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Domestic low-tech anaerobic digesters in Guiné-Bissau: a bench-scale preliminary study on locally available waste and wastewater

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Abstract Solid organic waste (SOW) and sewage (SEW), in developing contexts as Guiné-Bissau, can be converted into biogas in domestic low-tech anaerobic digesters (AD), avoiding their dispersion in the environment (cause of infective diseases) and simultaneously providing local sustainable/clean fuel to substitute firewood (cause of deforestation and respiratory diseases). Here, SOW and SEW, sampled from local markets/households of Bissau City, were processed in a bench-scale reactor, to define the potentials of low-tech mesophilic (30–37 °C) AD in removing pathogen microbial population, responsible for infective diseases spreading through untreated SOW/SEW and in domestic fuel generation in substitution to firewood. Pathogens removal above 99.9 % were obtained for *E. coli* and *Streptococci*. Considering a target scenario (4-persons household unit), a low-tech AD of 2.35 m^3 functional volume, co-digesting 32 L day^{-1} of SEW and 8 kg day^{-1} of SOW, would produce about 1.5 $Sm^3_{biogas} day^{-1}$ and substitute nearly 11 kg day^{-1} of firewood for cooking needs, avoiding black carbon particles emissions and inhalation in households. Alternatively, ten biogas lamps could work for 3 h day^{-1} or a 1-kW electric power generator run for over 2 h day^{-1}, with important socio-economic benefits. Finally, firewood substitution and the use of digestate as soil conditioner can simultaneously contribute in limiting deforestation and desertification, particularly in transition sub-Saharan tropical areas, such as Guiné-Bissau.

Keywords Biogas · Developing countries · Small-scale anaerobic digestion · Waste · Sewage · Sanitation

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1 Introduction

Energy supply in developing countries represents nowadays an important social and economical issue: according to the World Energy Outlook (IEA 2012), in some areas of the world, such as Africa, Latin America and developing Asia, 1.3 billions of people lack access to electricity, while 2.6 billions of people rely on the traditional use of biomass (i.e. combustion) for their essential needs as for daily cooking and heating; these numbers are going to increase in the next future because of the expansion of world population and consequent resource depletion (IEA 2012). Among developing countries, Guiné-Bissau is among the 20th poorest nation in the world (UNEP 2014): its economy is based mainly on farming and fishing, whereas mining resources are not exploited due to lack of infrastructures and finances. While rural populations are more marginalized and excluded from the services and communications, unsustainable urban expansion occurs (SEAT 2012). Direct consequences of this phenomenon are the lack of healthcare, drinkable water and sewers, progressive open-air rubbish accumulation (Fig. 1) with the diffusion of infective diseases; therefore, social and economic growth are very restricted, especially by the diffusion of diseases carried by polluted water (UNEP 2014). Especially, sewage (SEW) wastewater in general and solid organic waste (SOW) normally contain different pathogenic bacteria species as *Salmonella, Listeria, Escherichia coli, Campylobacter,* Streptococci, Clostridia and *Yersinia* (Dudley et al. 1980). Where waste and wastewater are not properly collected and treated, as happens in many developing countries, the risk of

Fig. 1 Illustrative photo shoots describing environmental and health-security problems in Guiné-Bissau. ^{a}Original photo shoot

contamination of superficial/deep water bodies (Fig. 1) and spreading of infections is of serious concern for both human and animal health (Larsen 1995).

At the same time, energy supply in many developing countries, especially of Africa and Latin America, mainly in rural/peri-urban areas, relies on combustion of biomass, mainly in the form of firewood, but also as straw and cattle manure (Wargert 2009) and so in Guiné-Bissau (UNEP 2014). The uncontrolled combustion of those materials brings many negative effects, mainly related to exposures to hazardous micro- and nanoparticles from the smoke produced during uncontrolled combustion (Gautam et al. 2009; Fig. 1). Another related environmental problem is represented by soil erosion and deforestation caused by unplanned collection of increasing amounts of firewood (Wargert 2009; Fig. 1). This mechanism is of particular concern in the so-called transition areas between desert and tropical forests, especially in the southern boundaries of the Sahara desert (as Guinè-Bissau), where deforestation has as direct consequence desertification and the irreversible expansion of infertile soils (D'Odorico et al. 2013).

To contrast unsustainable use of biomass, biogas is proposed as a candidate biofuel to be exploited in developing countries and evaluated as one of the most environmental/health friendly for bioenergy production (Weiland 2010): biogas can be produced by anaerobic digestion (AD) of a really wide range of biodegradable organic materials that are waste and/or residues of human activities (cattle/swine manure, crops residues, food wastes and wastewater). Biogas, produced in domestic or local small-scale low-tech digesters, can be used

