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Dynamics of Micro/Macro Elements and Heavy Metals during Anaerobic Treatment of Organic Fraction of Municipal Solid Waste (OFMSW)

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Authors' Contributions

This work was carried out in collaboration between all authors. Authors HOS and GOA supervised the experimentation process of the study. Author HOS managed the literature search. Author CBO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author GOA managed the analysis of the study. All authors read and approved the final manuscript.

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ABSTRACT

In this study, the dynamics of macro and micro elements (including heavy metals) during anaerobic treatment of organic fraction of municipal solid waste (OFMSW) was investigated to determine the effect of seasonal variation on the performance of the treatment process. The first anaerobic digestion (AD_H) process was conducted during the dry season (between March and May, 2016) while the second anaerobic digestion (AD_C) process was conducted during the rainy season (between July and early October, 2016). OFMSW was collected and subjected to anaerobic treatment inside one-stage 250 litre – capacity batch-type mesophilic reactors with useful volume of 230 litres, substrate (OFMSW) concentration of 5.53%, rumen juice as the source of microbial inoculum and a retention time of 84 days. To monitor the treatment process, temperature, pH,

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macro and micro elements including heavy metals were estimated with time. Result showed that average process temperature inside the reactors (AD_H and AD_C) during the dry and rainy season ranged from 29.7ºC to 39.3ºC and 26.8ºC to 30.8ºC respectively after 84 days. Inside the reactors (AD_H and AD_C), cumulative biogas increased to 34.8 L and 26.5 L while nickel, iron and cobalt ranged from 6.80 to 1.52 mg/l and 6.62 to 0.93 mg/l, 21.40 to 1.25 mg/l and 23.70 to 5.7 mg/l, and 2.14 to 0.63 mg/l and 2.21 to 0.64 mg/l respectively after 84 days. Cadmium, chromium and mercury ranged from 2.91 to 0.05 mg/l and 2.64 to 1.1 mg/l, 1.84 to 0.06 mg/l and 1.81 to 0.8 mg/l and 0.58 to 0.02 mg/l and 0.57 to 0.08 mg/l respectively after 84 days. This suggests that anaerobic digestion could be applied to reduce the concentration of heavy metals in biodegradable wastes to some degree before the wastes can be disposed into the environment. Nevertheless, it appears that the anaerobic digestion (AD_H) process conducted during the dry season may have performed better than the anaerobic digestion (AD_C) process conducted during the rainy season in terms of reducing the concentration of these elements as was biogas production with time.

Keywords: Anaerobic treatment; municipal solid waste; seasonal variation; heavy metals.

NOMENCLATURES

AD	=	*Anaerobic digestion*
OFMSW	=	*Organic fraction of municipal solid waste*
RJ	=	*Rumen juice*
AD_H	=	*Anaerobic digester (or digestion process) operated (or conducted) during the dry season, between March and May, 2016*
AD_C	=	*Anaerobic digester (or digestion process) operated (or conducted) during the rainy season, between July and October, 2016*
PW	=	*Paper waste*
FW	=	*Food waste*

1. INTRODUCTION

Municipal solid waste includes all solid wastes generated from residential, commercial, industrial, institutional, construction and demolition centres among others. This waste includes both organic and inorganic fractions [1, 2,3,4,5,6]. Municipal Waste generation is an unavoidable product of human activities, however, sustainable management of such waste is a challenge faced in Nigeria due to increase in urbanization as a result of increasing population pressure, changes in consumer pattern, industrialization, lack of adequate plans and infrastructure required for efficient and sustainable management of municipal solid waste respectively [7,8]. Municipal solid waste generation in Nigeria is a serious issue due to its human health and environmental sustainability implications that has yet to be properly addressed [1,9,10,11]. It constitutes a major environmental problem not just because of its ever-growing volume but also because of the risk its improper handling and disposal poses to human health [12,13,14,15]. The inefficient management of waste by individuals, households, consumers and waste management companies may be attributed to inadequate information on waste management benefits, lack of producers' involvement in waste management as well as poor implementation of government policies and individual attitude [14,16,17].

Leachates from municipal solid waste may contain micro/macro elements (including heavy metals) such as magnesium (Mg), potassium (K), nitrogen (N), phosphorus (P), calcium (Ca), sulphur (S), lead (Pb), mercury (Hg), cadmium (Cd), uranium (Ur), iron (Fe), zinc (Zn), copper (Cu), chromium (Cr), manganese (Mn), molybdenum (Mo), nickel (Ni) and selenium (Se) in concentrations that may be deleterious to biota and human life [18,19]. They are not degraded, so there is a risk that they may accumulate to toxic levels in the environment if the waste is not properly disposed [20]. Low concentrations of certain heavy metals (as micronutrient) and relatively higher concentrations of macro elements are necessary for microbial activity during anaerobic digestion of organic matter [21, 20,22,23,24,25,26,27,28,18,29].

As such, anaerobic digestion of municipal solid waste (which involves several stages of microbial activities) may be used to reduce the concentration of these elements or compounds that carry them to acceptable limits before the waste can be disposed in the environment [28,30]. It is of great importance in the management of solid waste because it will considerably decrease the volume of waste that is being generated as well as inactivate biological and biochemical processes so as to avoid landfill-gas and odour emissions, reduce landfill settlements and produce bioenergy and bio-fertilizer in the form of biogas and digestate respectively [28,30,31].

However, the success of an anaerobic digestion process depends on several factors which have been shown to affect anaerobic digestion of organic matter [28]. Two major seasons namely dry and wet (or rainy) seasons are experienced in Nigeria and they are characterized by difference in environmental temperature which is one factor that can affect anaerobic digestion of organic matter [28,30]. The objective of this study was to determine the dynamics of macro/micro elements (including some heavy metals) during anaerobic digestion of organic fraction of municipal solid waste (OFMSW) under ambient condition in other to evaluate the effect of seasonal variation on the efficiency of the digestion process.

2. MATERIALS AND METHODS

2.1 Anaerobic Digestion Set-Up

One-stage 250 litre–capacity (pilot scale) anaerobic digesters (AD) were configured for batch-type mesophilic reactors with useful volumes of around 230 litres respectively using rumen juice as the source of microbial inoculum (Figure 1). The feed for anaerobic digestion was prepared inside the 250 L-capacity substrate tank (top left of figure one) before it was loaded into the anaerobic digester. The tap heads attached to the body of the 250 L-capacity anaerobic digester are sample collection points. Biogas flows out of the anaerobic digester through the gas outlet controlled by a gas-tight valve into the hose. The gas flows through the hose into the gas collection and measuring unit. In this gas collection unit, the 7 L-capacity tank sited under the one above contains water saturated with salt (NaCl) to prevent the gas from dissolving inside it. When biogas flows into it, the gas displaces an equal volume of the water which flows into to the upper tank through the hose that connects them at the side.

