REPORT **D1.6**

wider uptake

Report on Monitoring of Irrigation Water and Biochar

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Report on Monitoring of Irrigation Water and Biochar

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ABSTRACT

This report presents activities of the Accra Demonstration Case of the WIDER UPTAKE Project in respect of the monitoring of water reuse for urban agriculture as well as production of biochar for use by SMEs. The monitoring of these two activities so far shows that the use of fecal sludge in combination with saw dust in a ratio of 2:1 produces biochar that is safe to use for heating and can serve as a substitute to wood-based charcoal. Additionally, the monitoring results show that the shallow reservoir designed to imitate the design of maturation ponds of waste stabilization ponds enhances further polishing of the treated wastewater from the SSGL and therefore, the water supplied from the shallow reservoir to farmers is safe for growing vegetables. Results from the monitoring of the vegetables show that they are safe. However, it is recommended that monitoring should be continued for both biochar, water and vegetables since this monitoring results were for a single climatic season.

KEYWORDS

Wastewater monitoring, vegetables, biochar, sludge, urban farmers

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym Name	Acronym Definition
AQI	Air Quality Index
BOD	Biochemical Oxygen Demand
BR	Burning rate
COD	Chemical Oxygen Demand
CSIR	Council for Scientific and Industrial Research
EPA	Environmental Protection Agency
FC	Fixed carbon
GAMA	Greater Accra Metropolitan Area
GSA	Ghana Standards Authority
MTP	Mudor Treatment Plant
NTNU	Norges Teknisk-Naturvitenskapelige Universitet
PM	Particulate matter
SMEs	Small and Medium Enterprises
SSGL	Sewerage Systems Ghana Limited
TCBS	Thiosulfate Citrate-Bile salt
TU	Technische Universiteit
UCT	Uncontrolled Cooking Test
WBT	Water Boiling Test
WHO	World Health Organization
WIDER	Wider Uptake of Water-Smart Solutions
WRI	Water Research Institute (CSIR)
XRF	X X-ray Fluorescence

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EXECUTIVE SUMMARY

The European Commission is funding the "Achieving wider uptake of water-smart solutions (WIDER UPTAKE)" Project to facilitate industrial symbiosis as a means to increase resource efficiency, limit emissions and develop sustainable business based on water-smart solutions WIDER UPTAKE is built around a set of innovative circular economy solutions co-developed by water utilities and private businesses from industry sectors with high water consumption, high use of material resources and energy—agriculture industry, building and manufacturing materials industry, and energy supply. Accra Demonstration Case is being implemented by CSIR as the research partner and Sewerage Systems Ghana Limited (SSGL), the wastewater treatment plant and innovation owner. This report presents the monitoring of the quantity and quality of water as well as biochar produced under the demonstration activities in the Accra Case (Task 1.2.2).

For water reuse, so far, SSGL has supplied a total of 1,490,000 liters (1490m^3) of treated wastewater to the demonstration site at CSIR. From the monitoring, the physico-chemical results indicate that the treated wastewater received from the shallow reservoir for the irrigation of the vegetables is of good quality. This had appreciable phosphate and ammonia concentrations which is useful for the growth of the vegetables. The heavy metal contents of the vegetables are also at acceptable levels for the samples analyzed.

The bacteriological quality of effluent of shallow reservoir generally satisfied EU guidelines of <10 cfu/100mL. Treated wastewater from SSGL had fairly good quality ranging from 0 to 2.8 log units with vibrio absent in the effluent of the shallow reservoir as well as the treated wastewater from SSGL. The vegetables generally were of good quality showing E. coli concentrations of <1 log unit. No oocyst or cyst of Cryptosporidium or giardia respectively were found on the vegetables, or in effluent from the reservoir or that of treated wastewater discharged from SSGL. Helminths or helminth eggs were also absent in the effluent from the shallow reservoir. Some samples are still being analyzed, including urine and water samples taken for the analyses of recalcitrant organic compounds in the category of analgesics, amphetamines, pesticides and antidepressants. Results would be reported on as soon as they are ready.

Biochar is a carbon-rich solid formed by heating biomass in an environment limited to oxygen. The use of biochar for various applications is gradually gaining roots in most industries because it is carbon neutral and promotes efficient management of resource needs without drawing from non-renewable carbon like fossil fuel. Producing biochar from fecal sludge (waste from sewerage treatment) enhances the circularity of wastewater treatment plants as well as the sustainability of the biochar production as it supplements carbon that would have otherwise been taken from trees (a major carbon dioxide sink). For the Accra Demonstration, SSGL has produced and supplied 2500Kg of biochar to selected SMEs.

Results from the monitoring show that the biochar produced from a composite of saw dust (wood waste) and fecal sludge at a ratio of 1:1 is demonstrated as having high quality, in terms

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of calorific value (25.8 MJ/kg), low moisture (2.38%) and total volatile matter content (37.2%) and high fixed carbon content (14.69%).

In addition, the fuel quality was monitored using the Water Boiling Test (WBT), whilst the environmental and health risk associated with the use of the biochar was monitored using a field procedure, Uncontrolled Cooking Test (UCT). The results from the WBT demonstrated that the burning characteristics of the composite biochar (burning rate, 10.5 g/min., firepower, 3.8 kW, and specific fuel consumption, 107.113 g/l) matched baseline data of most biomass fuels used in Ghana. Similarly, the UCT conducted at selected SMEs demonstrated that, during use of the biochar for their activities, average emissions of $PM_{2.5}$ (3-65 µg/m^3) and CO (8.2-15.1 mg/m^3) where within acceptable limits of exposure levels by WHO guidelines and therefore, do not pose adverse environmental and health risk when used.

I tis recommended that monitoring of the two solutions (biochar and water) continues until the demonstrations achieve a full year, taking into consideration the difference climatic seasons in Ghana.

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1 Introduction

There is tremendous understanding of the need to secure natural water resources. At the same time, the implementation of water-smart solutions around the world is limited. Barriers to water-smart solution are not only technological but also of organizational, regulatory, social and economic in character. Hence, the European Commission is funding the project "Achieving wider uptake of water-smart solutions (WIDER UPTAKE)" to facilitate industrial symbiosis as a means to increase resource efficiency, limit emissions and develop sustainable business based on water-smart solutions (Mannina et al., 2021). WIDER UPTAKE is built around a set of innovative circular economy solutions co-developed by water utilities and private businesses from industry sectors with high water consumption, high use of material resources and energy—agriculture industry, building and manufacturing materials industry, and energy supply.

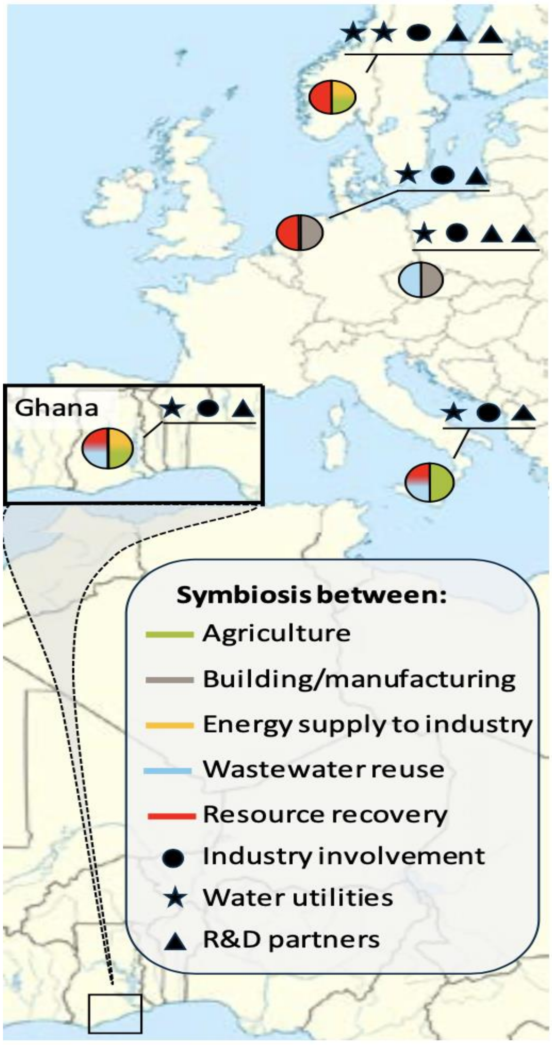

Figure 1: Geographical distribution of cases

Stiftelsen for Industriell og Teknisk Forskning (SINTEF) and Norges Teknisk-Naturvitenskapelige Universitet (NTNU) in Norway, Technische Universiteit (TU) Delft in the Netherlands, Czech Technical University and The University of Chemistry and Technology Prague in the Czech Republic, University of Palermo in Italy and the Council for Scientific and Industrial Research (CSIR) in Ghana has brought together 5 water utilities, 6 solution providers (5 SMEs and one publicly owned company) and several committed stakeholders representing different industry sectors and authorities in a north – south axis of five cases (Figure 1) that span different governance contexts, socio-economic conditions, availability of water resources, climate and environmental conditions, and scale.