Fig. 2 Examples of small-scale low-tech AD proposed by various experiences worldwide, biogas-fed stove, lamps and biogas-fuelled electric power generator. **a** Original photo shoot; **b** CSIR (2014); **c** http://blog.wildlifeworks.com/; **d** http://portfolio.co.ke/article/from-the-dung-pit-to-the-kitchen-the-biogas-myth/; **e** http://www.heringinternational.co.za/; **f** http://www.homepower.com/; **g** http://www.thehindu.com/; **h** www.acmeagro.org; **i** http://agroindustriindonesia.blogspot.it/

mainly for cooking and lighting (Gautam et al. 2009; Fig. 2) and brings many advantages: by replacing firewood, for example, deforestation and dangerous smokes for human health can be drastically reduced. Biogas, even at relatively small scales, can also be used to generate electricity and heat, and lastly as fuel for automotive (Pang and Li 2006; Fig. 2). While producing a clean biofuel, anaerobic co-digestion of different organic materials has also the chance of becoming a solution to reduce environmental problems and health risks linked to both SEW and SOW accumulations in the environment (Estoppey 2010; Fig. 2).

Together with the chance of producing territorially diffused energy, anaerobic digestion transforms organic waste and wastewaters into high-valuable fertilizer and soil conditioner. Digested slurries are rich in stabilized organic matter and soluble nutrients, and thus, they can be used both as excellent fertilizer and amendment substrate for soil (Schievano et al. 2008; Tambone et al. 2010). Contemporarily, anaerobic digestion is reported to ensure sanitation of possibly contaminated materials, for what concerns pathogenic microbial species: the anaerobic environment has been demonstrated to give efficient removal effects on a wide range of human pathogens (Strauch 1991). Pathogens removal rates through anaerobic digestion process depend on many factors, such as temperature, retention time of the materials inside the digester, pH, concentrations of volatile fatty acids (VFAs), ammonia and/or other chemical species and available amount of specific nutrients (Strauch 1991; Larsen 1995). Besides, strong interspecies competition (pathogens vs. anaerobic consortia) for available carbon and nutrients is an important factor favouring pathogen bacteria extinction, so that, in highly stabilized organic materials, most human pathogens find less favourable environment for their survival (Gendebien et al. 2010). However, temperature is the most important factor that ensures the control level of pathogens during anaerobic digestion (Dumontet et al. 1999). If "T90" is the time required to achieve a 90 % reduction of bacterial population, in thermophilic conditions (45–55 °C), T90 may range in the order of hours, while in the order of days in mesophilic (35–38 °C) conditions (Larsen et al. 1995). In general, temperatures higher than 40 °C are usually capable to reduce most of pathogens. Olsen and Larsen (1987) demonstrated that *Salmonella typhimurium, Salmonella dublin, E. coli, Staphylococcus aureus, Streptococcus faecalis, Erysopelotrix rhusiopathiae, Bacillus cereus, e Clostridium perfringens Salmonellae M. paratuberculosis* were inactivated in 24 h in an anaerobic thermophilic process, whereas the same result in mesophilic conditions generally requires some weeks (Plym-Forshell 1995). VFA, ammonia and other chemical species content have also a direct influence on pathogens. Their toxicity towards bacteria is also linked to pH value. For these reasons, small-scale digesters are reported to have the potential to give important contributions in sanitizing SEW and waste in low-infrastructured contexts (Estoppey 2010).

However, the real effectiveness of mesophilic anaerobic digestion in ensuring pathogenic species removal remains unclear. Estoppey (2010), for example, reported interesting data on a toilet-linked biogas digester in southern India. Here, co-digestion at 29.1 °C and pH of 6.91 of kitchen waste (various food wastes and organic waste water) and toilet wastewater (human excreta) resulted in reductions of 2.6 log unit ($\log_{10}$) for total coliforms (from an average content value of 1.7×10^8 CFU/100 mL in fresh feedstock) and 1.75 log unit ($\log_{10}$) for *E. coli* (from average content value of 1.5×10^8 CFU/100 mL in fresh feedstock). Similar results were found by Sidhu and Toze (2009) at 35 °C for *E. coli* ($1.51 \pm 0.6 \log_{10}$), while slightly lower ($0.35 \log_{10}$) for total coliforms from similar initial cell concentrations.

Such reduction yields would be insufficient, for instance, for many uses of the digested sludge as indicated by the world health organization (WHO) in the "Guidelines for safe use of wastewater, excreta and grey water" (WHO 2006). However, according to WHO, when the effluent sludge has a content of pathogens (*E. coli*) $<10^5$ colony forming units (CFU) in

100 mL, the usage of wastewater is only allowed for restricted irrigation (i.e. for crops that are not consumed raw).

For these reasons, small-scale digesters are reported to have the potential to give important contributions in sanitizing SEW and waste in low-infrastructure contexts.

This work takes part of a project aimed at diffusing anaerobic digestion household plants in Guiné-Bissau, in both urban and rural areas (Fig. 1): the conversion of many kinds of organic waste materials and household SEW into biogas might improve health and life conditions of many people living both in urban and rural areas of the country. As a first step, a varied group of organic waste materials were sampled from public market and household kitchens (Fig. 1), together with a sample of SEW from a household toilet, in the city of Bissau (Guiné-Bissau) and analysed for what concerns their chemical composition and their potential of generating biomethane. A mesophilic anaerobic digestion process was run at bench scale, with manual feeding and mixing to simulate a small-scale low-tech domestic digester and define operational and dimensional parameters, methane production yields and the characteristics of the digested materials, with particular attention to pathogenic indicators. The data obtained from this preliminary laboratory work should help in furnishing specific recommendations on digester operation (loading rate and temperature) and in evaluating the potential benefits of diffusing domestic low-tech biogas plants in Guiné-Bissau and in similar contexts in the next future.