Because the tanks are graduated, the volume of water displaced was directly recorded and estimated to be approximately equal to the volume of biogas produced. Furthermore, biogas pressure was estimated using the formula in equation one (1). Where rho is the density of water, g is acceleration due to gravity and h is the height of water displaced inside the tank sited below the upper one (Figure 1). Since the volume of biogas was estimated directly, the height of water displaced was estimated using the formula in equation two (2) because the tanks have the shape of a cylinder; where r is the radius of the tank and π is a constant (3.142857). Biogas quality was estimated using the alkaline (NaOH)-water displacement methods described in [32] by applying the formula in equation three (3).

The first anaerobic digestion (AD_H) process was conducted in duplicate during the dry season, between March and May (2016). The second anaerobic digestion (AD_C) process was conducted in duplicate during the rainy season, between July and early October (2016). The feed inside the substrate tank was prepared to arrive at the desired substrate concentration (Table 1) using the formula in equation one (4). Anaerobic digestion of the feed was conducted inside the 250L-capacity bio-digesters under ambient [field] condition with a retention time of 84 days.

$$P=\rho gh \qquad \text{(Eq. 1)}$$

$$V=\pi r^2 h \qquad \text{(Eq. 2)}$$

$$\text{Biogas quality} = \frac{\text{Volume of alkaline (NaOH) displaced x 100}}{\text{Volume of water } (H_2O) \text{ displaced}} \qquad \text{(Eq. 3)}$$

$$\text{Solid content (\%)} = \frac{\text{Mass of dry OFMSW X 100}}{\text{Mass of dry OFMSW + mass of rumen juice + mass of } H_2O} \qquad \text{(Eq. 4)}$$

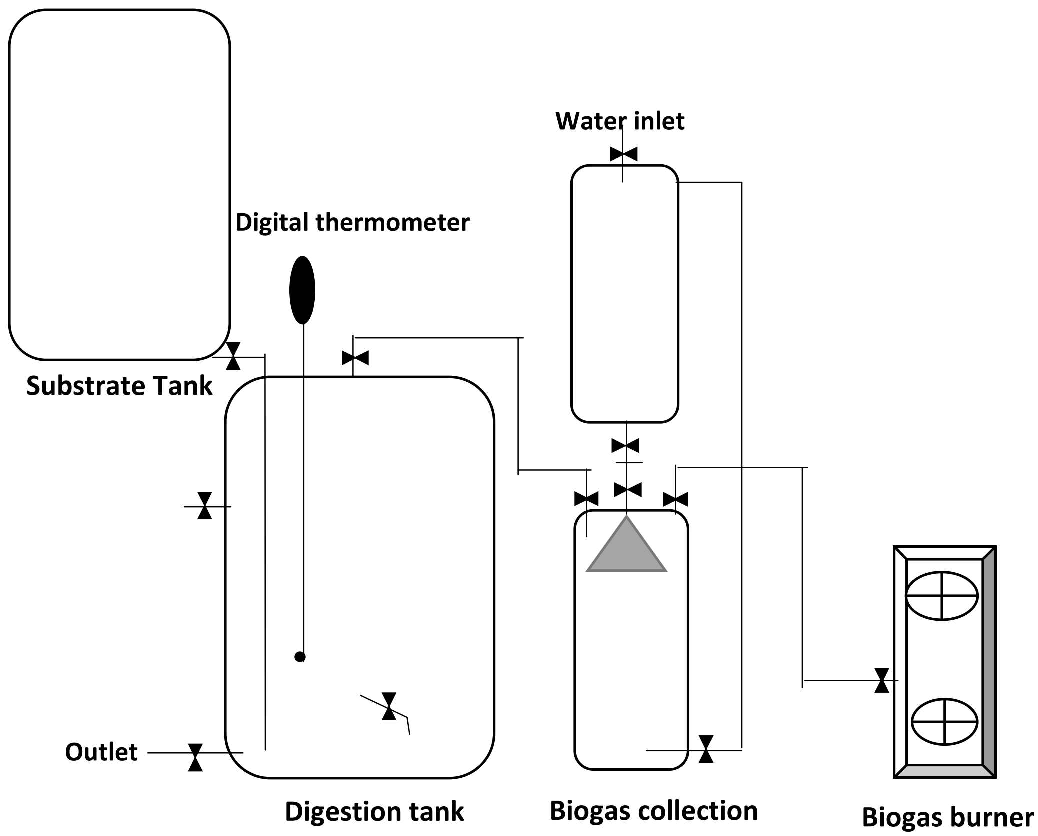

Figure 1. Design for the pilot – scale anaerobic digestion of organic fraction of municipal solid waste (OFMSW)

2.2 Preparation of Rumen Juice (RJ)

Cow's rumen juice was obtained and prepared as described by [33]. The filtered rumen juice was transferred into a 20 L-capacity gallon and supplemented with 200 g of glucose. This was done in order that the microbes trapped inside the juice would generate more energy from utilizing glucose as substrate to breakdown any complex organic polymer (such as cellulose) which may have been retained in the rumen juice after filtration. Following this, the rumen juice was injected with 18ml of $Na_2S.9H_2O$ (2% w/v) using a long needle attached to a 10 ml syringe and the gallon was screw capped with a specially designed cap which allowed us to evacuate biogas from the 20 L-capacity gallon with time. Addition of hydrated sodium sulphide was done to reduce the rumen juice in order to promote the growth of strict anaerobic bacteria trapped inside the juice [34]. Following this, the populations of aerobic and anaerobic bacteria were determined by cultural enumeration before and after subjecting the rumen juice to anaerobic digestion in the dark under ambient condition until biogas production was no longer observed (after a month).

2.3 Collection and Pre-treatment of Municipal Solid Waste

Paper waste was collected at source in Oba market, Benin City (Nigeria). After collection, the paper waste was shredded using paper shredder. The shredded paper waste was transferred into a pressure pot containing water and boiled for three hours. After boiling, the paper-water mixture was allowed to stand for two weeks. Thereafter, water was removed from the heat-treated paper by filtration (using a textile filter) and sun-drying. After drying, the paper was milled into powdered form and preserved in a nylon bag. This treatment procedure was applied in order to increase the biodegradability of the paper waste. Due to the high biodegradability of some municipal solid wastes such as food wastes we delayed their collection until we were ready to formulate the feed so as to prevent excessive loss of volatile solid if kept for long period. These fractions of municipal solid waste were collected at source from Oba market in Benin City Edo State (Nigeria) using waste collection bags. After collection, the wastes were pooled and milled together to produce a pasty homogeneous solid. Milling reduces particle size of the substrate, thus making it more bioavailable to the microbes [28].