To achieve the overall objectives of the WIDER UPTAKE, the following specific objectives will be achieved:

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A. Demonstrate innovative technical solutions that optimize water reuse, resource recovery and energy utilization in selected industry settings by:
    1. Running five demonstration case studies on innovative symbiotic solutions for wastewater reuse and resource recovery. This objective will be achieved through work package 1 (WP 1).
    2. Developing and applying monitoring and control schemes to adequately manage the health and quality risks associated with reuse of treated wastewater and recovered resources (WP 2).
    3. Optimization of the value chains to quantify the improved resource efficiency and economic benefits, also with respect to future applications (WP 3).

B. Facilitate wider uptake of water-smart solutions through:
    1. Governance assessment, design of innovative business models and identification of transition
    2. paths for industry – utility symbioses (WP 4).
    3. Evaluate water smartness and sustainability of the symbiotic CE solutions (WP 5).
    4. Network development and stakeholder dialogue around the key findings and their implications,
    5. including the establishment of a roadmap for implementation of water-smart solutions in an open access Virtual Learning and Sharing Centre (WP 6 and WP 7).

One of the demonstration cases in the WIDER UPTAKE Project being implemented is in Ghana. The objective of this case is to develop and demonstrate a value chain for use of treated wastewater for urban agriculture and promotion of biochar usage as substitute for wood-based charcoal use. Thus, the case study being demonstrated in Ghana has two arms: Water reuse and biochar production.

1.1 Objectives of the report

The objective of this report is to present the monitoring of the quantity and quality of water as well as biochar produced since the commencement of demonstration activities in the Accra Case from Task 1.2.2 (Production and supply of treated wastewater for irrigation and biochar for fuel) to be used in Task 1.2.3 (Public engagement, policy dialogues and the development of business models.

1.2 Organization of Report

This report is organized into five sections. The first section, the introduction, establishes the context of the report and is followed by the second section which provides an overview of the Accra demonstration and reports on the quantities of biochar and treated wastewater supplied to SMEs and Farmers. The third section of this report presents the monitoring of the water, crops, and soil in the water reuse; and section four of this report presents the monitoring of biochar fuel and its use. The fifth section presents the report's conclusion.

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2 The Accra demonstration

The Accra Demonstration Case is being implemented by CSIR as the research partner and Sewerage Systems Ghana Limited (SSGL), the wastewater treatment plant and innovation owner. Demonstration activities in Accra included conducting baseline studies to establish the quality and quantity of wastewater being used by farmers; quality of vegetables being produced; the willingness of farmers to pay for treated wastewater; as well as the assessment of wood-based fuel use among selected SMEs in Accra; and assessment of the feedstock for making biochar and laboratory produced biochar (see Deliverable 1.2).

Following from the completion of the baseline studies, two sites were selected to demonstrate the water reuse; however, due to land tenure issues, only one site was used in the end because the land for this site belongs to CSIR. A shallow reservoir was constructed at the site accompanied by storage tanks to store treated wastewater from SSGL. The reservoir design imitates the design of maturation ponds of waste stabilization ponds to enhance further polishing of the treated wastewater from the SSGL.

While the shallow reservoir was being constructed, SSGL re-evaluated the treatment processes of the Mudor Treatment Plant (MTP) from where the water will be supplied to the farm site for demonstration. The purpose of the re-valuation was to identify areas for improvements in the wastewater treatment for assurance that the quality of treated wastewater meets standards for crop irrigation. The re-evaluation was completed by SSGL after which a filtration system (see Figure 2) was added to further polish the water before delivery to the shallow reservoirs at the farm site.

In addition, SSGL finalized the setting up of a plant for the pilot production of biochar (see Figure 3) while CSIR recruited SMEs to participate in the trial use of the biochar to be produced by SSGL (Figure 4). In the end, 15 SMEs enrolled to trial use of the biochar produced by SSGL.

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Figure 2:Filtration system at SSGL

Figure 3:: SSGL biochar production plant

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Figure 4:: Meeting with selected SMEs

2.1 Supply of biochar and treated wastewater

Once the preparatory activities were completed, by way of the setting up the water and biochar production systems, constructing the shallow reservoir, as well as providing an irrigation system for the farmers, the demonstration activities commenced. SSGL produced the first batch biochar which was supplied to the selected SMEs

Due to the impact of the COVID-19 Pandemic, several of the SMEs had closed business whereas some of them had moved from the Accra to be relocated elsewhere. Hence, in the end, CSIR recruited 15 SMEs to trial the use of biochar produced by SSGL. Since the commencement of production, SSGL has produced and supplied 2500Kg of biochar to the selected SMEs (Table 1). It is important to point out that more than 1000kg was produced for the first batch due to the optimism SSGL had about the quality of the product. However, when the SMEs used that batch, the feedback was negative. As result, SSGL with the support of CSIR reformulated another batch of biochar which also was not the best (based on feedback from the SMEs), but which was much better than the first batch. Furthermore, based the experience with the SMEs, SSGL had to stagger production based on the needs of the SMEs (most of them dropped out of the trial used by the time the third batch was being produced).

Table 1: Quantity of biochar produced by SSGL

Batch of Biochar	Quantity (Kg)

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First batch of biochar	1000
Second batch of biochar	750
Third batch of biochar	750
Total quantity of biochar	2500

For water reuse, so far, SSGL has supplied a total of 1,490,000 liters (1490m^3) of treated wastewater to the demonstration site at CSIR. In 2021, SSGL completed the filtration system and began to supply wastewater to the shallow reservoir for trial (not supply to farmers) and supplied a total of 420,000 liters of water. In 2022 while CSIR was setting up the irrigation system and preparing the farms for the trial, SSGL supplied a total of 510,000 liters before supply was interrupted by technical challenges at SSGL. Hence, although the demonstration began to supply the treated wastewater to farmers in mid 2022, due to the challenges at SSGL, water was not supplied until early 2023. Hence, for 2023, SSGL has supplied a total of 590,000 liters of treated wastewater as of April (Figure 5. This water is being supplied to farmers at the demonstration site.

Figure 5: Quantity of wastewater supplied by SSGL

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3 Water reuse monitoring

3.1 Introduction

The need to reuse wastewater is increasingly becoming important in many developing countries such as Ghana. Peri-urban farmers in particular find it the reuse of wastewater attractive as it is a source of free and nutrient rich water. This however comes with many challenges as farmers and consumers are exposed to various health risks due to the presence of pathogens and hazardous compounds that may be present in untreated wastewater.

The wastewater quality monitoring component of the Ghana case of the WIDER UPTAKE Project seeks to promote the wider use of wastewater by making it safer and profitable as a resource. In a baseline study conducted earlier, data on the prevailing situation in relation to the quality and quantity of wastewater used by farmers at two study sites CSIR-Water Research Institute (CSIR-WRI) and CSIR-Animal Research Institute (CSIR-ARI) were evaluated. After the baseline studies, the CSIR-WRI study site was selected for some interventions due to its closer proximity to Sewerage Systems Ghana Limited (SSGL) where the treated wastewater is produced and this report presents findings of the interventions.

3.2 Objectives of Monitoring

The objective of this study is to

- Assess the quantity and quality of treated wastewater supplied to the CSIR-WRI site by SSGL
- Assess the quality of water pumped from the shallow reservoir for the irrigation of the vegetables,
- Assess the quality of the vegetables on farm at the time of sampling
- Assess the presence or otherwise of the presence of any heavy metals in the soil in which the vegetables are grown
- Assess the quality of the drain water currently used by other farmers who are not part of the project.