2 Materials and methods

2.1 Waste and wastewater sampling

Seven different samples of SOW from urban markets or households of Bissau city (Guiné-Bissau) were collected, as indicated in Table 1. These materials were dried (at 105 °C for 24 h) and grinded to pass 10 mm mesh, to undergo analytical procedures. A mixture of SOW was created, in the proportions shown in Table 1. Household sewage (hereafter SEW) was sampled from two different toilets mixed to as feeding material for small-scale continuous digester. Two different mixtures (M_1 and M_2) of SOW and SEW (SOW:SEW ratio on fresh matter of, respectively, 20:80 and 40:60) were used for anaerobic digestion tests (Table 2). This was done to test anaerobic digestion process stability with differently concentrated organic mixtures, to assess the organic load that might inhibit the process.

2.2 Experimental setup

The anaerobic digestion process was conducted in tank reactors, operated in wet conditions (dry matter content <10 % in the digestion body), without any automatic/continuous

Table 1 Organic materials sampled in city markets and households of Bissau City and composition of SOW

	Description	Origin	% (on FM) in SOW
1	Waste wheat flour	Local market	5
2	Onion straw	Local market	15
3	Mixed market waste	Local market	25
4	Mixed kitchen waste	Household	30
5	Rice husk and straw	Local market	10
6	Manioc crop residues	Local market	15
7	Orange peels waste	Household	15

Table 2 Composition of feed mixtures M_1 and M_2 and feed conditions

	M_1				M_2			
	% on FM	Loading g_{FM} $L_{dig.}^{-1}$ day^{-1}	OLR g_{VS} $L_{dig.}^{-1}$ day^{-1}	HRT days	% on FM	Loading g_{FM} $L_{dig.}^{-1}$ day^{-1}	OLR g_{VS} $L_{dig.}^{-1}$ day^{-1}	HRT days
SOW	20	3.4	0.986		40	10	2.90	
SEW	80	13.6	0.154		60	15	0.17	
Overall	–	17	1.140	59	–	25	3.07	40

stirring and feeding systems. The process was conducted in parallel with the two mixtures M_1 and M_2 in two small-scale 3-l volume digesters, at mesophilic temperature conditions (36 ± 1 °C), maintained by a temperature controlled water bath. The feeding was accomplished in semi-continuous mode (feeding three times a week) and after 10 days acclimation, the process was monitored for a period of 24 days. All feeding parameters for both feeding conditions are reported in Table 2: FM mixing ratios, FM loading, organic loading rate (OLR) and hydraulic retention time (HRT). Mixing was performed manually in parallel with the feeding (three times a week), to simulate a condition of minimum agitation. These simple process management procedures were performed to simulate a low-tech digester, without any automation, as a household small-scale digester should be for applications in developing countries.

Produced biogas volumes were accumulated in columns by water displacement and registered 3 days a week. Biogas composition (CH_4 and CO_2 relative concentrations, v/v) was determined by analysing a sample of the accumulated biogas, using a gas chromatograph (Agilent, Micro GC 3000A) equipped with two thermal conductivity detectors (TCD).

Digested sludge was withdrawn from digesters in equal amounts to the feeding and chemically analysed to monitor process parameters (TS, VS, pH, total nitrogen, ammonia and VFAs). Moreover, biochemical methane potential (BMP) test was applied to four representative samples (days 6, 12, 18, 24) of the digestate, to determine organic matter quality before and after the anaerobic digestion process and the residual potential production of biogas. This allowed the calculation of anaerobic digestion process efficiencies in terms of bio-methane yield (BMY), as suggested by Schievano et al. (2011).

Finally, digestate was characterized to assess and evaluate its potential safe use as soil conditioner/fertilizer. Microbiological analyses were performed to detect the main pathogen indicators (*Salmonella*, *E. coli* and *Streptococcus*), both on feeding and digested materials, to verify the effect of mesophilic anaerobic digestion on pathogenic microbial species as suggested by Olsen et al. (1985) and Plym-Forshell (1995).

2.3 Analytical procedures

Chemical analyses were performed to characterize the materials: total solids (TS), volatile solids (VS) and total organic carbon (TOC) according to standard procedures (IRSA CNR 1994). Total nitrogen (TN) (Kjeldahl method) and ammonia content ($N–NH_4$) were determined on fresh material, following analytical method used for wastewater sludge (IRSA CNR 1994). Analyses were performed also to determine total VFAs content according to the acid titration method (Lahav et al. 2002). The biochemical methane potentials (BMPs) of all samples (both fed mixtures and digestates) were determined by using the method reported by Schievano et al. (2009).

