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Evaluation of the Digestibility of Attached and Suspended Growth Sludge in an Aerobic Digester for a Small Community

Shohreh Azizi *, Ilunga Kamika and Memory Tekere

Department of Environmental Sciences, School of Agriculture and Environmental Sciences, University of South Africa, P.O. Box 392, Florida 1710, South Africa; kamiki@unisa.ac.za (I.K.); tekerm@unisa.ac.za (M.T.)

* Correspondence: azizis@unisa.ac.za or shohrehazizi1379@gmail.com; Tel.: +27-116-709-777

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Abstract: The aerobic sludge digestion process for waste sludge generated from suspended biomass (i.e., activated sludge process, ASP) and attached biomass (i.e., moving bed bioreactor, MBBR and modified packed bed biofilm, PBBR) reactors in a residential complex were analyzed. The rate of digestion with respect to different sludge characteristics generated through these various treatment processes were examined; the results revealed that waste sludge from ASP took 16 days to achieve complete digestion while MBBR and PBBR took nine and seven days, respectively. The most important factors influencing the sludge digestion such as sludge volume index (SVI), mixed liquor suspended solid (MLSS), and mixed liquor volatile suspended solid (MLVSS) were examined. The ASP which had the highest initial MLSS and MLVS took a longer time for digestion. Aerobic sludge digestion in all the treatment reactors was studied under laboratory scale conditions in batch experimentation to evaluate sludge characteristics and the rate of digestion as well as through a continuous bench scale pilot system to optimize the process parameters. Removal efficiencies of volatile solids (VS) 90.71% in ASP, 84.27% in MBBR and 84.07% in PBBR in aerobic digestion during batch mode were also observed. The study revealed that the aerobic sludge digestion process utilized in curbing sludge is not feasible application for a small community due to very long digestion times and a large amount of space although Packed Bed Biofilm (PBBR) used the lowest time (seven days) compared to the other systems.

Keywords: aerobic digestion; waste sludge; small community; activated sludge process; moving bed bioreactor; packed bed biofilm

1. Introduction

Aerobic biological treatment technologies are effectively employed for domestic wastewater treatment and offer an on-site effective solution in areas with low population densities, especially in small communities such residential complexes [1,2]. In biological treatment processes, as sludge builds up, it is regularly removed from treatment operations in all the treatment processes [1] and the aerobic stabilization is mainly influenced by the sludge retention time (SRT) factor. When the SRT is over 20 to 30 days, sludge stabilization may be almost complete in the aeration tank; whereas in plants requiring an SRT of less than 10 days, further sludge treatment would be essential [3–6]. This removal step is necessary for maintaining the food/microbe ratio in an activated sludge process to improve its ability to settle and to prevent the bulking of sludge or other related problems [7].

In wastewater treatment plants, waste sludge varies in its properties depending on its origin and previous treatment; however, their characterization can potentially give qualitative information [8,9]. Sludge contains highly-polluting substances, including pathogens (e.g., viruses, bacteria, protozoa, eggs of parasitic worms) and undigested organic substances [10].

The major issue associated with any aerobic biological process is the production of large amounts of waste requiring disposal [11,12]. The disposal of a large amount of waste sludge is crucial and creates a serious concern in environmental pollution [13,14]. The waste sludge requires further treatment because it is normally undigested (i.e., in the case of the activated sludge process and semi-digested in the case of attached growth process). The undigested or semi-digested sludge can potentially cause land disposal problems and the leachates can contaminate the ground water if disposed in the same vicinity of a residential complex [15]. The most common methods of sludge stabilization are aerobic and anaerobic digestion to degrade complex substrates in waste sludge by microbial action [16–18] resulting in the reduction of the volatile solids content [3].

The selection of a sludge digestion process depends on the costs of the process and the size of the wastewater treatment plant. Aerobic digestion is popular for smaller treatment facilities due to its low investment cost, simpler operation and ease of management and control [17,19,20]. Aerobic digestion is the biochemical oxidative stabilization of waste sludge under endogenous conditions; when there is insufficient external substrate available, heterotrophic microorganisms are added to begin to digest their own cellular mass [3,21]. The aerobic digester works on a similar principle as the activated sludge process [21].