3.3 Methods

3.3.1 Sampling

Water, vegetable and soil samples were collected and analyzed for physicochemical, microbial and parasitic contaminations. Urine samples of farmers and consumers of the vegetable produce as well as some water samples were also analyzed for the presence of some recalcitrant organic compounds. The water samples included,

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(i) treated wastewater supplied by SSGL, this was sampled before discharge into 10,000-litre capacity storage tanks (Figure 6) at the CSIR-WRI demonstration site,

(ii) effluent from the shallow reservoir (consisting of four ponds with baffles in the first and last pond) which is pumped out to irrigate crops on the demonstration farm, Figure 7,

(iii) raw wastewater from drain (taken upstream, midstream and downstream) (Figure 8).

(iv) Additionally, soil and vegetables (*Lactuca sativa* [lettuce], *Amaranthus* and *Hibiscus sabdariffa* [spinach]) samples from farm beds at the demonstration site were collected and analyzed (Figures 9). Three (3) replicate samples of the effluent, vegetables and soils were collected at each sampling time for a period of four weeks. Effluent, vegetable and soil samples were taken thrice every week between 09.00 hours and 10.00 hours GMT while the drain was sampled weekly from March to April 2023.

Figure 6: Discharge of water from SSGL RAW water into polytank

Figure 7: Reservoir with baffles

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Figure 8: Sampling Drain water

Figure 9: Collection of vegetable samples

1.1.1. Physico-chemical Analyses

The analyses were carried out at the CSIR-WRI Laboratories in Accra. The following parameters were determined:

Drain water samples

- pH
- Biochemical Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- Ammonia-Nitrogen (NH_3 – N)

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- Phosphate –Phosphorous (PO_4 - P)
- Nitrate – Nitrogen (NO_3 – N)
- Lead
- Cadmium
- Chromium
- Iron
- Zinc

Soil and vegetable samples

- Lead
- Cadmium
- Chromium
- Iron
- Zinc

All the analyses were performed according to methods which are outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 2017) and outlined in Table 2.

Table 2: Analytical methods employed for physico-chemical analyses of the water samples.

Parameter	**Method Employed**
pH	Schott Gerate pH meter C G 818
Ammonia – nitrogen	Direct Nesslerization Method
Nitrate – nitrogen	Hydrazine Reduction Method
Phosphate – phosphorous	Stannous Chloride Method
Chemical Oxygen Demand	Potassium Dichromate Reflux Method
Biochemical Oxygen Demand	Dilution and Dissolved Oxygen Determination after Incubation at 20°C for 5 days
Lead	Atomic Absorption Spectrophotometer
Cadmium	Atomic Absorption Spectrophotometer
Chromium	Atomic Absorption Spectrophotometer
Iron	Atomic Absorption Spectrophotometer
Zinc	Atomic Absorption Spectrophotometer

3.3.2 Bacteriological and Parasitological Analyses

All the water sources (SSGL raw, Effluent and Drain), soil and vegetable samples (Lettuce, *Amaranthus* and *Hibiscus sabdariffa* were collected for microbial and parasitological analyses as shown in the plates above. Three (3) replicates of each vegetable, effluent and drain samples were collected during each sampling time at the demonstration farm. Samples were

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analyzed immediately upon arrival in the laboratory. All samples were collected using sampling techniques and protocols in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2017).

3.3.3 Laboratory Analyses of wastewater and vegetable samples

All the water sources (SSGL raw, Influent, Effluent and Drain) were collected into sterile 500ml sampling bottle and 1liter clean bottles for the determination of the bacteria and intestinal parasites respectively. Additionally, 100 g of each vegetable was used for the bacteria analyses. The vegetable samples were collected aseptically and placed in a sterile ziplock bags. For bacteriological analyses, 10 grams of the vegetable was weighed and aseptically placed in a sterile beaker containing 100 ml of sterile alkaline peptone water. This was then agitated to dislodge attached bacteria into the water. These samples were analyzed for indicator and pathogenic bacteria using the membrane filtration technique on Hicrome Coliform agar media and Thiosulfate Citrate-Bile salt (TCBS) agar for the enumeration of total coliform, *E. coli* and *Vibrio spp* respectively incubated at 37 $\pm$0.5^{o}C for 16 – 24 hours. MFC media was used for the enumeration of fecal coliform and incubated at 44^{o}C $\pm$0.5^{o}C for 16-24 hours. The results were expressed as colony forming units (cfu) per 100ml of the water samples and cfu per 1gm for the vegetables (APHA 2017).

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3.4 Results

The physico-chemical characteristics of the drain and treated water were compared to the Ghana Standards Authority (GSA) guideline values for the discharge of wastewaters into receiving water bodies (GS1212:2019) to establish whether the requirements were met. The metals contents in the irrigation water, soil and vegetables were compared with FAO/WHO 2001 (irrigation water and soils) and FAO/WHO 2007 (vegetables). The physico-chemicals results are presented in Table 3 while Tables 4 to 8 show the results obtained for the biological parameters.

Table 3: Physico-chemical quality results alongside the Ghana Standard guideline values and FAO/WHO values of wastewater, soil and vegetable at CSIR-WRI site

Treated wastewater from Mudor Treatment Plant																
Standards used	**sample ID**	**pH**	**cond**	**TDS**	**TURB**	**TSS**	**Nitrate**	**Phosphates**	**Ammonia**	**COD**	**BOD***	**Pb***	**Cd***	**Cr***	**Fe***	**Zn***
FAO/WHO (2001), Ghana Standard values		**6 – 9 [b]**					**50 [b]**	**2 [b]**	**1 [b]**	**250 [b]**	**50 [b]**	**5.00**	**0.01**	**0.10**	**5.00**	**2.00**
21/02/23	SSGL	7.38					0.131	3.88	7.50	192	14.9	<0.005	<0.010	<0.010	0.324	0.044
27/02/23	SSGL	7.35					<0.001	3.39	5.88	230	21.9	<0.005	<0.010	<0.010	0.237	0.028
3/3/2023	SSGL	7.46					<0.001	3.92	13.9	259	23.7	<0.005	<0.010	<0.010	0.368	0.035
8/3/2023	SSGL	7.46					0.410	3.12	5.30	195	11.9	<0.005	<0.010	<0.010	0.294	0.045
12/4/2023	SSGL	7.52					5.85	0.293	6.32	144						
13/04/23	SSGL	7.62					4.26	0.450	5.42	86.4						
Untreated water from drain and Treated Wastewater from shallow reservoir																
28/03/23	Drain	7.39	1053	579	87.0	100	0.101	2.49	10.2	106		<0.005	<0.010	<0.010	0.390	0.025
	Drain	7.36	1108	609	98.0	102	0.146	1.77	3.31	86.4		<0.005	<0.010	<0.010	0.701	0.023

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Treated wastewater from Mudor Treatment Plant																
Standards used	**sample ID**	**pH**	**cond**	**TDS**	**TURB**	**TSS**	**Nitrate**	**Phosphates**	**Ammonia**	**COD**	**BOD***	**Pb***	**Cd***	**Cr***	**Fe***	**Zn***
	Drain	7.40	1123	618	85.0	97.0	0.326	1.49	13.4	96.0		<0.005	<0.010	<0.010	1.03	0.020
28/03/23	Effluent 1	9.32	2589	1424	248	252	0.276	1.42	2.93	234		<0.005	<0.010	<0.010	0.390	0.027
	Effluent 2	9.28	2527	1390	229	242	0.240	1.80	5.37	256		<0.005	<0.010	<0.010	0.011	0.018
	Effluent 3	9.39	2565	1411	216	234	0.218	1.09	5.40	362		<0.005	<0.010	<0.010	0.046	0.011
30/03/23	Effluent 1	9.26	2596	128	262	277	0.565	3.18	9.23	215		<0.005	<0.010	<0.010	0.140	0.019
	Effluent 2	9.25	2586	1422	248	259	0.545	3.35	7.66	202		<0.005	<0.010	<0.010	0.648	0.022
	Effluent 3	9.23	2609	1435	244	261	0.305	3.87	11.2	291		<0.005	<0.010	<0.010	0.130	0.010
4/4/2023	Drain	6.53	566	311	100	76.0	2.01	0.555	13.8	86.4						
	Drain	6.48	585	322	73.0	74.0	2.00	0.745	17.5	83.2						
	Drain	7.07	593	326	62.0	61.0	2.01	0.405	17.4	99.2						
4/4/2023	Effluent 1	7.49	2253	1239	25.0	4.00	0.325	4.43	13.8	447						
	Effluent 2	7.52	2196	1208	20.0	14.0	0.475	4.50	12.0	176						
	Effluent 3	7.32	2216	1219	20.0	22.0	0.455	4.33	13.8	179						
6/4/2023	Effluent 1	7.38	2254	1240	41.0	27.0	5.51	0.293	4.70	205						
	Effluent 2	7.46	2224	1223	43.0	34.0	5.07	0.814	5.14	170						
	Effluent 3	7.43	2223	1223	44.0	34.0	0.623	1.32	5.88	243						
11/4/2023	Drain	7.44	1006	553	68.0	59.0	4.93	0.236	5.02	141						
	Drain	7.46	1081	595	71.0	61.0	6.68	0.346	7.39	192						
	Drain	7.45	1026	564	68.0	63.0	6.08	0.444	8.08	128						
	Effluent 1	8.89	2058	1132	145	138	1.49	0.665	2.32	179						