2.4 Preparation and Characterization of the Substrate

The substrate was prepared by mixing the pre-treated powdered paper waste (PW) with the pasty solid derived from mechanically pre-treating the food waste (FW) in the ratio of 1:4 to form the wet solid substrate. After preparation, samples of the substrate were collected to determine some of its physical and chemical properties such as dry (or total) solids (DS), water content (WC), volatile solid (VS) and ash content (AC), total organic carbon (TOC), total nitrogen (TN), phosphorus (P) and potassium (K) contents using Standard Methods [35,36]. The population of culturable aerobic and anaerobic bacteria were also enumerated in order to determine their presence in the substrate.

2.5 Determination of Physicochemical Parameters

As part of the anaerobic digestion (AD) monitoring process, anaerobic digester slurry samples were collected at weekly interval (for 84 days) to determine important physicochemical parameters. Daily online bio-digester process temperature (PTM) was measured using digital thermometers with probes (SCT-lilliput, Scichem Tech) which extended into the anaerobic digesters. Daily ambient temperature (ATM) was also measured using digital thermometer (SCT-lilliput, Scichem Tech). Weekly process pH was determined using hand-held digital pH meter (SCT-lilliput, Scichem Tech) as described by [37]. Total sulphate (SO_4^{2-}) was determined by the Nephelometeric protocol described in Standard methods [35]. Magnesium (Mg) and calcium (Ca) were determined using the EDTA titrimetric protocol described in Standard methods [35]. Potassium (K) was determined using the flame emission photometric protocol described in Standard methods [35]. Total nitrate (NO_3^-), ammonia nitrogen (NH_4-N), total nitrogen (N), phosphorus (P), micro elements (such as Mn, Zn, Fe, Cu, Ni, Co) and other heavy metals (such Pb, Cd, Cr and Hg) were determined using the spectrophotometric protocols described in Standard methods [35].

3. RESULTS AND DISCUSSION

3.1 Physicochemical/Biological Properties of the Substrate (OFMSW)

Physicochemical/microbiological properties of the substrate (OFMSW) which was subjected to anaerobic digestion (AD_H) during the dry season (between March and May, 2016) and that which was subjected to anaerobic digestion (AD_C) during the rainy season (between July and October, 2016) are presented in Table 2.

Although, the result shows that the physicochemical/biological properties of these two substrates (pre-treated OFMSW) were slightly different, the differences observed between them may not have been significant as shown in Table 2. Furthermore, the slight differences that were observed between the substrates may have been due to seasonal variation [2]. The volatile solid content of both substrates (70.38% and 70.41%) shows that both of them were readily biodegradable [28]. This means that around 70.38% and 70.41% of the respective substrate was biodegradable at the time. In the rumen juice collected during the dry season for AD_H, the population of aerobic bacteria reduced from $3.6x10^3$ CFU/ml to $2.2x10^2$ CFU/ml, while the population of strict anaerobic bacteria increased from $3.3x10^5$ CFU/ml to $7.8x10^7$ CFU/ml after a month of subjecting the rumen juice to anaerobic digestion. In the rumen juice collected during the rainy season for AD_C, the population of aerobic bacteria reduced from $3.9x10^3$ CFU/ml to $1.6x10^2$ CFU/ml, while the population of strict anaerobic bacteria increased from $4.1x10^5$ CFU/ml to $9.2x10^7$ CFU/ml after a month. This is desirable because higher initial population of strict anaerobic bacteria is usually required for an efficient (or effective) start-up of the digestion process [28].

Nevertheless, the presence of aerobic (most likely facultative) bacteria inside the anaerobically treated rumen juice is also beneficial because any oxygen that may have been present inside the anaerobic digesters at the start of the pilot scale digestion process is expected to be consumed by them, thus promoting the proliferation of strict anaerobic bacteria with time [28]. Furthermore, since the rumen juice was subjected to anaerobic digestion for a month in the dark, the population of aerobic bacteria enumerated after the digestion period may in fact be facultative anaerobic bacteria rather than strict aerobes. This could have been the reason why they survived the anaerobic digestion process [28].

3.2 Dynamics of Biogas Production

The pressure and volume of cumulative biogas inside the anaerobic digester (AD_H) operated during the dry season (between March and May, 2016) increased to 16.542 mbar (Figure 2) and 34.80L (Figure 3) respectively after 84 days. The pressure and volume of cumulative biogas inside the anaerobic digester (AD_C) operated during the rainy season (between July and October, 2016) increased to 12.596 mbar (Figure 2) and 26.50 L (Figure 3) respectively after 84 days. Cumulative volume of CO_2 and CH_4-rich biogas inside the AD_H system increased to 7.38L (Figure 4) and 27.42 L (Figure 5) respectively after 84 days. Inside the AD_C system, cumulative volume of CO_2 and CH_4-rich biogas increased to 11.25 L (Figure 4) and 14.75L (Figure 5) respectively after 84 days. This suggests that the quality of cumulative biogas inside produced inside the AD_H and AD_C systems may have increased to around 78.79% and 55.66% respectively after 84 days.

The result above shows that the dynamics of biogas production observed inside AD_H and AD_C systems respectively resembled the batch growth dynamics that is usually observed in batch microbial culture [38]. This is because biogas production is the result of the microbial activities taking place inside the anaerobic digester ecosystems [39,40,41,28]. Moreover, this was expected because the anaerobic digestion processes were conducted in batch mode. Nevertheless, the result also showed that the quantity and quality of biogas produced inside the anaerobic digester (AD_H) operated during the dry season (between March and May, 2016) was significantly ($p < 0.05$) higher than that which was produced inside the anaerobic digester (AD_C) operated during the rainy season (between July and October, 2016). This may have resulted from the variation in weather condition between the periods when the anaerobic digestion processes were conducted. Environmental temperature (and consequently process temperature) appeared to have played a role in this as discussed in section 3.3.