Aerobic digestion can possibly offer a suitable biodegradable environment for different volatile solid fractions when compared with anaerobic digestion; therefore, the system is more effective in reducing toxic compounds in waste sludge [13,19]. However, the major drawback of aerobic digestion is that it requires a huge input of power to supply oxygen, even for small plants [22].

The most important features of effective digestion are the amount of solid mass reduction and the improvement of the sludge quality, both in terms of toxic substances, pathogens and viruses [17,19].

This study presents the results of an investigation, applicable for both batch and continuous systems, of an aerobic sludge digestion process for the waste sludge generated from three various treatment systems based on two basic concepts of aerobic treatment processes: the suspended growth process (i.e., ASP) and the attached growth process (i.e., MBBR and PBBR) for small communities, specifically in residential complexes.

2. Materials and Methods

The waste sludge was collected daily from the three biological systems—an activated sludge process (ASP), a moving bed bioreactor (MBBR) and a packed bed biofilm (PBBR)—used to treat wastewater from a residential complex. The waste sludge from the biological systems was transferred to an aerobic digestion reactor. The samples were taken from the inlet and outlet of the aerobic digestion reactors and were analyzed to test chemical oxygen demand (COD); the open reflux method was performed using a COD digestion apparatus model 2015 from spectra lab.

Biological oxygen demand (BOD) was determined by a five-day test and the principle of the method involves measuring the difference in the oxygen concentration between the sample and after incubating it for five days at 20 °C.

Dissolved oxygen (DO) was also determined by azide modification of the wrinkle method.

Suspended solids (SS) was considered to be an important factor when assessing the operational performance of microfiltration processes in wastewater treatment; suspended solids is determined by a known-volume sample filtered through a weighted standard glass fibre filter (whatman 934-AH Buckinghamshire, United Kingdom) and the residue on the filter is dried to a constant weight at 103 to 105 °C in an oven, and the increasing in the weight of the filter is considered to be the suspended solids.

Volatile suspended solids (VSS) are determined by taking a total suspended solids sample and igniting this at 550 °C in muffle furnace for 30 min; the weight lost on the heating of the solids represents the volatile solids.

Ammonia nitrogen (NH_3-N) is carried out by the semi-micro-Kjeldahl distillation method and then titrated with Hydrogen Chloride Acid (HCl).

Phosphate (PO_4-P) is determined by the stannous chloride method and 50 mL of filtered clear sample was taken in a conical flask. To the sample, 2 mL ammonium molybdate and five drops of stannous chloride solution were added. A blue color appeared and a reading was taken on a Ultraviolet Visible light spectrophotometer (Model U-2000, Hitachi, Tokyo, Japan) at 690 nm and the standard curve phosphate values were calculated.

The sludge volume index (SVI) was also determined by placing a mixed liquor sample in a one litre cylinder and measuring the settled volume after 30 min [23]. The reported analytical values are the mean of five replicates. The particle size analysis was carried out by laser diffraction methods using the Malvern Mastersizer 2000® U.K. [23–25]. The reported analytical values are the mean of five replicates.

2.1. Batch Mode Sludge Digestion

A laboratory-scale batch experiment was conducted to investigate the digestion of sludge from various aerobic treatment systems (e.g., ASP, MBBR, and PBBR) under aerobic digestion. Two liters (2 L) of waste sludge were collected from different aerobic treatment systems and aerated continuously without any addition of nutrients or organic supplementation. The air supply was regulated and aeration was sufficient to maintain the sludge in suspension.

2.2. Continuous Mode Sludge Digestion

The waste sludge generated from three wastewater treatment systems was investigated for sludge digestion in an aerobic continuous mode reactor system, see Figure 1. The aerobic digester was fed with an optimum volume of waste sludge as determined through batch experimentation taken from the ASP, MBBR and PBBR systems. A rectangular-shaped aerobic digester was used and had a mixing device located on its top, see Figure 1. The total volume of the reactor was 12 L with a working volume of 7.2 L. The reactor inlet was on the bottom, with the outlet at located on the top of the reactor. The maximum flow rate of the air into the reactor was kept at 80 L/h. The results of the studies carried out in this continuous mode aerobic digester were used to assess the feasibility of such a system for small residential communities.