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Treated wastewater from Mudor Treatment Plant																
Standards used	**sample ID**	**pH**	**cond**	**TDS**	**TURB**	**TSS**	**Nitrate**	**Phosphates**	**Ammonia**	**COD**	**BOD***	**Pb***	**Cd***	**Cr***	**Fe***	**Zn***
	Effluent 2	9.02	2047	1125	149	126	0.287	0.822	4.75	134						
	Effluent 3	9.02	2053	1129	154	146	0.153	0.932	5.97	186						
13/04/23	Effluent 1	8.56	2006	1103	145	2006	0.797	0.519	5.09	211						
	Effluent 2	9.17	1778	978	113	1778	0.722	0.728	4.66	234						
	Effluent 3	9.30	2065	1136	196	2065	0.759	1.22	6.24	224						
18/04/23	Drain	7.67	7.67	987	543	106	0.155	1.17	4.59	224						
	Drain	7.61	7.61	996	548	119	0.123	1.27	4.39	262						
	Drain	7.49	7.49	1011	556	115	0.128	1.43	4.15	131						
	Effluent 1	8.33	8.33	1958	1077	81.0	0.168	1.63	0.930	234						
	Effluent 2	9.27	9.27	1879	1033	171	0.148	1.55	0.744	189						
	Effluent 3	8.90	8.90	1994	1097	129	0.129	1.92	0.759	202						
						Soil samples (mg/kg)*										
												Pb	**Cd**	**Cr**	**Fe**	**Zn**
FAO/WHO (2001)												**100**	**3**	**50**	**5000**	**300**
						Vegetable samples (mg/kg)*										
FAO/WHO (2007)												**0.30**	**0.20**	**2.30**	**425.5**	**60.0**

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Treated wastewater from Mudor Treatment Plant																
Standards used	**sample ID**	**pH**	**cond**	**TDS**	**TURB**	**TSS**	**Nitrate**	**Phosphates**	**Ammonia**	**COD**	**BOD***	**Pb***	**Cd***	**Cr***	**Fe***	**Zn***
28/03/23	Lettuce													0.061	1.463	0.099
	Amarantus													0.039	1.476	0.146
	Sure													0.161	1.587	0.100
30/03/23	Lettuce													0.116	0.931	0.070
	Amarantus													0.099	1.20	0.117
	Sure													0.120	1.096	0.080
01/04/23	Lettuce													0.023	1.057	0.086
	Amarantus													0.035	1.089	0.132
	Sure													0.106	0.874	0.098
04/04/23	Lettuce													0.243	4.551	0.048
	Amarantus													0.050	3.596	0.142
	Sure													0.010	0.455	0.027
11/04/23	Lettuce													<0.010	0.699	0.09
	Amarantus													<0.010	1.024	0.061
	Sure															
13/04/23	Lettuce													<0.010	0.729	0.025
	Amarantus													<0.010	1.31	0.05
	Sure															
15/04/23	Lettuce													<0.010	0.810	0.022
	Amarantus													<0.010	0.440	0.030
	Sure															
18/04/23	Lettuce														1.110	0.015
	Amarantus														0.412	0.043
	Sure															

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Units of the wastewater samples are in mg l^{-1} while those of the soil and vegetable samples are in mg/kg, unless otherwise stated.
*BOD and heavy metal concentration of some samples are still being analyzed
[b] =Ghana standard limit

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Table 4: Bacterial counts in wastewater sample from drain

Sample	E. coli (cfu/100ml)	Log E. coli count/100ml	Vibrio (cfu/100ml)	Log Vibrio /100ml
Drain	5580	3.7	6	0.8
Drain	2790	3.4	20	1.3
Drain	1860	3.3	1	0.0
Drain	4650	3.7	0	0.0
Drain	5580	3.7	8	0.9
Drain	3720	3.6	15	1.2
Drain	660	2.8	0	0.0
Drain	960	3.0	27	1.4
Drain	2790	3.4	10	1.0
Drain	465	2.7	0	0.0
Drain	379	2.6	12	1.1
Drain	465	2.7	0	0.0

Table 5: Bacterial count in treated wastewater from SSGL

		Log_{10}	*Vibrio* spp (cfu/100ml)	Log_{10} *Vibrio* spp /100ml
	E. coli /100ml	E. coli /100ml		
SSGL	13	1.1	0	0
SSGL	92	2.0	0	0
SSGL	400	2.6	0	0
SSGL	7	0.8	0	0
SSGL	108	2.0	0	0
SSGL	279	2.4	0	0
SSGL	184	2.3	0	0
SSGL	156	2.2	0	0
SSGL	10	1.0	0	0
SSGL	186	2.3	0	0
SSGL	0	0.0	0	0
SSGL	0	0.0	0	0
SSGL	0	0.0	0	0

Table 6: Bacteria count in effluent from shallow reservoir

Sample	E. coli (cfu/100ml)	Log EC conc	Vibrio (cfu/100ml)	Log Vibrio conc
Effluent	0.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	10.0	1.0	0.0	0.0
Effluent	19.0	1.3	0.0	0.0
Effluent	5.0	0.7	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	1.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0

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Sample	E. coli (cfu/100ml)	Log EC conc	Vibrio (cfu/100ml)	Log Vibrio conc
Effluent	0.0	0.0	0.0	0.0
Effluent	6.0	0.8	0.0	0.0
Effluent	7.0	0.8	0.0	0.0
Effluent	7.0	0.8	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	8.0	0.9	0.0	0.0
Effluent	7.0	0.8	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0
Effluent	3.0	0.5	0.0	0.0
Effluent	8.0	0.9	0.0	0.0
Effluent	5.0	0.7	0.0	0.0
Effluent	8.0	0.9	0.0	0.0
Effluent	4.0	0.6	0.0	0.0
Effluent	1.0	0.0	0.0	0.0
Effluent	3.0	0.5	0.0	0.0
Effluent	1.0	0.0	0.0	0.0
Effluent	3.0	0.5	0.0	0.0
Effluent	1.0	0.0	0.0	0.0
Effluent	0.0	0.0	0.0	0.0

Table 7: Bacteria count on vegetable samples

Sample	E. coli (cfu/100ml)	Log EC conc	Vibrio (cfu/100ml)	Log Vibrio conc
Lettuce	4	0.6	0	0
Lettuce	2	0.3	0	0
Lettuce	2	0.3	0	0
Amarantus	9	1.0	0	0
Amarantus	1	0.0	0	0
Amarantus	2	0.3	0	0
Hibiscus	9	1.0	0	0
Hibiscus	4	0.6	0	0
Hibiscus	11	1.0	0	0
Lettuce	6	0.8	0	0
Lettuce	2	0.3	0	0
Lettuce	5	0.7	0	0
Amarantus	1	0.0	0	0