Microbiological analyses were performed both on fresh feedstock (M_1 and M_2) and digested sludge taken from each digesters to verify the presence of *E. coli, Salmonella* and Streptococci. Hygienic parameters were detected following standard procedures: APAT CNR-IRSA 7080 Man. 29-2003 for *Salmonella* spp.; APAT CNR-IRSA 7030 for *E. coli*; APAT CNR-IRSA 7040 Man. 29-2003 for faecal Streptococci (IRSA CNR 1994).

3 Results and discussion

3.1 Characteristics and potentials of locally sampled waste/wastewater

The results of chemical characterization of all samples are reported in Table 3. The cumulated results of the BMP test performed on the same samples are also shown in Table 3. Samples 1 and 5 were almost dry, while the others showed DM contents in the range 91–397 g $\mathrm{kg}_{\mathrm{FM}}^{-1}$. All samples collected from markets and households reported relatively high organic matter content (in the range 765–975 $\mathrm{g}_{\mathrm{VS}}\mathrm{kg}_{\mathrm{DM}}^{-1}$, Table 3) with the only exceptions of rice husk and straw (540 $\mathrm{g}_{\mathrm{VS}}\mathrm{kg}_{\mathrm{DM}}^{-1}$) that was probably influenced by the presence of sand/soil residues.

The BMP of the single samples $\left(240-480\ \mathrm{Ndm}_{\mathrm{CH}_4}^{3}\mathrm{kg}_{\mathrm{DM}}^{-1}\right)$ were relatively satisfactory (Table 3), for all types of materials, when compared with biomass normally used for biogas production, even in full-scale industrial plants (Schievano et al. 2011). This potential is likely to be entirely exploited because local small-scale digesters have the advantage that can be promptly fed with fresh market or household waste and sew, avoiding partial degradation and losses in BMP during waste collection and/or dispersion in the environment. The local and diffused implementation of these low-cost facilities would help in efficiently exploit this renewable and low-cost energy potential.

According to the different proportions of SOW and SEW and their different DM contents (Table 3), M_1 and M_2 were differently characterized in terms of DM and VS

Table 3 Chemical characteristics of organic materials

Sample	DM	VS	TN	N–$\mathrm{NH_4}^+$	TOC	C/N	BMP	
	g $\mathrm{kg}_{\mathrm{FM}}^{-1}$	g $\mathrm{kg}_{\mathrm{DM}}^{-1}$	gN $\mathrm{kg}_{\mathrm{DM}}^{-1}$	gN $\mathrm{kg}_{\mathrm{DM}}^{-1}$	gC $\mathrm{kg}_{\mathrm{DM}}^{-1}$		$\mathrm{Ndm}_{\mathrm{CH}_4}^{3}\mathrm{kg}_{\mathrm{DM}}^{-1}$	$\mathrm{Ndm}_{\mathrm{CH}_4}^{3}\mathrm{kg}_{\mathrm{FM}}^{-1}$
1	956	860 ± 4	17.5 ± 0.5	–	396 ± 19	22	480 ± 83	459 ± 79
2	142	855 ± 4	7.3 ± 1.2	–	414 ± 9	56	342 ± 4	49 ± 1
3	221	765 ± 3	5.7 ± 0.3	–	282 ± 7	49	380 ± 2	84 ± 1
4	91	850 ± 2	9.2 ± 0.1	–	419 ± 15	45	350 ± 14	32 ± 1
5	983	540 ± 6	16.5 ± 0.5	–	360 ± 3	22	270 ± 18	265 ± 18
6	397	975 ± 2	23.7 ± 1.5	–	381 ± 7	16	342 ± 4	135 ± 2
7	327	940 ± 1	24.6 ± 0.6	–	385 ± 3	16	468 ± 14	153 ± 5
SEW	16	710 ± 3	168.2 ± 0.1	63.0 ± 2.7	382 ± 4	2	243 ± 29	3.9 ± 0.5
SOW	358	810 ± 1	17.0 ± 0.2	–	368 ± 3	22	371 ± 1	135 ± 1
M_1	84	797 ± 3	15.1 ± 0.2	7.72 ± 0.8	370 ± 8	24	362 ± 32	34 ± 3
M_2	153	801 ± 2	14.7 ± 0.4	5.04 ± 0.5	369 ± 10	25	368 ± 43	44 ± 5

(Table 3): M_1 was more diluted (84 $g_{DM}kg_{FM}^{-1}$ and less rich in VS (797 ± 3 $g_{VS}kg_{DM}^{-1}$) than M_2 (153 $g_{VS}kg_{DM}^{-1}$; 801 ± 2 $g_{VS}kg_{DM}^{-1}$). C/N ratio of M_1 and M_2 were of 24 and 25, respectively, acceptable values for anaerobic digestion process as indicated by various authors (Wilkye et al. 1986; Kayhanian and Rich 1995).