3.3 Temperature Dynamics

During the dry season (between March and May, 2016) when the first anaerobic digestion (AD_H) of OFMSW was conducted, daily average ambient temperature (ATM) ranged from 30.3^{o}C to 33.6^{o}C after 84 days. However, during the rainy season (between July and October, 2016) when the second anaerobic digestion (AD_C) of OFMSW was conducted, daily average ambient temperature ranged from 26.3^{o}C to 30.5^{o}C after 84 days. Daily average process temperature (PTM) inside the anaerobic digester (AD_H) operated during the dry season ranged from 29.7^{o}C to 39.3^{o}C after 84 days. However, daily average process temperature (PTM) inside the anaerobic digester (AD_C) operated during the rainy season ranged from 26.8^{o}C to 30.8^{o}C after 84 days. The result suggests that daily average ambient temperature recorded during the dry season (between March and May, 2016) was relatively higher than the daily average ambient temperature observed during the rainy season (between July and October, 2016).

This correlated with a higher process temperature inside the anaerobic digester (AD_H) operated during the dry season compared to the anaerobic digester (AD_C) operated during the rainy season. This indicates that environmental temperature dynamics may have contributed to the process temperature dynamics inside the anaerobic digestion (AD_H and AD_C) systems to some degree with time [28]. Several authors have shown anaerobic digestion of organic matter to be more efficient at higher temperatures compared to otherwise [42,30,43, 44,45]. Because daily average process temperature was higher inside the AD_H system than inside the AD_C system, this may have resulted to a better performance of the anaerobic digester (AD_H) operated during the dry season compared to the anaerobic digester (AD_C) operated during the rainy when ambient temperature appeared to have reduced to between 26.3^{o}C and 30.5^{o}C.

3.4 Process pH Dynamics

Daily average process pH inside the anaerobic digester (AD_H) operated during the dry season ranged from 6.67 to 5.32 after 84 days. However, daily average process pH inside the anaerobic digester (AD_C) operated during the rainy season ranged from 6.40 to 4.60 after 84 days. The decrease in process pH observed inside both anaerobic digestion (AD_H and AD_C) systems with time may be attributed to the production of organic acids as a result of microbial activity [28]. However, it appears that accumulation of these organic acids may have occurred faster inside the anaerobic digester (AD_C) operated during the rainy season than the anaerobic digester (AD_H) operated during the dry season. This suggests that the AD_H system was less acidic than the AD_C system with time.

3.5 Dynamics of Macro/Micro Elements and Heavy Metals of Interest

Inside the anaerobic digester (AD_H) operated during the dry season, total sulphate (SO_4^{2-}) and total nitrate (NO_3^-) decreased from 92.64 mg/L to 2.33 mg/L and 132.22 mg/L to 3.11 mg/L respectively after 84 days (Figure 6 and Figure 7). Inside the anaerobic digester (AD_C) operated during the rainy season, total sulphate (SO_4^{2-}) and total nitrate (NO_3^-) decreased from 94.60 mg/L to 0.12 mg/L and 134.50 mg/L to 0.33 mg/L respectively after 84 days (Figure 6 and Figure 7). Inside the anaerobic digester (AD_H) operated during the dry season and the anaerobic digester (AD_C) operated during the rainy season, the concentration of ammonia nitrogen (NH_4-N) increased from 43.20 mg/L and 16.40 mg/L to 135.30 mg/L and 108.44 mg/L respectively after 84 days (Figure 8). Total nitrogen (TN) reduced from 195.01 mg/L and 199.50 mg/L to 193.70 mg/L and 143.23 mg/L respectively after 84 days (Figure 9). Carbon/nitrogen ration (C/N) reduced from 19.72 and 19.44 to 0.55 and 6.54 respectively (Figure 10). The concentration of phosphorus (P) reduced from 96.43 mg/L and 116.63 mg/L to 46.40 mg/L and 62.50 mg/L respectively after 84 days (Figure 11).

The concentration of potassium (K), Magnesium (Mg), calcium (Ca), Manganese (Mn), zinc (Zn) and copper (Cu) inside the anaerobic digester (AD_H) operated during the dry season and the one (AD_C) operated during the rainy season reduced from 84.01 mg/L and 81.51 mg/L to 11.42 mg/L and 18.90 mg/L (Figure 12), 47.20 mg/L and 46.40 mg/l to 2.40 mg/L and 20.43 mg/L (Figure 13), 54.11 mg/L and 59.30 mg/L to 9.50 mg/L and 15.70 mg/L (Figure 14), 6.20 mg/L and 6.26 mg/L to 1.10 mg/L and 3.20 mg/L (Figure 15), 21.40 mg/L and 21.44 mg/L to 10.40 mg/L and 12.50 mg/L (Figure 16) and 9.53 mg/L and 15.40 mg/L to 1.21 mg/L and 3.10 mg/L (Figure 17) respectively after 84 days.

Likewise, the concentration of nickel (Ni), lead (Pb), cobalt (Co), iron (Fe), molybdenum (Mo), cadmium (Cd) chromium (Cr) and mercury (Hg) inside the anaerobic digesters (AD_H and AD_C) operated during the dry season and rainy season (2016) reduced from 6.80 mg/L and 6.62 mg/L to 1.52 mg/L and 0.93 mg/L (Figure 18), 3.80 mg/L and 4.17 mg/L to 0.42 mg/L and 1.20 mg/L (Figure 19), 2.14 mg/L and 2.21 mg/L to 0.63 mg/L and 0.64 mg/L (Figure 20), 21.40 mg/L and 23.70 mg/L to 1.25 mg/L and 5.70 mg/L (Figure 21), 2.34 mg/L and 1.84 mg/L to 0.91 mg/L and 0.18 mg/L (Figure 22), 2.91 mg/L and 2.64 mg/L to 0.05 mg/L and 1.10 mg/L (Figure 23), 1.84 mg/L and 1.81 mg/L to 0.06 mg/L and 0.08 mg/L (Figure 24) and 0.58 mg/L and 0.57 mg/L to 0.02 mg/L and 0.08 mg/L (Figure 25) respectively after 84 days of the anaerobic digestion process.