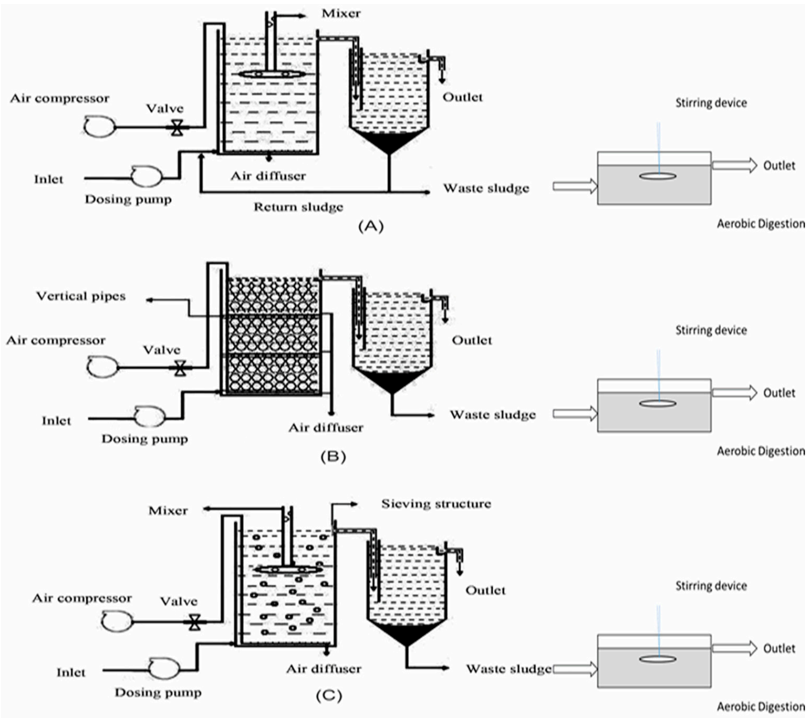


Figure 1. The schematic appearance of biological treatment process in the presence of an aerobic digester (**A**) ASP: Activated Sludge Process, (**B**) PBBR: Packed Bed Biofilm, (**C**) MBBR: Moving Bed Bioreactor.

3. Results

3.1. Comparative Analysis and Characterization of Sludge Generated from ASP, MBBR and PBBR

The comparative analysis of aerobic processes was done in accordance with a method previously reported [25]. Table 1 depicts the sludge characteristics of ASP, MBBR, and PBBR. The comparison indicates that the attached growth processes are most appropriate for small residential complexes, as they would create a small foot print due to the lower hydraulic retention time (HRT). The PBBR system is most suitable, as it had the lowest HRT and the least amount of sludge waste [25], still, the associated sludge disposal issues need to be tackled [20].

Table 1. A comparative analysis of the performance and the characteristics of the sludge from the three biological treatment processes [25].

Parameters	ASP	MBBR	PBBR
Optimum Hydraulic retention time (HRT)	6	3	2
COD reduction (%)	84.54	85.37	87.04
BOD reduction (%)	90.05	91.12	92.21
TSS reduction (%)	76.78	80.03	82.08
NH3–N reduction (%)	73.83	77.50	79.03
PO4-P reduction (%)	35.64	40.28	43.31
Total coliform reduction (%)	94.25	93.27	95.44
Characteristics of Waste Sludge from Three Treatment Systems			
Parameters	**ASP**	**MBBR**	**PBBR**
MLSS	5080 ± 286	3240 ± 216	2568 ± 128
MLVSS	3556 ± 234	1450 ± 112	1130 ± 82
SVI	138 ± 18	76 ± 14	62 ± 10
Particle size (μm)	40–550	25–130	10–50

3.2. Sludge Digestion in Batch Mode Experiments

MLSS, MLVSS, SVI, COD, and DO Profiles in Batch Experiments

The waste sludge collected from different treatment systems such as ASP, MBBR, and PBBR were analysed under batch aerobic digestion for the evaluation of their sludge characteristics and rate of digestion. The reduction in the MLSS and MLVSS concentrations were studied at various time intervals. The obtained results showed that the waste sludge from ASP took 16 days of digestion, while the MBBR and PBBR systems took nine days and seven days, respectively (Figure 2A,B). The reduction in solids increased with the digestion time (Figure 2A) For the first 24 h, increases for the MLSS were associated with the microorganisms' access to the remaining organic substances from the wastewater treatment system, after which there was a decline [25,26]. The rapid decrease in MLSS after 24 h was possibly due to the solubilized organic matter being consumed by micro-organisms for their growth [24,27]. Finally, the MLSS observed showed 87.40%, 88.15% and 88.31% decreases in their primary sludge value from the ASP, MBBR, and PBBR, respectively. The rate of digestion depended on the total sludge concentration and particle size, therefore, the high efficiency of aerobic digestion was determined at high concentrations of small particle size solids in the biological wastewater process [28,29].