In BMP tests, SOW resulted in 371 ± 1 $Ndm_{CH_4}^{3}kg_{DM}^{-1}$ which is similar to the literature data regarding organic fractions of household waste (Schievano et al. 2009). Bio-methane production of SEW resulted lower $\left(243 \pm 29\ Ndm_{CH_4}^{3}kg_{DM}^{-1}\right)$. Almost equal BMP resulted for M_1 $\left(362 \pm 32\ Ndm_{CH_4}^{3}kg_{DM}^{-1}\right)$ and M_2 $\left(368 \pm 43\ Ndm_{CH_4}^{3}kg_{DM}^{-1}\right)$, while when considering the same data on FM unit, M_2 was nearly 25 % more productive than M_1 (Table 3), being more concentrated.

3.2 Performances of the low-tech anaerobic digestion process

Figure 3a reports the daily rates of biogas and bio-methane production in 24-day observation of the digester fed with M_1 (i.e. OLR of 1.14 g_{VS} L^{-1} day^{-1}, HRT = 58 days). The average (along 24 days) productivity of biogas and bio-methane were, respectively, 0.652 N dm^3 $L_{dig.}$ day^{-1} and 0.425 $Ndm_{CH_4}^{3}L_{dig.}d^{-1}$, with average methane content of 65.1 % v/v (Table 4).

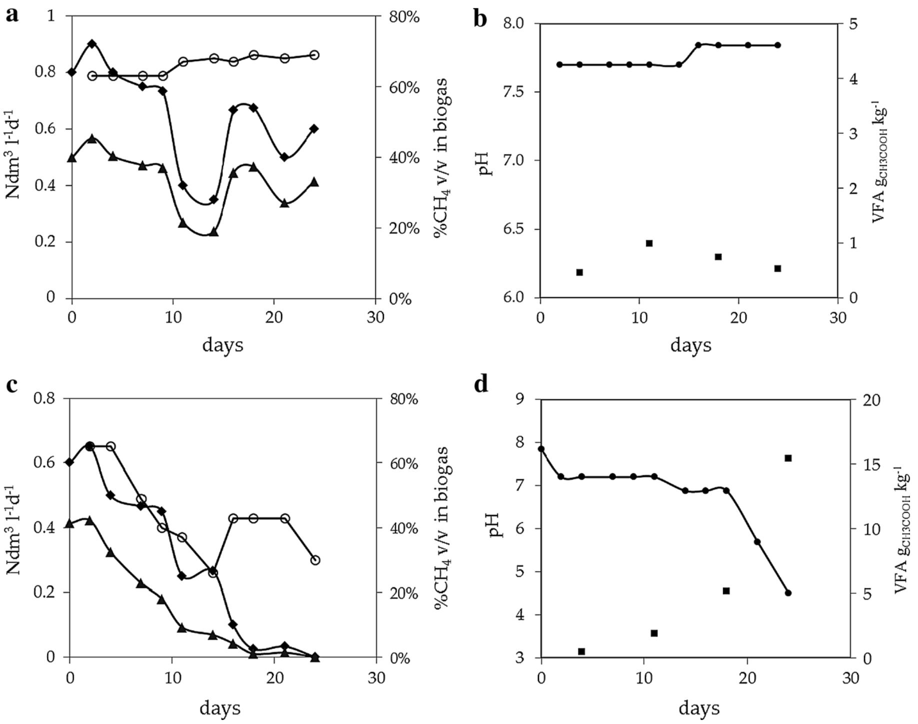

Fig. 3 Trends of biogas (*filled diamond*), bio-methane (*filled triangle*) daily production rate and methane content in biogas (*open circle*) for M_1 (**a**) and M_2 (**c**). Trends of pH (*filled circle*) and VFA (*filled square*)for M_1 (**b**) and M_2 (**d**)

Table 4 Average process parameters and yields for the digester fed with M_1 (HRT = 58 days, OLR = 1.14 $g_{VS}\ L_{dig.}^{-1}\ day^{-1}$)

Biogas production	Unit	Average of 24 days (variance per day)
Volumetric biogas production rate	$Sdm_{biogas}^{3}\ L_{dig.}^{-1}\ day^{-1}$	0.652 (0.174)
Methane content in biogas	% v/v	65.1 (2.6)
Volumetric methane production rate	$Sdm_{CH_4}^{3} L_{dig.}^{-1} d^{-1}$	0.425 (0.102)