The result shows that concentration of micro/macro elements and heavy metals decreased during anaerobic digestion of OFMSW inside the anaerobic digesters (AD_H and AD_C) operated during the dry and rainy season respectively in 2016. However, ammonia nitrogen appears to have increased with time inside both bio-digesters (Figure 8). The decrease in concentration of these elements/compounds may be attributed to the activities of the microbial communities taking part in the anaerobic digestion process inside the bio-digesters (AD_H and AD_C). This is because microbes need most of these elements/ compounds (especially the macro/micro elements) for their physiological well-being as well as biomass production [20,28]. This would have made them to consume the elements or compounds that carry the element (or nutrient) of interest thereby decreasing the concentration of that element (or compounds carrying the element) with time. For example, the decrease in the concentration of sulphate and nitrate inside both anaerobic digesters (AD_H and AD_C) may have been due to the activities of sulphate reducing bacteria (SRB) and nitrate reducing bacteria (NRB) respectively because these groups of bacteria have been known to consume sulphate and nitrate in anaerobic environments, converting them to sulphide and compounds of nitrogen (such as nitrite, nitrous oxide, nitric oxide, ammonia nitrogen (NH_4-N)) or nitrogen respectively [46,47,48,28]. Furthermore, the decrease in the concentration of heavy metals such as chromium, cadmium and mercury inside the anaerobic digesters (AD_H and AD_C) over time may be attributed to bioaccumulation as well as bio-assimilation by the digester microbes [20].

Table 1. Composition of the Feed for anaerobic digestion

System	Substrate	PW:FW	DS(Kg)	WC(Kg)	*WS(Kg)	*RJ(L)	*WA(L)	Total(L)	%TS
AD_H	OFMSW	1:4	12.69	3.21	15.90	6.36	207.74	230.00	~5.53
AD_C	OFMSW	1:4	12.74	3.16	15.90	6.36	207.74	230.00	~5.53

*PW = Paper waste, FW = Food waste, DS = Dry solid, WC = Water content, WS = Wet solid, RJ = Rumen juice, WA = Water, AD_H = Anaerobic digester operated during the warmer period (between March and May, 2016), AD_C = Anaerobic digester operated during the rainy season (between July and October, 2016), * = Feed components, OFMSW = Organic fraction of municipal solid waste*.

Table 2. Physico-chemical properties of the substrate (MSW)

Parameters	Concentration (AD_H)	Concentration (AD_C)	Rumen juice before & after preservation (AD_H)	Rumen juice before & after preservation (AD_C)
Dry solid (%)	79.81	80.12	ND	ND
Water content (%)	20.19	19.87	ND	ND
Ash content (%)	29.62	29.59	ND	ND
Volatile solid (%)	70.38	70.41	ND	ND
Total organic carbon (g/L)	884.58	891.94	ND	ND
Total nitrogen (g/L)	41.85	42.77	ND	ND
C/N Ratio	21.14	20.85	ND	ND
Phosphorus (g/L)	20.98	26.68	ND	ND
Potassium (g/L)	17.32	18.63	ND	ND
Aerobic Bacteria (CFU/ml)	4.8×10^5	5.2×10^5	3.6×10^3 & 2.2×10^2	3.9×10^3 & 1.6×10^2
Strict anaerobic Bacteria (CFU/ml)	5.4×10^4	4.6×10^4	3.3×10^5 & 7.8×10^7	4.1×10^5 & 9.2×10^7