The MLVSS of the sludge from an activated sludge process before aerobic digestion was 70% of the MLSS, indicating highly-undigested sludge, which leads to longer degradation times. Figure 2E shows that in an activated sludge system, sludge volume index (SVI) decreased from 138 to 28 mL/g after 16 days of processing, indicating a considerable floc size reduction. This phenomenon indicates that partial breakup of the floc had taken place. When sludge digestion occurred in the MBBR and PBBR, the SVI dropped from 76 to 15 mL/g and 62 to 16 mL/g, respectively, with biological stabilization of the sludge caused by the reduction of floc size. Therefore, the decrease of the floc structure in aerobic digestion was due to changes in environmental conditions caused by changes in the bacterial growth rate and their adaption to starvation conditions [30]. This is mainly due to the fact that small size solids provide more sites for cavitation [31] and exposes more particles to the resulting shear force [32,33]. Table 1 indicates that particle size is inversely proportional to the maximum substrate utilization rate of the microorganism [18]. A biological stabilization period did not occur simultaneously at the time when physical parameters of sludge were optimum for further treatment performance [33]. On the other hand, the long digestion time caused rapid growth of the finest sludge fractions, which seriously hindered the filtration and dewatering of the sludge.

The COD profile of the three systems in Figure 2C shows that the sludge decomposition resulted in an increase in the organic fraction in the initial period and that this was due to the insufficiency of the microorganisms required to degrade the high amount of soluble organic compounds [34].

The organic fraction was measured by analysing the COD. The rate of COD removal was lower in the ASP compared to the other two reactors. The lower COD removal rate in the sludge generated from the ASP was due to the higher organic fraction of ASP sludge than MBBR and PBBR sludge. In all the tests, COD fluctuation was observed, which indicates sorption and desorption of secondary metabolic products diffuse out from the dead cells [25]. To maintain a positive level of DO throughout the digestion period, a continuous supply of aeration was provided. Positive DO prevents any anaerobic conditions and proliferation of odors caused by sulfate-reducing bacteria and other pathogens which can prosper in oxygen-deprived conditions [35,36]. The DO levels in low suspended solid conditions were high throughout the digestion time. Figure 2D shows that at the end of the digestion period in the ASP, the DO level reached 2.5 mg/L, whereas the DO levels were 2.7 mg/L and 3.2 mg/L after nine days in MBBR and PBBR, respectively. The DO level increase from the approximate initial 1.0 mg/L level indicates that the sludge digestion and organic degradation had reached its maximum levels.