	Unit	IN	OUT	Removal efficiency (%)
Process parameters				
DM	$g_{DM}\ kg_{FM}^{-1}$	0.084	21.5 ± 4	
	$g_{DM}\ L_{dig.}^{-1}\ day^{-1}$	1.435	0.357	75.1
VS	$g_{VS}\ kg_{DM}^{-1}$	797 ± 3	704.5 ± 65	
	$g_{VS}\ L_{dig.}^{-1}\ day^{-1}$	1.144	0.251	78.0
BMP	$Sdm_{CH_4}^{3} kg_{DM}^{-1}$	362 ± 32	223 ± 53	
	$Sdm_{CH_4}^{3} L_{dig.}^{-1} d^{-1}$	0.519	0.080	84.7
pH		6.86	7.77	
VFA	$mg\ _{CH_3COOH} kg_{FM}^{-1}$	–	686 ± 442	
TKN	$mg_N\ kg_{FM}^{-1}$	1,429 ± 13	1,456 ± 32	
$N–NH_4^+$	$mg_N\ kg_{FM}^{-1}$	705 ± 63	1,255 ± 42	
N-org	$mg_N\ kg_{FM}^{-1}$	724 ± 56	201 ± 45	
Pathogenic indicators				
Escherichia coli	CFU/mL	5×10^3	udl	99.99
Streptococci	CFU/mL	7.5×10^3	7	99.91 (3 $\log_{10}$)
Salmonella	CFU/mL	udl	udl	–

udl under detection limit

As shown in Fig. 3a, a decrease of productivity was observed after 10 days: this phenomenon was probably caused by the formation of floating fibrous material that was observed on the liquid surface (thickness = 33–37 mm), hence partially obstructing biogas liberation to gaseous phase. However, the process was relatively stable with optimal trends of pH (between 7.4 and 7.8) and concentrations of VFA $\left(686 \pm 442\, mg_{CH_3COOH} kg_{FM}^{-1}\right)$, as shown in Fig. 3b.

The second digester, fed with M_2 (higher TS and VS content) (OLR = 3.07 g_{VS} - $L_{dig.}^{-1}\ day^{-1}$ and HRT = 40 days, Table 2), promptly showed instability, and the biogas production decreased progressively (Fig. 3c). Inhibition of methanogenic process in anaerobic digestion, typically caused by excess in organic load, was observed, as Fig. 3d indicates: a sudden pH drop from 7.8 to 4.7 was observed at day 18, as a direct consequence of a progressive VFA accumulation in the water solution (from 0.47g $_{CH_3COOH}kg^{-1}$ to 15.8g $_{CH_3COOH}kg^{-1}$, Fig. 3d). This time a thicker layer (thickness = 62–69 mm) of floating fibrous material was observed on the liquid surface after 10 days operation, and this was probably one important cause of the observed process imbalance.

As indicated by various authors, digesters fed with relatively high OLR need improved mixing, to avoid stratification of organic materials, to favour biogas liberation to the gaseous phase and to ensure optimal contact between methanogenic microflora and the fermented organic matter in the solution (Karim et al. 2005). Gòmez et al. (2006) evaluated the effect of mixing during a co-digestion of primary sludge with the fruit/vegetable fraction of municipal solid waste and showed that a digesting system with continuous low mixing condition (80 rpm) was capable of stable performances and to absorb an increase of organic load, while the absence of agitation at the same feeding conditions, resulted in a reduction of specific gas production. Karim et al. (2005) studied the effect of different modes of mixing on the performance of lab-scale digester fed first with more diluted cow manure (5 %), then with a thicker one (10 %), finding that digesters fed with the latter, mixed by slurry recirculation, impeller mixing and biogas recirculation, produced approximately 29, 22 and 15 % more biogas than the unmixed digester, where stratification and deposition/flotation of solids seemed to be critical in reducing the effective volume of the digester leading to possible failure of the process with the increase in scale of the digester.

In this work, the proposed process was deliberately operated by once-a-day manual agitation, to simulate the condition of a low-tech digester operated at domestic level, which is supposed not to have any automation and to be manually mixed and fed by domestic users. This operational mode actually limits the OLR that could potentially be applied to the same digestion volume. The performed test was useful to determine a threshold for OLR of such type of digesters, at least when fed with similar kind of biomass mixtures. The proposed organic mixture (M_1), OLR of 1.14 $g_{VS}\ L_{dig.}^{-1}\ day^{-1}$ was considered as threshold able to guarantee stable and efficient process in similar systems.

In fact, considering the characteristics of M_1 before and after anaerobic digestion process, relatively high degradation efficiencies in terms of DM and VS were found (Table 4), also when compared to values reported for industrial-scale biogas plants by Schievano et al. (2011). Anaerobic digestion process determined strong reductions of both DM content (75.1 %) and VS content (78.0 %) in digested material (from 1.435 to 0.357 $g_{DM}\ L_{dig.}^{-1}\ day^{-1}$ and from 1.144 to 0.251 $g_{VS}\ L_{dig.}^{-1}\ day^{-1}$, respectively, Table 4).