ND = Not determined

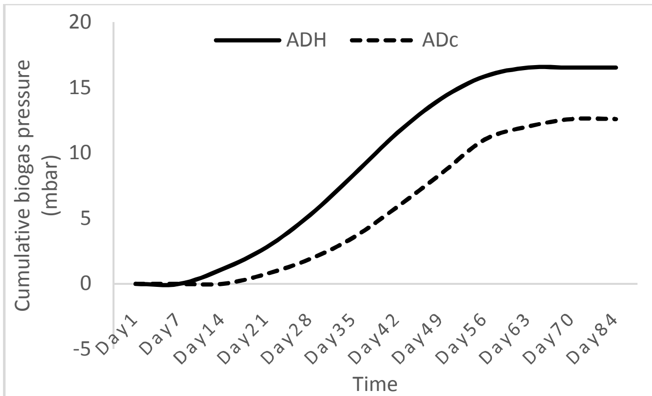

Figure 2. Pressure of cumulative biogas produced

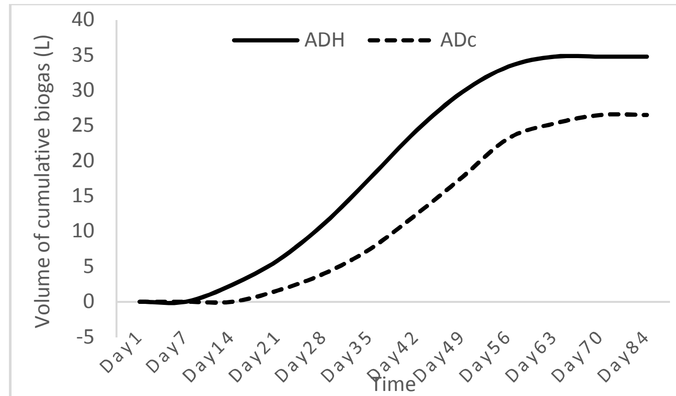

Figure 3. Volume of cumulative biogas produced

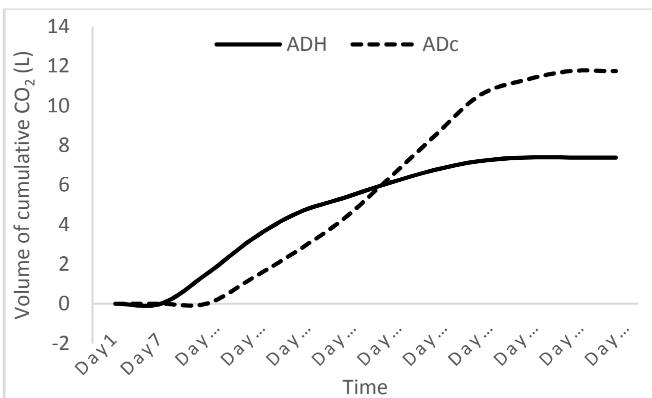

Figure 4. Volume of cumulative CO2 produced

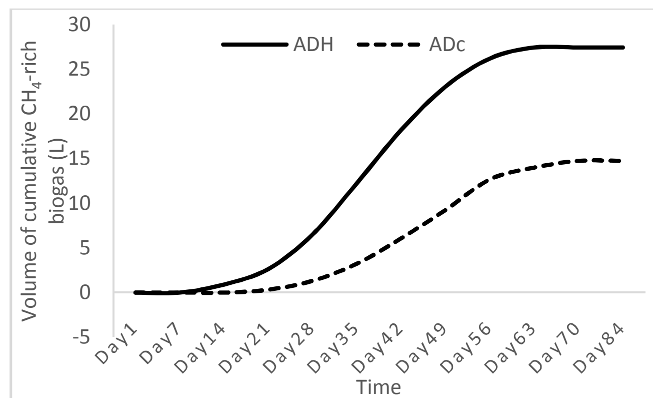

Figure 5. Volume of cumulative CH4-rich biogas produced

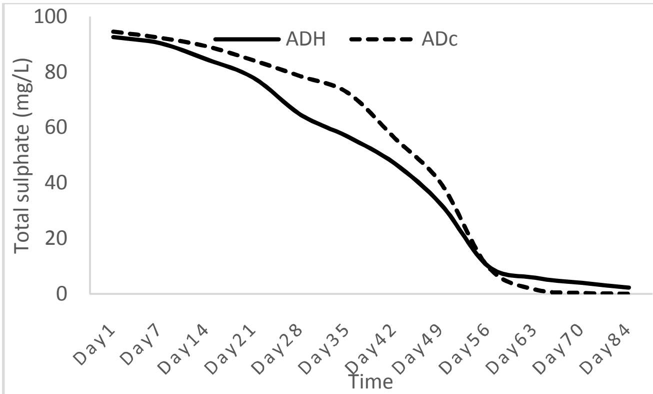

Figure 6. Concentration of sulphate (SO42-)

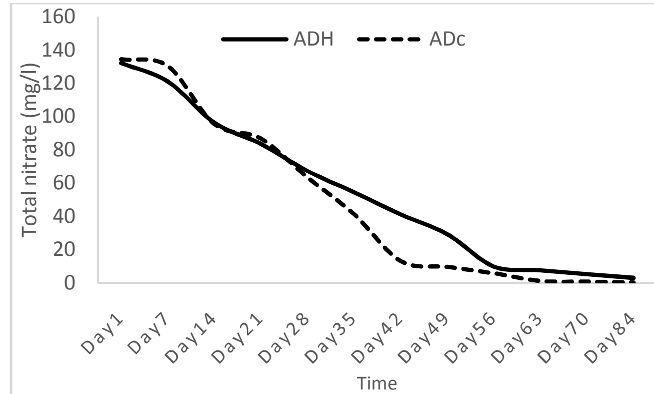

Figure 7. Concentration of nitrate (NO_3^-)

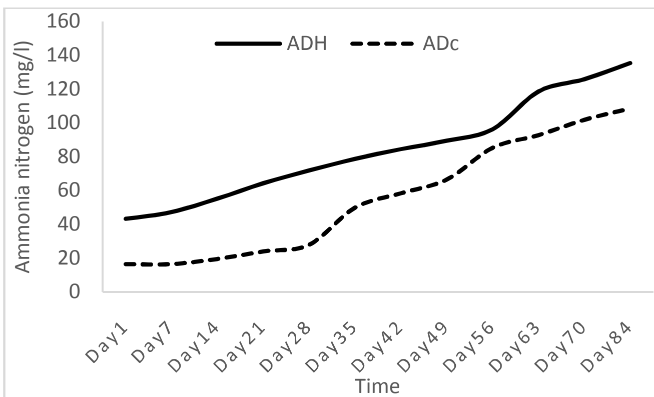

Figure 8. Concentration of ammonia-nitrogen (AN)

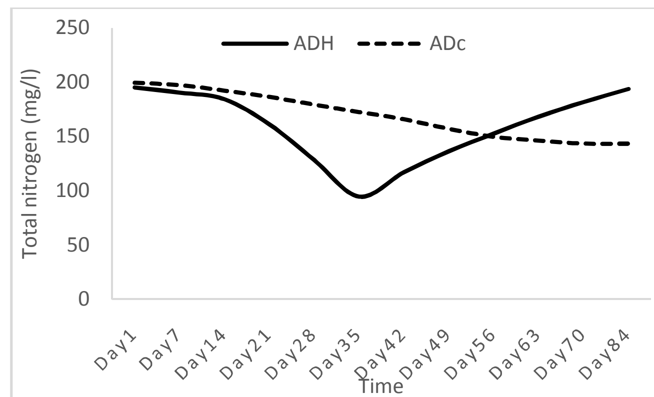

Figure 9. Concentration of total nitrogen (TN)

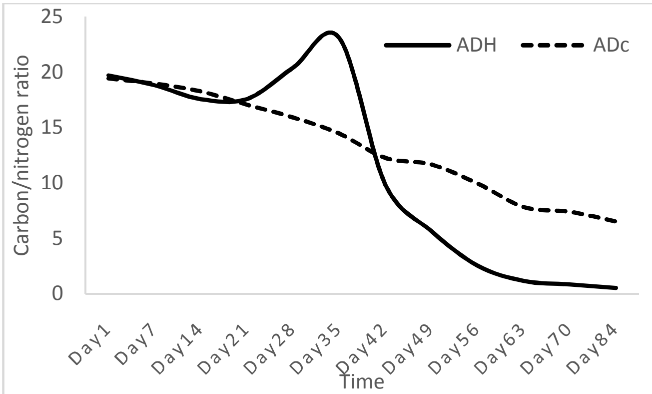

Figure 10. Dynamics carbon/nitrogen (C/N) ratio

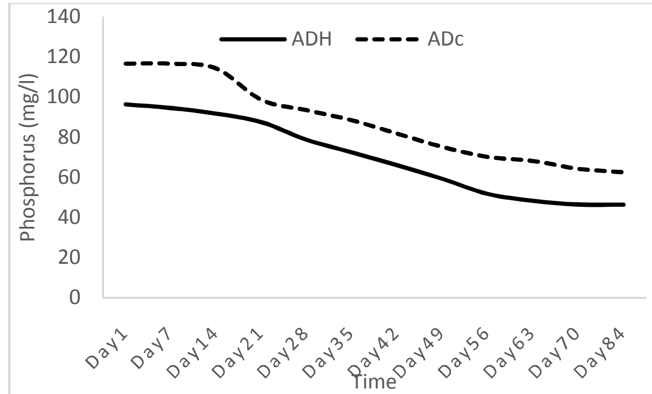

Figure 11. Concentration of phosphorus (P)

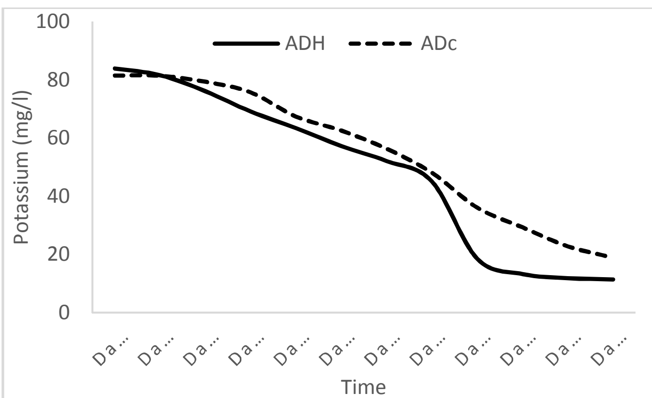

Figure 12. Concentration of potassium (K)