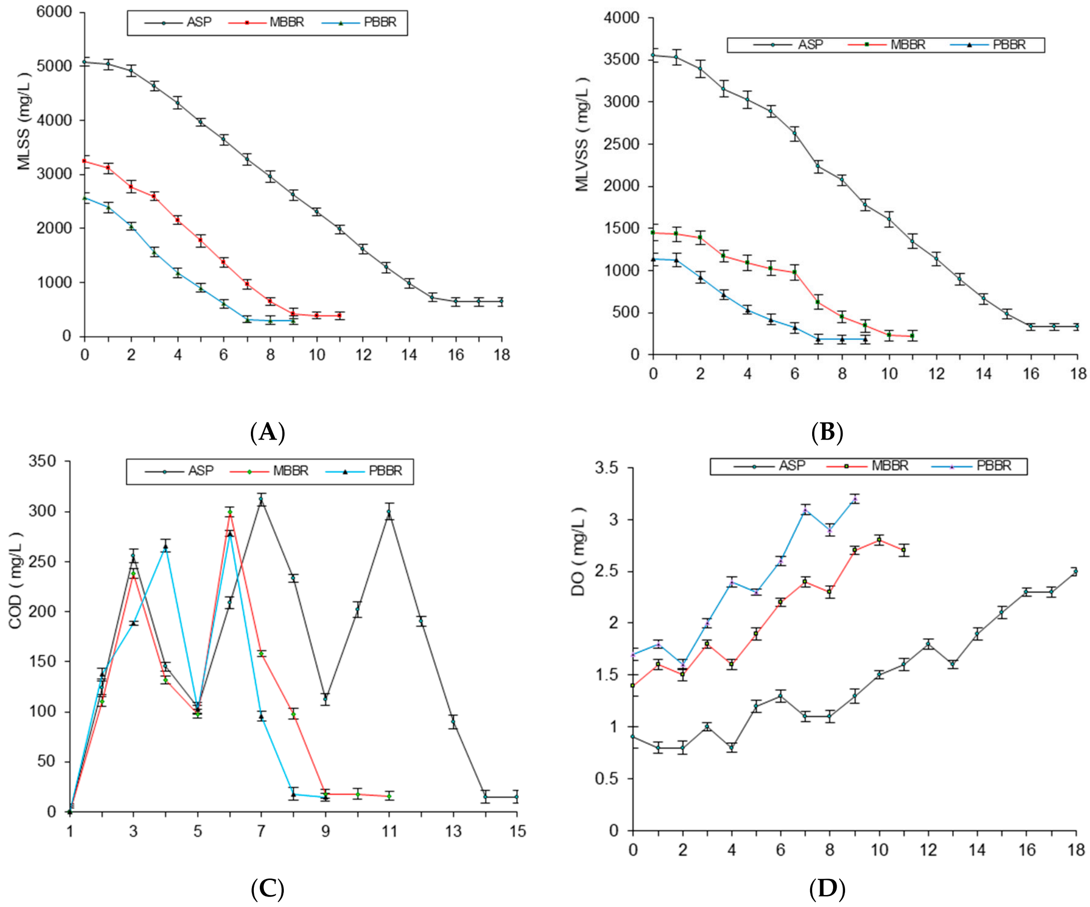
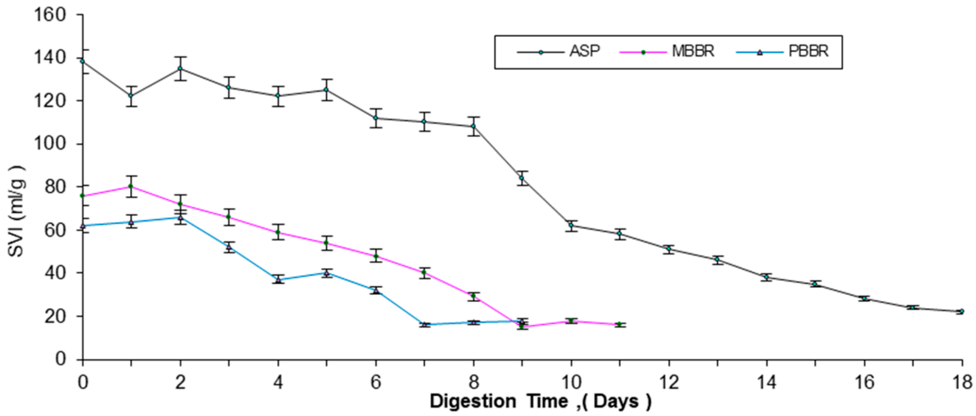


Figure 2. *Cont.*



(**E**)

Figure 2. Variation in * MLSS (**A**), MLVSS (**B**), COD (**C**), and DO (**D**) SVI (**E**) during batch aerobic digestion. * legend MLSS: Mixed Liquor Suspended Solid; MLVSS: Mixed Liquor Suspended Solid; COD: Chemical Oxygen Demand; DO: Dissolved Solid; SVI: Sludge Volume Index.

3.3. Sludge Digestion in Continuous Mode Experiments

During the experimentation period, all process parameters were maintained as per the data generated from batch experiments, including the sludge digestion time and the amount of air supplied (Table 2). The waste sludge produced in all three systems was evaluated on the basis of the MLSS, MLVSS, DO and SVI.