Besides, strong modifications of the organic matter quality also occurred, as indicated also by Tambone et al. (2010). In particular, biodegradability of the total OM, detected as BMP, was also affected: residual potential biogas was reduced in the output material $\left(\left(223 \pm 53\ Sdm_{CH_4}^{3} kg_{DM}^{-1}\right)\right.$, Table 3) from a starting value of $\left(362 \pm 32\ Sdm_{CH_4}^{3} kg_{DM}^{-1}\right)$ in the fed material (Table 3). This implied a reduction from 0.519 $Sdm_{CH_4}^{3} L_{dig.}^{-1} d^{-1}$ (input as BMP) to 0.08 $Sdm_{CH_4}^{3} L_{dig.}^{-1} d^{-1}$ (residual BMP output), with a corresponding BMY of 84.7 %, according to Schievano et al. (2011). This yield is also comparable to what is normally obtained in industrial full-scale anaerobic reactors, with continuous agitation and automation (as indicated by Schievano et al. 2011), even if in those cases, the OLR could be higher (up to 2.8 $g_{VS}\ L_{dig.}^{-1}\ day^{-1}$ for mesophilic anaerobic digestion) than the threshold found here (1.14 $g_{VS}\ L_{dig.}^{-1}\ day^{-1}$). In any case, in low-tech/manually operated digesters, reasonably limiting the OLR is a good strategy to ensure high biodegradation and methane yields.

3.3 Digestate properties and pathogenic indicators

The chemical forms of nitrogen from fed material to the digestate deeply changed due to the degradation of organic nitrogen inside the digester. The fed N-org (724 ± 56 $mg_{N\text{-}org}\ kg_{FM}^{-1}$, Table 4) was reduced to 201 ± 45 $mg_{N\text{-}org}\ kg_{FM}^{-1}$, i.e. mineralized to ammonium form, which increased from 705 ± 56 to 1,255 ± 42 $mg_{N-NH4+}\ kg_{FM}^{-1}$ (Table 4). TN concentrations were almost constant throughout the process, as expected (Table 4).

These results indicate that the proposed operational anaerobic digestion mode (mesophilic, manually fed and manually mixed once a day low-tech digester) was effective in stabilizing the organic matter (high biodegradation yields, Table 4) and in mineralizing nutrients in soluble forms (N-org to $N–NH4^+$), in accordance with various authors that report similar results for efficient and high-tech anaerobic digestion plants (Birkmose and Pedersen 2008; Tambone et al. 2010). These properties drive to consider the obtained digestate contemporarily as a good fertilizer (soluble and readily available nutrients such as $N–NH_4{}^+$) and soil conditioner (stabilized organic matter) (Tambone et al. 2010).

For what concerns hygienic parameters, the microbiological analyses showed a considerable decrease of number of *Streptococci* (from 7.5×10^3 to 7 CFU/mL, Table 4), i.e. reduction of 99.91 % (3 $\log_{10}$ units). This result was higher than what observed by Dahab and Surampalli (2002), with pathogen inactivation of 1.98 $\log_{10}$ units during anaerobic digestion at mesophilic condition of 35°. *E. coli* were found under detection limit in the digested slurry thus achieving efficient sanitation, even compared to previous results found by Gantzer et al. (2001) (1.5 ± 0.6 $\log_{10}$ units) or by Horan et al. (2004) (1.66 $\log_{10}$ units), at mesophilic anaerobic digestion conditions. Unfortunately, *Salmonella* were not found in the inlet materials and so in digested slurry, and no comparison was possible with previous results. Dahab and Surampalli (2002), for instance, observed significant reduction of *Salmonella* during mesophilic anaerobic digestion at 35 °C in the range of 0.86–2.26 $\log_{10}$ units.

Despite the positive results obtained in this work, according to various authors, not always a complete elimination of pathogenic bacteria such as *E. coli* and *Salmonella* is ensured in mesophilic conditions (Moce-Llivina et al. 2003). In these cases, even with absence of *E. coli*, the usage of digested slurry might be allowed in agriculture, limited to restricted irrigation according to WHO (2006). To ensure hygienic standards and widen the possibility of spreading and land use of such slurry, to fully exploit their potentials as fertilizers for local agriculture, horticulture and soil conditioners to preserve soil fertility, thermophilic (45–55 °C) temperature ranges are in any case preferred and to be pursued, as indicated by many authors (Olsen et al. 1985; Larsen et al. 1995; Plym-Forshell 1995). Fortunately, in many developing countries (as Guiné-Bissau in particular), where these kinds of low-tech anaerobic digestion facilities would be useful, maintain even high temperature ranges in a digester may normally not be a concern, when proper use of solar heat is done and transmitted to the digester, for example through greenhouses or solar panels.

3.4 Sizing low-tech anaerobic digestion digesters in Guiné-Bissau and evaluating their potentials

According to the results obtained by digesting at bench scale the biomass samples collected at Bissau city, some useful calculations were provided here to draw some potential scenarios of possible diffusion of small-scale low-tech domestic/local anaerobic digesters (AD), in that or similar contexts. Given increasing number of persons per family/household unit (Table 5) and considering a production of household wastewater (SEW) of 8 L day^{-1} per person, in countries where water main hardly exist (UNEP 2014), the corresponding minimum amount of mixed SOW was calculated, based on M_1 composition. With a maximum OLR of 1.14 $g_{VS}\ L_{dig.}^{-1}\ day^{-1}$, the minimum functional digestion volumes required for a household full-scale plant were sized (Table 5) and the potential daily biogas and methane productions were reported, in proportion to the volumetric production rates obtained in this work at bench scale (Table 5).