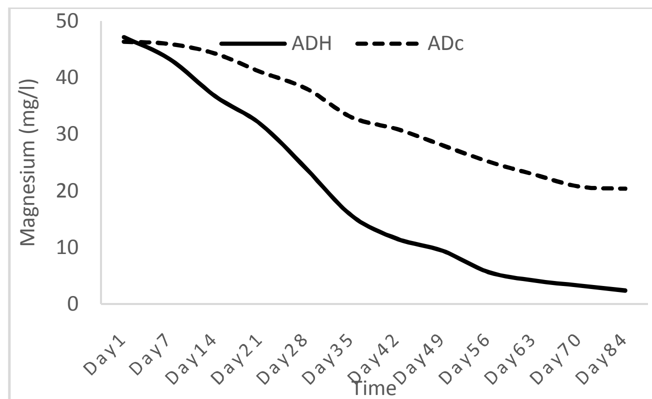

Figure 13. Concentration of magnesium (Mg)

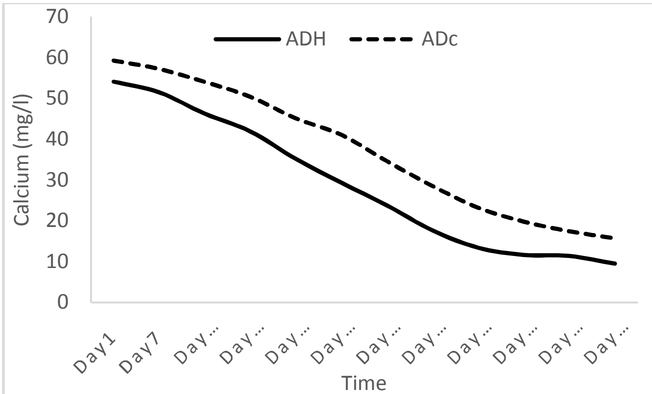

Figure 14. Concentration of calcium (Ca)

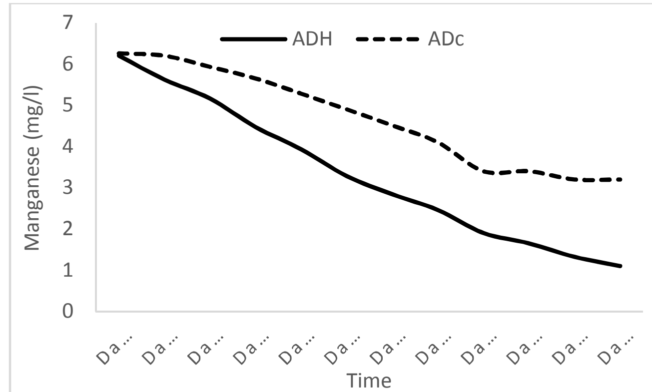

Figure 15. Concentration of manganese (Mn)

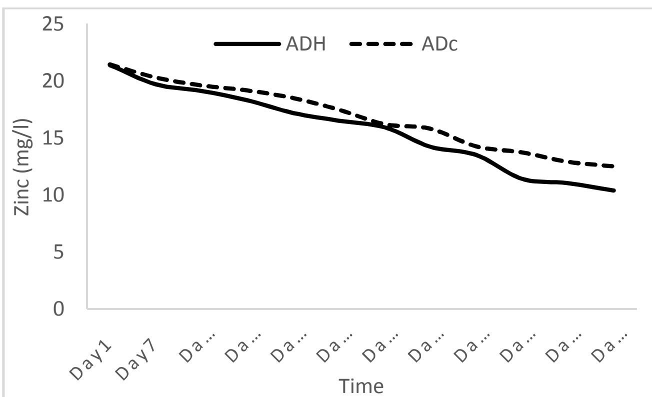

Figure 16. Concentration of zinc (Zn)

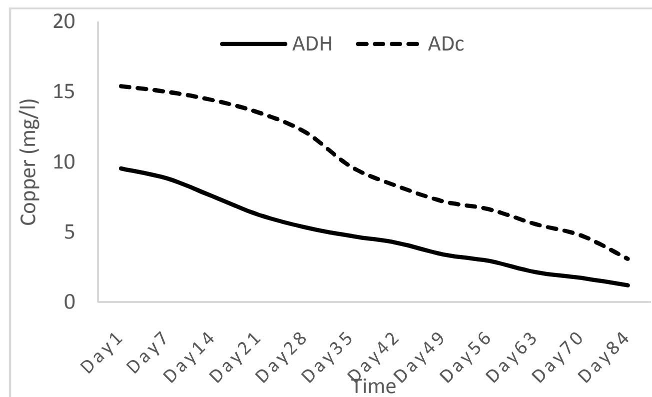

Figure 17. Concentration of copper (Cu)

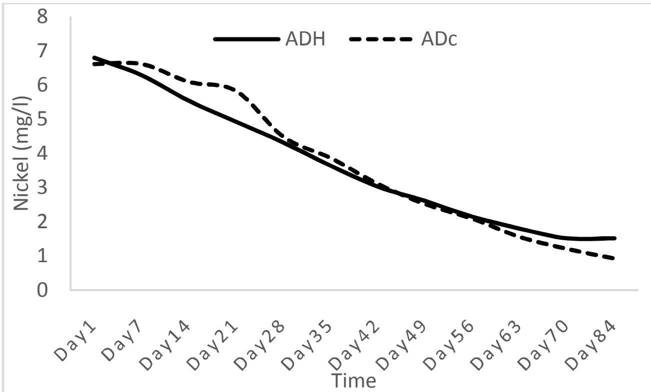

Figure 18. Concentration of nickel (Ni)

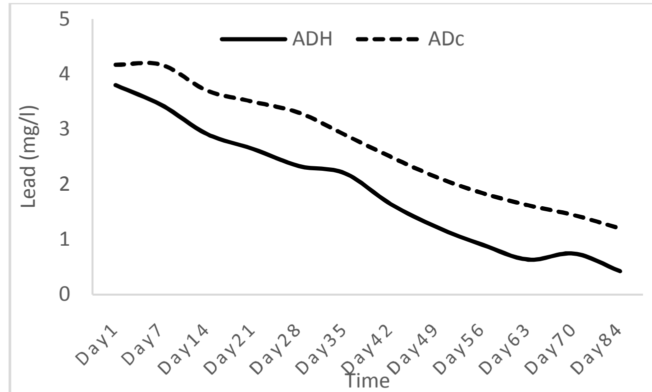

Figure 19. Concentration of lead (Pb)