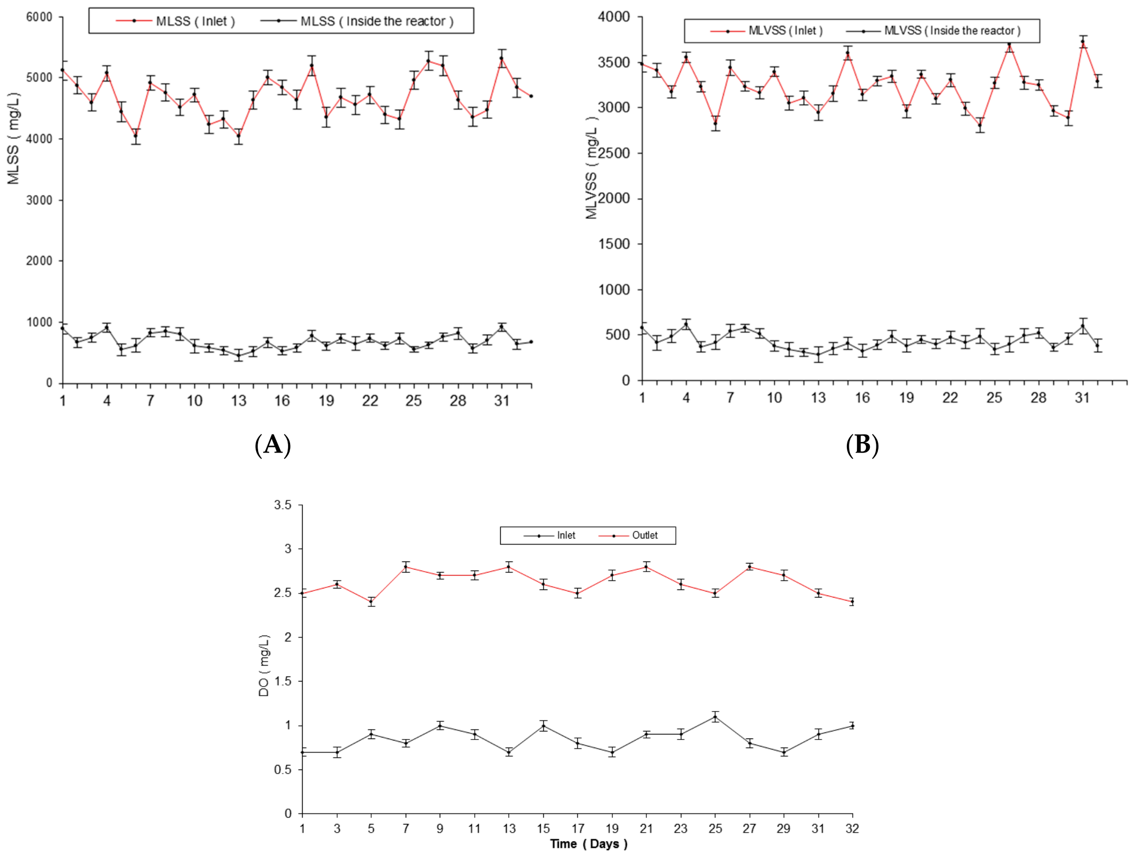
Table 2. Optimum process conditions for a continuous mode sludge digestion system.

Different Parameters	ASP	MBBR	PBBR
Sludge digestion time, days	16	9	7
Air supplied, l/h	80	80	80

3.3.1. Aerobic Digestion in Continuous Mode for Sludge Generated from Activated Sludge Process

To study the aerobic digestion pattern in a continuous system of sludge generated from ASP, a series of experiments was carried out over a period of 33 days. Limited studies are available on aerobic digestion in continuous mode for sludge generated from an activated sludge process and the attached biomass reactors, no data could be found to either corroborate or disprove our findings.

The waste sludge from the activated sludge process contained a high concentration of organic mass in the sludge (68.93% of VSS). On a continuous basis, the sludge at the inlet was 4691.25 $\pm$ 340.18 mg/L of MLSS. During the digestion time, the MLSS concentration inside the reactor was 682.56 $\pm$ 121.90 mg/L MLSS, indicating an 85.56% reduction in MLSS at the optimum sludge digestion time. The average level of DO at the inlet was 0.852 $\pm$ 0.1 mg/L, whereas inside the reactor it was measured as 2.62 $\pm$ 0.1 mg/L. The MLVSS concentration was found to be 3233.8 $\pm$ 233.4 mg/L and 438.0 $\pm$ 85.9 mg/L at the inlet and inside the reactor, respectively. The overall removal was about 86.58% of the initial MLVSS. Figure 3A–C shows MLSS, MLVSS, and DO profiles, respectively.