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Sample	E. coli (cfu/100ml)	Log EC conc	Vibrio (cfu/100ml)	Log Vibrio conc
Amarantus	0	0.0	0	0
Amarantus	1	0.0	0	0
Hibiscus	3	0.5	0	0
Hibiscus	0	0.0	0	0
Hibiscus	0	0.0	0	0
Lettuce	0	0.0	0	0
Lettuce	2	0.3	0	0
Lettuce	0	0.0	0	0
Amarantus	0	0.0	0	0
Amarantus	0	0.0	0	0
Amarantus	0	0.0	0	0
Hibiscus	20	1.3	0	0
Hibiscus	0	0.0	0	0
Hibiscus	0	0.0	0	0
Lettuce	2	0.3	0	0
Lettuce	8	0.9	0	0
Lettuce	0	0.0	0	0
Amarantus	0	0.0	0	0
Amarantus	0	0.0	0	0
Amarantus	0	0.0	0	0
Hibiscus	2	0.3	0	0
Hibiscus	0	0.0	0	0
Hibiscus	0	0.0	0	0
Lettuce	9	1.0	0	0
Lettuce	4	0.6	0	0
Lettuce	2	0.3	0	0
Amarantus	20	1.3	0	0
Amarantus	5	0.7	0	0
Amarantus	2	0.3	0	0
Hibiscus	9	1.0	0	0
Hibiscus	10	1.0	0	0
Hibiscus	11	1.0	0	0
Lettuce	0	0.0	0	0
Lettuce	0	0.0	0	0
Lettuce	3	0.5	0	0
Amarantus	0	0.0	0	0
Amarantus	0	0.0	0	0
Amarantus	0	0.0	0	0
Hibiscus	0	0.0	0	0
Hibiscus	6	0.8	0	0
Hibiscus	0	0.0	0	0
Lettuce	11	1.0	0	0
Lettuce	7	0.8	0	0

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Sample	E. coli (cfu/100ml)	Log EC conc	Vibrio (cfu/100ml)	Log Vibrio conc
Lettuce	5	0.7	0	0
Amarantus	4	0.6	0	0
Amarantus	5	0.7	0	0
Amarantus	8	0.9	0	0
Lettuce	2	0.3	0	0
Lettuce	1	0.0	0	0
Lettuce	11	1.0	0	0
Amarantus	3	0.5	0	0
Amarantus	0	0.0	0	0
Amarantus	0	0.0	0	0
Lettuce	9	1.0	0	0
Lettuce	4	0.6	0	0
Lettuce	10	1.0	0	0
Amarantus	0	0.0	0	0
Amarantus	2	0.3	0	0
Amarantus	1	0.0	0	0
Lettuce	9	1.0	0	0
Lettuce	2	0.3	0	0
Lettuce	20	1.3	0	0
Amarantus	9	1.0	0	0
Amarantus	0	0.0	0	0
Amarantus	1	0.0	0	0
Lettuce	9	1.0	0	0
Lettuce	9	1.0	0	0
Lettuce	0	0.0	0	0
Amarantus	2	0.3	0	0
Amarantus	2	0.3	0	0
Amarantus	4	0.6	0	0

Table 8: Parasitological observations in drain effluent, reservoir effluent and vegetable samples

	Drain effluent			**Reservoir effluent**			**Vegetable samples**		
Date	***H/ HE (/l)***	***CO /l***	***GC /l***	***H/ HE (/l)***	***CO /l***	***GC /l***	***H/ HE (/g)***	***CO /g***	***GC /g***
04/04/2023	<1	<1	<1	<1	<1	<1	4	<1	<1
	3	<1	<1	<1	<1	<1	<1	<1	<1
	4	<1	<1	<1	<1	<1	3	<1	<1
	<1	<1	<1	<1	<1	<1	<1	<1	<1
06/04/2023	7	<1	<1	<1	<1	<1	<1	<1	<1
	2	<1	<1	<1	<1	<1	<1	<1	<1
	2	<1	<1	<1	<1	<1	<1	<1	<1
	3	<1	<1	<1	<1	<1	<1	<1	<1
08/04/2023	3	<1	<1	<1	<1	<1	1	<1	<1
	4	<1	<1	<1	<1	<1	<1	<1	<1

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	Drain effluent			Reservoir effluent			Vegetable samples		
Date	***H/ HE (/l)***	***CO /l***	***GC /l***	***H/ HE (/l)***	***CO /l***	***GC /l***	***H/ HE (/g)***	***CO /g***	***GC /g***
	<1	<1	<1	<1	<1	<1	8	<1	<1
	<1	<1	<1	<1	<1	<1	<1	<1	<1
13/04/2023	<1	<1	<1	<1	<1	<1	2	<1	<1
	<1	<1	<1	<1	<1	<1	4	<1	<1
	<1	<1	<1	<1	<1	<1	<1	<1	<1
	15	<1	<1	<1	<1	<1	<1	<1	<1
	<1	<1	<1	<1	<1	<1	<1	<1	<1
18/04/2023	25	<1	<1	<1	<1	<1	6	<1	<1
	1	<1	<1	<1	<1	<1	3	<1	<1
	<1	<1	<1	<1	<1	<1	<1	<1	<1
	1	<1	<1	<1	<1	<1	<1	<1	<1
	<1	<1	<1	<1	<1	<1	<1	<1	<1

H/E: Helminth/Helminth Eggs; CO: Cryptosporidium oocyst; GC: Giardia Cyst

3.5 Discussion

3.5.1 Physico-chemical characteristics

Treated wastewater received from Mudor Treatment Plant (MTP) contained low nitrate concentrations ranging from 0.001 to 5.85 mg/L, compared to the maximum acceptable guideline value of 50 mg/L by the Ghana Standards Authority (GSA). However, the phosphate (0.293-3.92 mg/L) and ammonia (5.30-13.9 mg/L) values far exceeded their individual acceptable limits of 2 mg/L and 1 mg/L, respectively. Similarly, the results for pH, COD, BOD, and the metals (Pb, Cd, Cr, Fe, Zn) are all below their acceptable limits. The BOD per EU guideline is however 20.0mg/L and some of the samples had BOD that is slightly above that (ie 21.9, 23.7 mg/L).

The pH of the treated wastewater received from the MTP had an average of 7.46 compared to 9.28 from the shallow reservoir. This was a result of the presence of algae in the reservoir, their photosynthetic activity resulting in the uptake of carbon dioxide.

Nitrate concentrations in both the drain and shallow reservoir effluent are far below the acceptable limit, although the reservoir effluent generally contains higher concentrations than the drain water. On the other hand, ammonia concentrations in all the water samples are far above the acceptable limits, with the drain water containing higher concentrations than the reservoir effluent. Phosphate concentrations for both water samples (drain and reservoir effluent) are generally within the acceptable limit.

Heavy metal concentration in reservoir effluent, treated wastewater from MTP and drain water were all below the EU and FAO/WHO (2001) recommended levels.

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3.5.2 Bacteriological quality of Irrigation water, soil and vegetable samples

The bacteriological quality of the irrigation water (effluent of shallow reservoir) generally satisfied EU guidelines of <10 cfu/100mL (Directive 91/271/EEC). The vegetables grown by the farmers (lettuce, hibiscus and Amaranthus) belongs to category A of the EU classification, being food crops, including root crops consumed raw and where the edible portion is in direct contact with the reclaimed water (Alcalde-Sanz and Gawlik, 2017). The drain water quality had concentrations varying from 2.6 to 3.7 log units of E. coli and 0-1.4 log units of Vibrio. Treated wastewater from SSGL had fairly good quality ranging from 0 to 2.8 log units. This showed the absence of vibrio as do the effluent of the shallow reservoir. The quality of vegetables generally was of good quality showing E. coli concentrations of <1 log unit. No oocyst or cyst of Cryptosporidium or giardia respectively were found on the vegetables, or in effluent from the reservoir or that of treated wastewater discharged from SSGL. Helminths or helminth eggs were also absent in the effluent from the shallow reservoir but helminth eggs were observed on some vegetable samples (Table 8). These however were generally low.

3.5.3 Recalcitrant organic compounds

Urine and water samples analyzed for recalcitrant organic compounds in the category of analgesics, amphetamines, pesticides and antidepressants are currently being analyzed in Germany. Results would be reported on as soon as they are ready.

3.6 Conclusion and Recommendations

The physico-chemical results indicate that the treated wastewater received from the shallow reservoir for the irrigation of the vegetables is of good quality. This had appreciable phosphate and ammonia concentrations which is useful for the growth of the vegetables. The heavy metal contents of the vegetables are also at acceptable levels for the samples analyzed.

The bacteriological quality of effluent of shallow reservoir generally satisfied EU guidelines of <10 cfu/100mL. Treated wastewater from SSGL had fairly good quality ranging from 0 to 2.8 log units with vibrio absent in the effluent of the shallow reservoir as well as the treated wastewater from SSGL. The vegetables generally were of good quality showing E. coli concentrations of <1 log unit. No oocyst or cyst of Cryptosporidium or giardia respectively were found on the vegetables, or in effluent from the reservoir or that of treated wastewater discharged from SSGL. Helminths or helminth eggs were also absent in the effluent from the shallow reservoir.

