with the literature [20, 34]. Thus, a low level of education moderates the probability of access to clean cooking fuels by even income groups that can afford them [1]. Educated individuals turn to be more aware of the health implications of using unclean cooking fuels.

As regards access to toilet facility, households with toilet facility are more likely to adopt the SSHTABD compared to those without toilet facility.

Likewise, households with a clean source of cooking fuel were found to be more likely to adopt the SSHTABD compared to those with unclean cooking fuel. This finding supports other works in Ghana and across the globe.

The SSHTABD has tremendous advantages over the mesophilic and thermophilic biogas digesters that have been in existence in the following ways: it produces hygienized digestates compared to the other mesophilic and thermophilic digesters which cannot kill all pathogens such as *Salmonella senftenbengensis* [35, 36]. The digestate produced during biogas production is a by-product of the anaerobic digestion process leading to biogas production. The removal of volatile solids (VS) (83.2%) was higher in the SSHTABD compared to 73.8% reported by [37] and 62% obtained by [38] when BW was treated under mesophilic conditions. Thermophilic and hyper-thermophilic methanogens have an about 50% higher rate of organic degradation and thus a higher biogas yield [36] compared to mesophilic methanogens. Operations under mesophilic conditions require a longer residence time for maximum biogas production compared with those under thermophilic conditions and even hyper-thermophilic conditions.

Conclusion

In this study, the willingness to adopt the SSHTABDs if they were constructed for every household in Elmina was assessed. In summary, the willingness to adopt the SSHTABD at Elmina, Ghana, was high. The study indicated that the joint effects of biogas use and income level have significant influence on the willingness to adopt the SSHTABD proposed in this study. The study also found some socio-cultural and socio-environmental factors such as formal government sector, formal private sector and informal private sector employees to mediate the willingness of households to adopt the SSHTABD. Biogas use, income status and employment status were significantly related to household willingness to adopt this digester. However, other important socio-cultural and socio-environmental factors such as sex, age, education, household size, availability of toilet facility and type of cooking fuel were non-significant in the complementary log–log models. These findings are crucial with significant implications to biogas use at the household level. The promotion of education and increase in household income level by creating employment opportunities will go a long way to increase the willingness to adopt the SSHTABD by households. The implications of this study are that the SSHTABD has tremendous advantages over the mesophilic and thermophilic biogas digesters that have been in existence in the following ways: to produce hygienized digestates and ensure higher VS removal. It has an about 50% higher rate of organics degradation, thus a higher biogas yield. Methanogens in the SSHTABD are also fast growing.

Abbreviations

BW: Black water; CI: Confidence interval; CP: Construction pioneers; EA: Evaluation areas; ESI: Elmina Salt Industry; GHG: Greenhouse gases; GLMs: Generalized linear models; HBS: Household-Based Survey; HCRA: High-class residential area; K.E.E.A.: Komenda Edina Eguafo Abirem; LCRA: Lower class residential area; MCRA: Middle-class residential area; OR: Odds ratio; SSA: Sub-Saharan African; SSHTABD: Single-Stage Solar-Supported Hyper-Thermophilic Anaerobic Biogas Digester; UCC: University of Cape Coast.

Acknowledgements

The authors wish to acknowledge the efforts of the teaching assistants in the Department of Environmental Science, University of Cape Coast, for helping with the administration of their structured interview guide during the field survey.

Authors' contributions

The corresponding author (IMB) conceived the idea of the research, carried out the field survey for data with the assistance of the second author (A-RA). IMB also constructed the demonstrative biogas digester, wrote part of the manuscript, answered some of the questions to the reviewers in the revised manuscript and edited the revised manuscript for submission. A-RA helped with the data collection, analyzed the data using generalized linear models and wrote part of the manuscript. He also assisted with some of the questions to the revised manuscript. All authors read and approved the final manuscript.

Funding

This work has not received any form of funding.

Availability of data and materials

The data used for this manuscript are all available and are in the repository of the authors.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interest.

Received: 24 February 2020 Accepted: 19 May 2021
Published online: 28 May 2021

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