(**A**) (**B**) (**C**)

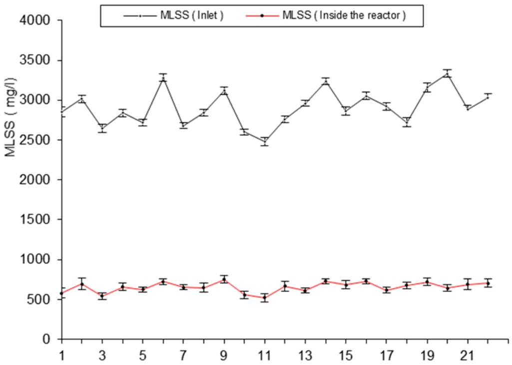
Figure 3. (**A**) MLSS profile in continuous mode aerobic digester (ASP sludge); (**B**) MLVSS profile in continuous mode aerobic digester (ASP sludge); (**C**) DO profile in continuous mode aerobic digester (ASP sludge).

3.3.2. Aerobic Digestion in Continuous Mode on Sludge Generated from the Attached Biomass Reactors (MBBR and PBBR)

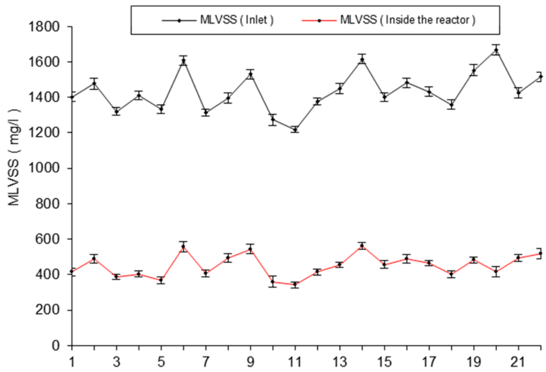
The waste sludge collected from the MBBR and PBBR systems was subjected to continuous aerobic digestion for a period of 22 days. The MLSS, MLVSS, and DO profiles of the MBBR sludge in the continuous mode aerobic digester are also shown in Figure 4A–C, respectively. The volatile fraction was approximately 49.34% and 43.20% of the MLSS in the sludge obtained from the MBBR and PBBR systems. The presence of a low organic fraction in the attached biomass reactors indicates effective sludge digestion during the treatment of sewage. The sludge generated in the MBBR and PBBR systems is the sloughed biomass from the carrier media. The sloughed biomass normally has the dead biomass which is dislodged from the reactor due to endogenous activity inside the biofilm. The MLSS of the MBBR system was 2907.40 ± 112.56 mg/L at the inlet of the bioreactor, whereas the biomass in the sludge digester was 656.09 ± 32.45 mg/L, showing a reduction of 77.46% MLSS.

Similarly, the MLVSS at the inlet was 1434.86 ± 71.76 mg/L and the MLVSS at the inside the reactor was 450.81 ± 22.46 mg/L, resulting in an average reduction of 68.72%. It should be noted that the DO concentration was maintained at 3.01 ± 0.176 all through the experiments, with an inlet DO concentration of less than 1 mg/L.

The result of the PBBR system indicate an MLSS reduction of 86.59% and an MLVSS reduction of 81.27% after the optimum sludge digestion time. The MLSS at the inlet was 2400.6 ± 128.5 mg/L, whereas the MLSS inside the reactor was 324.6 ± 71.61 mg/L. Similarly, the average MLVSS in the inlet was found to be 1054.4 ± 59.5 mg/L and after digestion, the MLVSS was 199.3 ± 14.9 mg/L inside the reactor, indicating an 81% reduction of the organic fraction. The oxygen concentration of the sludge slurry at the inlet was 1.45 ± 0.1 mg/L, which rose to 3.35 ± 0.1 mg/L inside the reactor. The MLSS, MLVSS, and DO profiles of the of PBBR sludge in the continuous mode aerobic digester are shown in Figure 5.