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4 Monitoring of biochar fuel

4.1 Introduction

Biomass sources include agricultural waste/residue, algae, sawdust, food waste and sewage sludge. The use of such materials as energy feedstock is a net zero as well as carbon neutral as it promotes efficient management of energy needs without drawing from carbon from virgin forests or release stored non-renewable carbon from fossil fuel thus improving the circularity of energy solutions (Bhatia , Jha, Sarkar, & Sarangi, 2023).

Biochar is a carbon-rich solid formed by heating biomass in an environment limited to oxygen. The use of biochar for various applications is gradually gaining roots in most industries. The potential of biochar as recoverable fuel from various types of biomass is notable with others serving as co-firing materials (USEIA, 2023). Sewage sludge are solid residual materials with high organic matter content and some levels of nutrients (European Commission , 2023) which can be valuable raw materials for a new process from typical end of cycle materials (after wastewater treatment processes involving aerobic, anaerobic, dewatering etc. to remove essentially pathogens and nutrient induced eutrophication agents before discharge into the environment). The sludge is often used as soil amendment to improve soil fertility. Sewage sludge may also contain pathogens and harmful elements which when not properly managed can have a negative impact on the environment (European Commission , 2023). Carbonization is a pyrolytic or thermochemical reaction where heat is applied at high temperatures (400 - 700 ^{o}C) in the absence of oxygen for the formation of carbon from organic matter. Carbonization is known to cause the thermal breakdown of pathogens making the sludge safe to handle. Thus, sewage sludge carbonization is an effective means of reducing residual pathogen load of the waste and at the same time converting them into valuable by-products for use. Carbonization also increases the energy density of the biomass by reducing moisture and volatile matter content (Nunes, Matias, & Catalao, 2017). The characteristics of a biochar (proximate analysis, heating value as well as the gaseous emission from combustion) are highly dependent on the operational temperature and time of the carbonization process as well as the type of biomass used. The intervention of the Wider Uptake project focuses on enhancing the circularity of sewerage treatment facility in Accra (SSGL) by ensuring valorization of the fecal sludge as a source of fuel for small and micro enterprises (SMEs).

4.1.1 Sludge- Saw dust composite briquettes

Initial observation from the baseline study on the quality of biofuel produced from sewage sludge indicated that the fuel quality properties of the briquette such as volatile matter, ash content, fixed carbon and calorific value were generally low. Studies have shown that the combination of diverse biomass materials increases the quality and economic viability of the compacted briquettes (Bot, Axaopoulos, Sakellariou, Sosso, & Tamba, 2022). To improve the energy density, a briquette formulated from a composite of carbonized sludge enriched with carbonized saw dust was explored. Sawdust is a by-product of most wood processing industries around the vicinity of SSGL. It is highly available and obtained at low cost. The use

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of sawdust contributes to environmental management as well as technical and economic feasibility of the product.

4.1.2 Monitoring of biochar fuel use by SMEs

The use of biomass in many developing countries is a continued area of interest for businesses because it is renewable and has attractive carbon credit rating. In recent years, improved fuels and cookstoves have been designed and disseminated to households to help mitigate the harmful health and environmental impacts of traditional open fires from inefficient cookstoves and fuels that generate a lot of smoke. Combustion of firewood and other non-torrefied biomass fuels causes emissions of carbon monoxide and particulate matter. Diseases related to indoor air pollution include cancer, upper and chronic respiratory diseases as well as increasing the risk of environmentally triggered inflammations like asthma. Exposure to smoke from incomplete combustion due to ineffective stoves has a big impact on the health of the people living in the developing world. WHO have estimated that 3.2 million people die prematurely every year due to indoor air pollution (WHO, 2022). The global health problem related to exposure to indoor air pollutants necessitated the establishment of guidelines for indoor air quality. Traditional cooking with solid fuels which produces particulate matter (PM) in the form of smoke and carbon monoxide (CO) because of incomplete combustion has negative impact on health. The effect of PM emissions transcends the local environment. PM has a high global warming potential. Black carbon is a short-lived pollutant with a lifetime of a few days to a few weeks, however the pollutant is very effective on absorbing light and warming surroundings and have 460-1500 times stronger warming impact on climate than CO_2 per unit of mass.

4.2 Objectives of monitoring

The main objectives of the monitoring study were to

1. determine the fuel quality (burning rate and firepower, Calorific value, Heavy metals, Proximate Analysis) of biochar briquettes produced from the demonstration plant in Accra,
2. reduce environmental risk by determining emission of noxious gases (CO, $PM_{2.5}$, AQI) and heavy metals (Pb, As, Cd, Cu and Zn) into the fuel as well as the ash and
3. reduce health risk associated with exposure to the harmful effluents (particularly indoor air pollutants in uncontrolled cooking conditions as well as heavy metals from residual ash) during use of the biochar product by evaluating, the exposure to indoor air pollutants (CO, $PM_{2.5}$) directly from the use of the biochar by SMEs as well as CO_2 savings from the use of a renewable source of fuel during a batch production,
4. determine the emissions from utilization of the biochar from the sludge, the burning characteristics and the potential time saving enables discussion on the potential adaption of the fuel as a cleaner energy alternative.

4.3 Methods

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4.3.1 Laboratory formulation and monitoring of fuel quality

Sewage sludge was obtained from the Mudor treatment plant of the Sewerage Systems Ghana Limited situated in Accra. The sludge was carefully collected to avoid collecting sand from the drying bed so as not to compromise the composition of the sludge into sacks.

The sludge was then transported to the CSIR-IIR, further dried to reduce moisture to constant weight before conversion into biochar using an LPG fired batch kiln. The sludge was carbonized at 600 °C for 2 hours with a heating rate of 15 °C per min. After carbonization, the samples were allowed to cool to below 40 °C and stored. Saw dust from a carpentry shop at CSIR-IIR derived from mixed wood species was also carbonized at 400 °C for 2 hrs with limited air supply, the heating stopped and allowed to cool to below 40 °C and stored.

The briquettes were formed by mixing the different ratios of carbonized biochar with carbonized sawdust (1:1, 1:2 and 2:1) with a binder added at a predetermined ratio. 40 g of the sample were carefully placed in a cylindrical mold and hydraulic pressed at forming pressure of 2 bars to obtain the briquettes. The briquettes are air dried to obtain constant weight (Figure10).

Figure 10: Laboratory produced biochar using different ratios of sludge and saw dust

The physical (bulk density) and mechanical (hardness, using Izod impact test) properties were determined using ASTM D653 Method B and ASTM D256 respectively.

4.3.2 Burning characterization of the composite biochar samples

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The fuel quality was assessed by conducting proximate analysis to determine, Moisture content (ASTM D3173, 2002), Volatile matter (ASTM D3175, 2002), Ash content (ASTM D3174), and Fixed carbon (FC). The percentage Fixed Carbon (FC) was computed using Equation 1

$$\%FC = 100 - (MC + VM + ASH) \qquad \text{Equation 1}$$

Where, *MC* is percentage Moisture Content, *VM* is the percentage total Volatile Matter and *ASH* is the percentage Ash Content.
Water Boiling Test (WBT) methods was used to determine the Burning rate (BR), Firepower (FP), Specific fuel consumption (SPC). A bomb calorimeter was used to determine the heating or Calorific Value (CV) of the fuel.

4.3.3 Elemental analysis was conducted using XRF

The elemental analysis of the powdered samples was determined by the hazardous waste test methods SW-846 test method 6200 (EPA, 2007) using an Oxford Twin-X X-ray Fluorescence (XRF) Spectroscopy.

4.3.4 Field monitoring

The methodology used in collecting monitoring data consisted of a pre-selection of SMEs in the Greater Accra Metropolitan Area (GAMA), A questionnaire was designed to obtain information on their activities, cooking energy sources and types of stoves and to understand the processes, preferences and perceptions in terms of heating fuel usage.