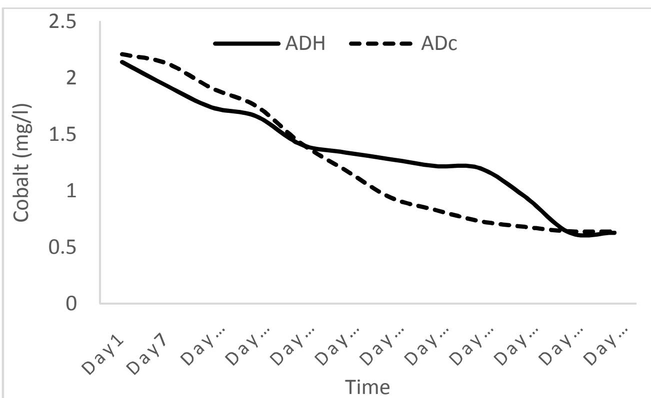

Figure 20. Concentration of cobalt (Co)

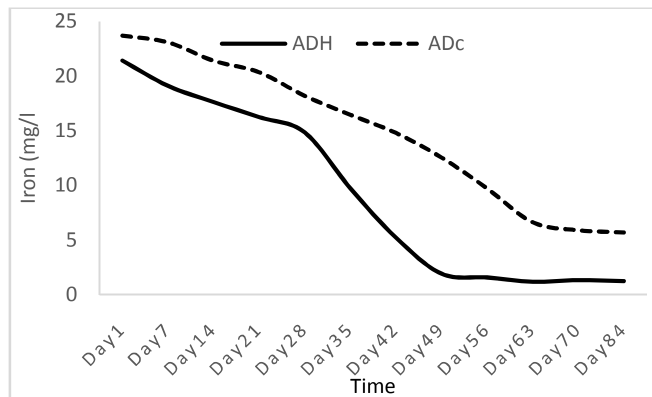

Figure 21. Concentration of iron (Fe)

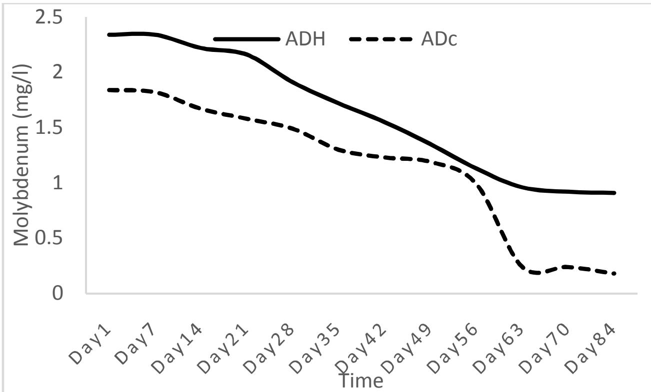

Figure 22. Concentration of molybdenum (Mo)

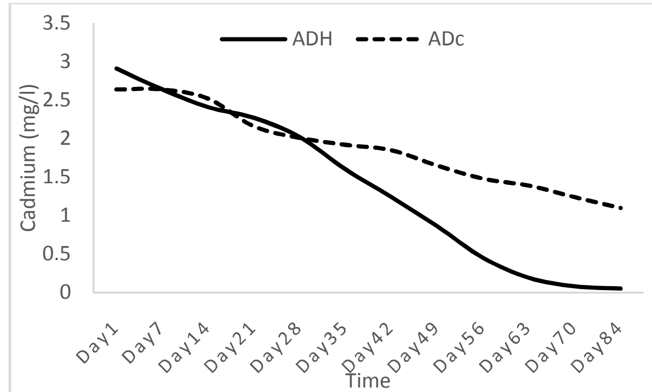

Figure 23. Concentration of cadmium (Cd)

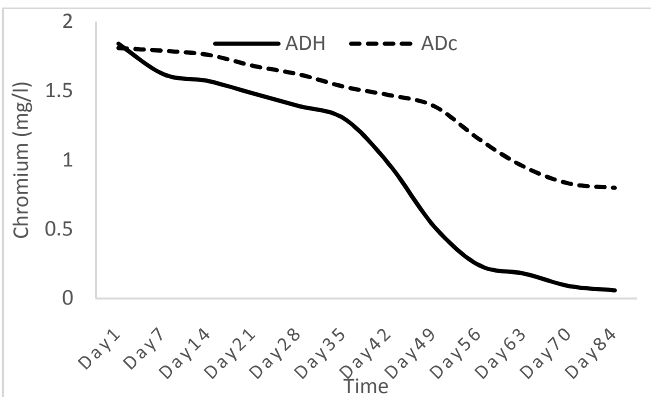

Figure 24. Concentration of chromium (Cr)

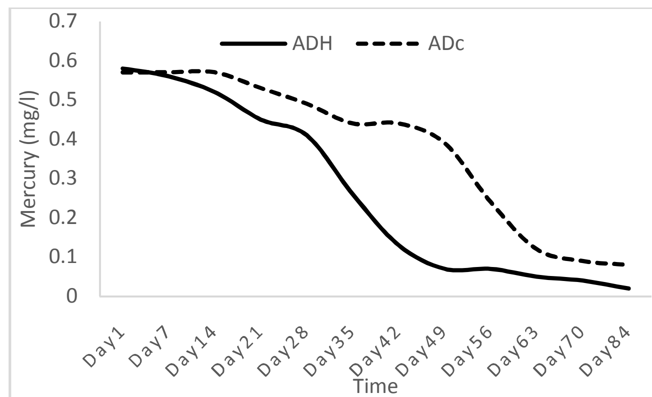

Figure 25. Concentration of mercury (Hg)

4. CONCLUSION

Since the concentration of the heavy metals decreased during anaerobic digestion of OFMSW inside AD_H and AD_C, it may be possible to assume that anaerobic digestion could be used to treat organic wastes which contain certain amount of heavy metals to some degree before they can be disposed into the environment. Although, the concentration of most of the macro and micro elements (including the heavy metals) decreased inside both anaerobic digestion (AD_H and AD_C) systems with time, it appears that the anaerobic digestion (AD_H) system operated during the dry season (between March and May, 2016) performed better than the anaerobic digestion (AD_C) system operated during the rainy season (between July and October, 2016) with time as indicated by the Figures above.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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