Table 5 Dimensions and energetic potentials (alternatively cooking or lighting or electricity generation) of small-scale low-tech digesters, manually operated at domestic level, at increasing number of persons per household unit

Number of persons per family/household unit	Estimated daily amount of SEW[a] L day^{-1}	Minimum daily amount of SOW kg day^{-1}	Minimum functional digestion volume m^3	Potential daily biogas and methane production Sm^3_{biogas} day^{-1} $Sm^3_{CH_4} d^{-1}$	Time cooking in biogas stove[b] Hours day^{-1}	Avoided firewood in traditional stoves[c] kg day^{-1}	Number of biogas lamps for 3 h day^{-1} lighting[d]	Time running a 1-kW electric generator[e] Hours day^{-1}
2	16	4	1.18	0.767 0.5	2.5	5.7	5	1.1
4	32	8	2.35	1.534 1	5	11.3	10	2.2
6	32	13.5	3.97	2.589 1.688	8.4	19.1	17	3.7
8	64	16	4.71	3.068 2	10	22.6	20	4.4
10	54	20	5.88	3.835 2.5	12.5	28.3	26	5.5

[a] Assumed production of 8 L SEW per capita a day at household level (UNEP 2014)

[b] Assumed consumptions of $0.2 Sm^3_{CH_4} h^{-1}$ for a biogas stove (ASHDEN 2004)

[c] Assumed consumptions of $50 Sdm^3_{CH_4} h^{-1}$ for a biogas lamp (ASHDEN 2004)

[d] Assumed minimum consumption of dry firewood of 2.26 kg h^{-1} for stove combustion (Miah et al. 2009)

[e] Assumed consumption of $0.7\ m^3_{biogas} kWhe^{-1}$ (Wuan Acme Agro-tech Co., Ltd., China)

To describe an average possible scenario, a family/household unit of four persons, for example, would produce nearly 32 L day^{-1} of SEW from toilet flushing and/or sinks; the corresponding treatable amount of SOW would be around 8 kg day^{-1} and the digester (2.35 m^3 of minimum functional volume), fed at similar conditions to the bench scale tested in this work, would produce around 1.5 m^3 day^{-1} of biogas (nearly 1 m^3 day^{-1} of CH_4). This would allow nearly 5 h day^{-1} of cooking time in a biogas stove, simultaneously avoiding the combustion of approximately 11 kg day^{-1} of firewood in inefficient traditional stoves. This, as already reported for transition areas as the Sahel-Guinea (Wargert 2009; D'Odorico et al. 2013), would simultaneously avoid deforestation and consequent soil fertility depletion, strongly reduce the negative effects on human health of both uncontrolled combustion (Gautam et al. 2009) and spreading of untreated sewage (Gendebien et al. 2010). At the same time, mineralized nutrients and stabilized/hygenized organic matter could be returned to soils, to preserve their fertility.

Alternatively to the use of biogas for cooking purposes, the biogas could feed gas lamps for lighting or an electric generator. In the case of a 4-person household unit, ten biogas lamps could work for 3 h day^{-1} of lighting or, on the other case, a 1-kW electric power generator could run for more than 2 h day^{-1} (Table 5). These applications would be really useful in contexts were electric power and night illumination are hardly diffused and available to population, in rural/semi-urban contexts but often also in urban neighbourhoods.

Resuming locally available organic waste and wastewaters can be efficiently converted into a sustainable and clean biofuel in low-tech, small-scale and territorially diffused facilities. Biogas produced can locally substitute the traditional use of firewood for cooking, avoiding consequent air pollution and health problems connected with black carbon particles inhalation. Furthermore, firewood substitution with biogas and the use of digested organic/mineral matter in soils can contribute to limit deforestation and desertification, with increased importance in transition areas, such as Guiné-Bissau and the sub-Saharan tropical areas. Besides, other uses of biogas would be efficiently achievable, such as for direct lighting in gas lamps or for feeding small electricity generators, with important impacts on socio-economical life of population. Finally, anaerobic digestion of both organic waste and SEW, locally diffused especially in urban contexts, would help in limiting their uncontrolled spreading in the environment and guarantee partial/total sanitation from most pathogenic species, with consequent positive impact on public health.

4 Conclusions

Small-scale low-tech digesters, when diffused both in rural and urban contexts of Guiné-Bissau and other countries with similar socio-economical situations, have the potential of playing a fundamental role simultaneously under various aspects (environmental, socio-economical and sanitarian), moving towards the path of sustainable development of local population. This study has stressed the crucial importance of:

- the choice of a reasonable thresholds of OLRs, to ensure process efficiency;
- working under thermophilic conditions, to both increase process yields and ensure complete sanitation;
- the choice of adequate digester designs to guarantee minimum manual mixing to avoid solids accumulation and flotation, above all in presence of fibrous ligno-cellulosic materials.

To draw a realistic scenario, in a context like Guiné-Bissau, further data and experiences would be useful, such as a follow-up study at thermophilic conditions to prove pathogenic elimination and, at real scale, regarding local waste/wastewater availability, adequacy of low-tech and low-cost digester types, their characteristics and productivities.

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