4.3.4.1 Study Area

The current monitoring exercise covered four (4) out of fifteen (15) administrative districts in the Greater Accra Metropolitan Area: New Legon (Adentan), Ogbojo (Accra Metropolitan), Ashaiman and Gbetsile (Kpone Katamanso) with focus on SMEs shown in Figure 11

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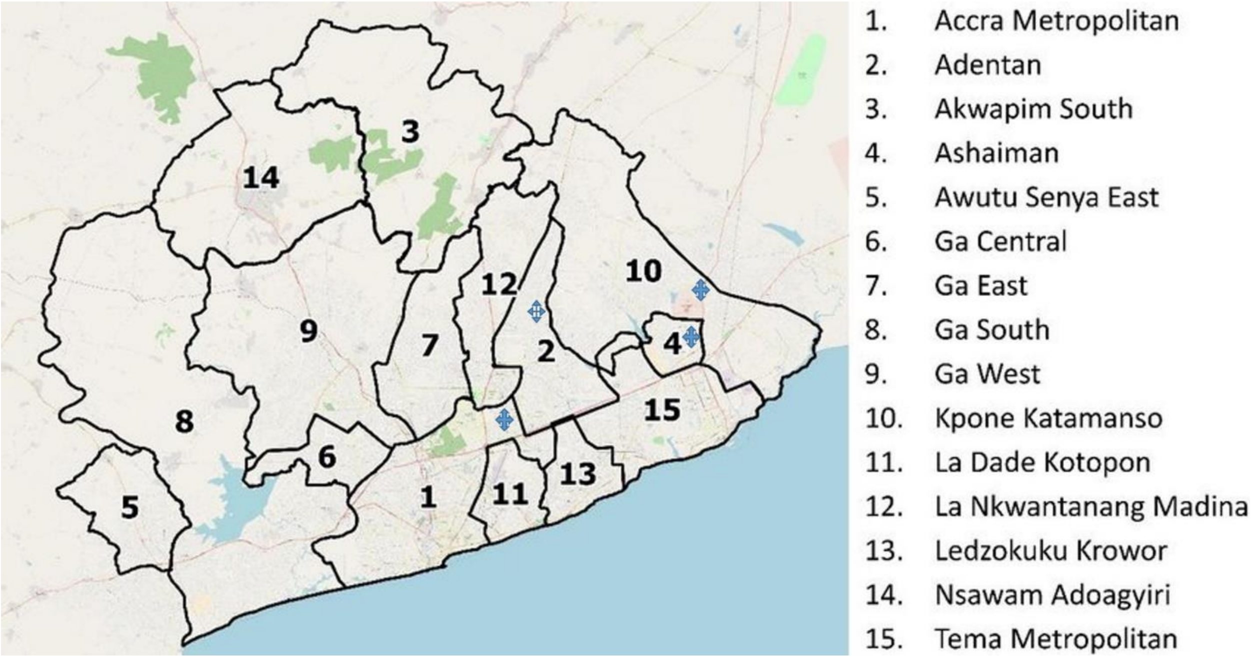

Figure 11: Map of the greater Accra Metropolitan Area indicating the locations of the SMEs monitored in the use of the biochar fuel (Koppelaar, et al., 2018).

4.3.5 Uncontrolled Cooking Test (UCT)

The Uncontrolled Cooking Test (UCT) is a field test that measures stove performance in comparison to traditional cooking methods when a user prepares any local meal of their choice. The UCT allows the user to operate the stove in any manner they feel is appropriate and using any pots they feel suited to the tasks. Field tests are important for demonstrating results for carbon credits, health risks assessment from exposure to air pollutants during the use of the fuel and estimating contributions to greenhouse gas emissions. Parameters measured include the quantity of products produced per batch, quantity of fuel used, personal exposure to emissions of CO and $PM_{2.5}$, cooking time and specific consumption of the biochar compared to the current fuel being used. The ash was sampled for analysis of heavy metals.

4.3.5.1 Fuel Consumption

To calculate the fuel consumption and ash production a series of different parameters was considered. Gross fuel consumption (g) is amount of fuel used during the whole cooking process. This was calculated using a large pile of biochar that was measured before the start of cooking. At the end of cooking the remaining biochar in a container and any withdrawn fuel from the stove was weighed and subtracted from the weight of the large pile.

4.3.5.2 Personal Exposure and Air Quality Index

The personal exposure to the cook during the use of the biochar was measured using an Aprovecho Indoor Air Pollution Meter mounted at the back of the cook with an inlet pipe close

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to the nose of the cook. Whilst the ambient levels of air pollutants were measured with BR SMART and Bosean Air Quality Meters (Figure 12).

Figure 12: Air monitoring meters used for monitoring air quality. Left meter is the Aprovecho IAP used in measuring personal exposure of the cook to CO and $PM_{2.5}$ during the use of the biochar.

4.4 Results

4.4.1 Calorific values of the biochar fuels

The results as shown in Figure 13 indicate that carbonization increases the heating value of the saw dust by 36% whilst the calorific value of the sludge increases by 6.25% through carbonization. However, though increasing the content carbonized sludge in the composite briquette from 33% to 66% does not lead to a significant change in calorific values (26 MJ/kg to 25.7 MJ/kg) the Sulphur content of the briquette increases almost six-fold (0.25% to 1.66%).

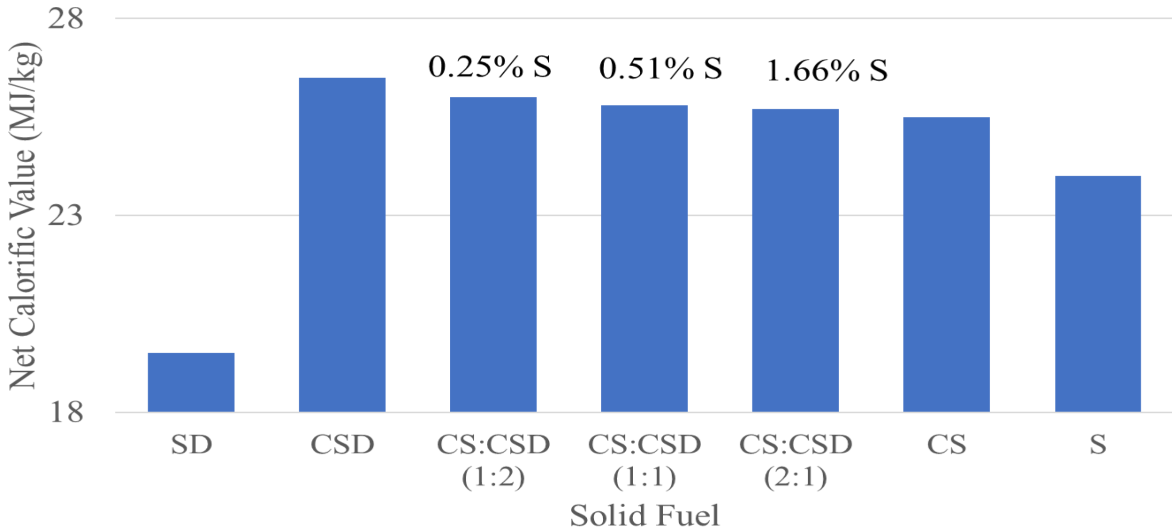

Figure 13: Heating values of solid fuels produced calorific value from co-carbonized sludge and saw dust with the Sulphur content of the fuel

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4.4.2 Burning characteristics of the mixed carbon biochar using Water Boiling Test

Biochar briquette with equal ratio of carbonized sludge and saw dust presents superior quality solid fuel in terms of the burning characteristic (burning rate, specific fuel consumption, firepower) and emission levels (CO and $PM_{2.5}$) (see Table 9).

Table 9::Burning characteristics of the fecal sludge-sawdust composite biochar

Burning characteristics	Ratio of sludge to sawdust	
	1:1	2:1
Burning rate (g/min)	10.51 ± 1.62	8.50 ± 1.37
Specific Fuel Consumption (g/l)	107.13 ± 9.29	142.98 ± 46.51
Firepower (kW)	3.80 ± 0.59	3.45 ± 0.56
CO (g/kg)	59.64 ± 12.45	215.48 ± 42.17
CO_2 (g/kg)	1739.67 ± 19.63	1495.00 ± 66.36
$PM_{2.5}$ (g/kg)	4.76 ± 0.50	22.95 ± 1.93
Density (g/cm^3)	0.73 ± 0.03	0.810 ± 0.02
Hardness (MJ/m^2)	6.902 ± 2.45	10.33 ± 4.54

4.4.3 Proximate analysis of biochar

Adding saw dust to the sludge to produce biochar briquettes significantly improves the fuel value of the biochar as indicated in Table 10 with about seven-fold improvement in the fixed carbon compared to the raw fecal sludge (from 2.14% to 14.69%).

Table 10: Comparison of the proximate analysis of biochar with varying ratios of sludge and uncarbonized sludge

Proximate parameter	Mean ± Standard Deviation		
	Biochar briquette (saw dust to sludge ratio 1:1)	Carbonized sludge	Dried fecal sludge
Moisture Content (%)	2.38 ± 0.33	3.60 ± 0.3	8.20 ± 0.50
Volatile Matter (%)	37.20 ± 0.57	38.90 ± 2.3	59.60 ± 3.16
Ash Content (%)	45.24 ± 0.38	60.00 ± 2.1	36.50 ± 1.20
Fixed Carbon (%)	14.69 ± 0.78	0.58	2.14

Similar reduction in moisture content and volatile matter is indicative of the improved fuel value. The ash content remains high compared to the raw sludge and this could be due to the inorganic polymer used as a binder in the briquette formulation. Thus, biochar briquette with ratio 1:1 was recommended for scale-up production by Sewerage Systems Ghana Limited and use in the uncontrolled cooking test during the field monitoring exercise.

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4.4.4 Results of field monitoring using Uncontrolled Cooking Test (UCT)

The results from the monitoring exercise show that even for SMEs that use fuel types high on the energy ladder like LPG, they still have cookstoves for biomass use. The use of a particular type of stove is dependent mainly on the affordability of the energy source. Though their processes are diverse, roasting and boiling are the predominant cooking methods used in the processes (See Table 11). The operations of the SMEs were in either well ventilated sheds or in open spaces (Figure 14).

Figure 14: Field monitoring of use of biochar in uncontrolled cooking tests at the SMEs

Table 11: Key activities of SMEs' processes monitored during the reporting period.

	Cookstoves device	Fuel	Process	Use of heat	Freq. of production (batches/Month)	Date of monitoring
SME 1	1. Agyapa (Improved charcoal stove with ceramic lining) 2. Liquified Petroleum Gas (Propane) Cookstove	1. Charcoal 2. LPG	1. Processing of local malted drink 2. Production of soaps and cosmetics 3. Roasting of grains and nuts	1. Boiling 2. Warming 3. Roasting	12	21st to 24th February 2023
SME 2	1. Agyapa 2. Metal charcoal stove without	1. Charcoal 2. Fuelwood 3. LPG	1. Roasting of nuts	1. Roasting	8	14th to 17th March 2023

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	Cookstoves device	Fuel	Process	Use of heat	Freq. of production (batches/Month)	Date of monitoring
	ceramic lining 3. Metal fuelwood stove without lining 4. LPG					
SME 3	1. Agyapa	1. Charcoal	1. Roasting nuts	1. Roasting	4	20th to 23rd March 2023
SME 4	1. Modified 3-stone stove with Tyre rim	1. Fuelwood	1. Preparing corn dough mix (local staple)	1. Boiling	32	11th to 14th April 2023

Table 12: Estimation of carbon savings from the use of the biochar compared to LPG for a similar process at 67% Relative Humidity and 36 °C.

Key Parameters Measured	Fuel type	
	Biochar	LPG
Time to complete cooking (min.)	291	201
Specific Fuel Consumption (g of fuel/kg of food)	87.69	14.61
Specific Fuel Consumption (g of carbon/kg of food)	48.02	11.95
Equivalent non-renewable CO_2 produced (kg)	0	9.18

Table 13: Estimation of emission levels from the use of the biochar from different types compared to LPG for a similar process at 65±2.94 % Relative Humidity and 35.2 ± 0.67 oC.

SME	Type of fuel	Type of cookstove	$PM_{2.5}$ (µg/m³)	CO (mg/m³)
SME 3	Biochar	Truncated pyramidal unlined metal	64	8.22
SME 1	Biochar	Ceramic lined stove	65	11.61
SME 1	LPG	LPG burner	21	0.78
SME 2	biochar	Tyre rim charcoal stove, unlined	3	15.14

4.5 Discussions

The CO_2 savings for using the biochar briquettes from a renewable source compared to LPG (fossil source) was about 9.18 kg (Table 12) per the activity of the SME 1 monitored (see Table 11). This demonstrates significant carbon credit from the SCES. $PM_{2.5}$ is the most dangerous pollutant because it can penetrate the lung barrier and enter the blood stream causing various morbidities. Thus, reducing air pollution reduces the burden of diseases of countries. According to the WHO the maximum allowable average annual concentrations of $PM_{2.5}$ for outdoor situations should be 5 μg/m^3, and for 24-hour period the average exposure but the interim target 1 is 75 μg/ m^3 and the mean maximum allowable concentrations of CO over 24-hour period is 7 μg/m^3 (WHO, 2021). The average exposure to $PM_{2.5}$ using biochar fuel ranged from 3 μg/m^3 to 65 μg/m^3. Whilst the CO exposure levels ranged from 8.48 μg/m^3 – 15.69 μg/m^3. Emission levels was dependent on the stove type and design. The values for $PM_{2.5}$ were within the primary targets of the WHO guidelines. CO levels were higher than the WHO 24-hour exposure limit of 7 mg/m^3.

The Total Air Quality Index from using biochar (31.5) was however, very similar to that of charcoal (30.46) which were all within the 0-50 threshold for good in terms of levels of health concern (Table 14).

Table 14: Classification of AQI in the United States (AirNow, 2023)

Air Quality Index (AQI) Values	**Levels of Health Concern**
0 to 50	Good
51 to 100	Moderate
101 to 150	Unhealthy for Sensitive Groups
151 to 200	Unhealthy
201 to 300	Very unhealthy
301 to 500	Hazardous

Further monitoring is required to estimate the Risk Characterization Ratio in the use of the biochar with respect to both gaseous emissions and heavy metals.

4.5.1 Adoption and usage

Feedback from users indicate favorable comments on the quality of the fuel for use in the applications monitored as well as the Air Quality Index in the cooking environment compared to charcoal. However, affordability and availability are major drivers to the wider uptake of the SCES in preference to alternative sources of energy feedstock like LPG, Charcoal and Fuelwood.

4.6 Conclusions and recommendations

Significant carbon savings of up to 9.18 kg of CO_2 can be achieved by the use of the biochar as an alternative source of fuel. The emission levels of $PM_{2.5}$ (3 μg/m^3 -65 μg/m^3) are within the WHO guidelines for air quality and however, CO (8.22 mg/m^3 – 15.14 mg/m^3) was higher than the WHO maximum concentration of 7 mg/m^3. Thus, the use of the biochar poses no adverse health risk when used as a source of heating energy in well ventilated areas. Heavy metal residues in the fecal sludge feedstock as well as the biochar fuel and the ash from the combustion process need to be monitored continuously to assess the environmental and health risk associated with the disposal of the ash.

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5 Conclusion

This report presents activities of the Ghana case study, which involves the reuse of water and production of biochar from fecal sludge. Ghana's demonstration is going well following series of challenges that have since been overcome.

SSGL has produced three different batches of biochar of different qualities for distribution to selected SMEs in Accra for trials. A total 2,500kg of such biochar has been supplied to SMEs in an ongoing and need-basis. The different batches of have come about due to feedback received from the SMEs while using the biochar. Some of the SMEs dropped out of the trial due to their experiences with the first batch of biochar. However, following the feedback and with the support of CSIR, SSGL's production of the third batch has been well received. This batch comprises a mixture of sludge and saw dust in a ration of 2:1.

Monitoring results from CSIR shows that the use of the third batch of biochar poses no adverse health risk when used as a source of heating energy in well ventilated areas. Heavy metal residues in the fecal sludge feedstock as well as the biochar fuel and the ash from the combustion process need to be monitored continuously to assess the environmental and health risk associated with the disposal of the ash. Looking forward and to ensure the wider uptake of the biochar, issues relating to its affordability and availability are drivers that need to be addressed to ensure its preference as against other alternative sources such as wood-based charcoal.

Feedback from farmers involved in the water reuse expressed satisfaction in the use of the water, especially when water was available for free. The monitoring tests by CSIR (physico-chemical) shows that the treated water discharged from the shallow reservoir to farmers is of good quality with respect to nutrients and safety. Furthermore, the vegetables' levels of heavy metals were within safe limits. Bacteriologically, the qualities of water from SSGL, shallow reservoir discharged to farmers, and vegetables produced from water reuse were good. Results for recalcitrant organic compounds in the category of analgesics, amphetamines, pesticides and antidepressants were not ready during the preparation of this report. The results will be provided to the WP2 database when finalized.

Notwithstanding the results of the monitoring of the biochar and water reuse solutions so far, it is recommended that monitoring continues until the demonstrations achieve a full year taking into considerations the difference climatic seasons in Ghana.

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