(**A**)



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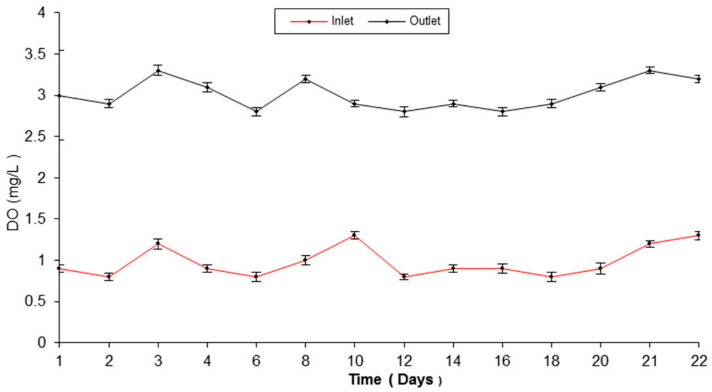
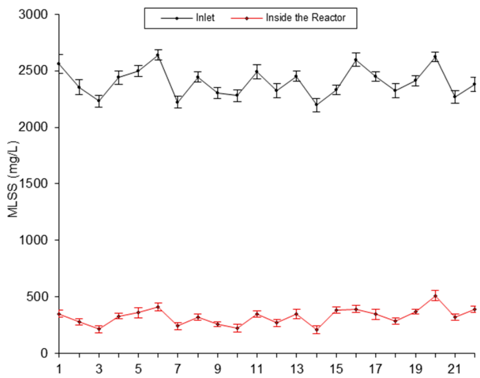
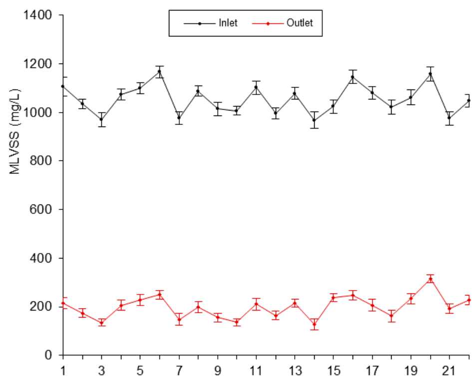


(**C**)

Figure 4. (**A**) MLSS profile in continuous mode aerobic digester (MBBR sludge); (**B**) MLVSS profile in continuous mode aerobic digester (MBBR sludge); (**C**) DO profile in continuous mode aerobic digester (MBBR sludge).

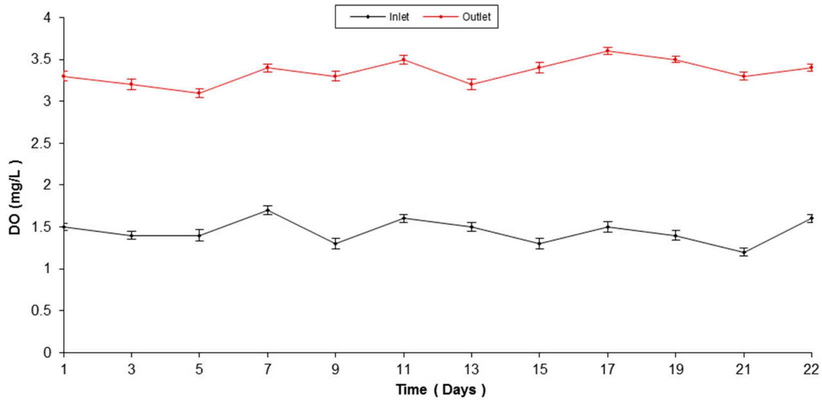


(**A**)



(**B**)

Figure 5. *Cont.*



(**C**)

Figure 5. (**A**) MLSS profile in continuous mode aerobic digester (PBBR sludge); (**B**) MLVSS profile in continuous mode aerobic digester (PBBR sludge); (**C**) MLVSS profile in continuous mode aerobic digester (PBBR sludge).

4. Discussion

This study shows that the direct relationship between the digestion time and organic matter reduction is presumed to be difficult, but the waste sludge from different biological systems reveals that the biomass concentration plays a major role in digestion stabilization. When the biomass concentration was high, the time required for the desired reduction of organic matters increased.

A previous study [25] revealed that among the three selected systems (ASP, MBBR, and PBBR), the PBBR system based on an aerobic attached growth stationary phase bioreactor is most suitable for small community, but the waste sludge associated with the system was considered to be a difficult task. Sludge handling in small premises is always considered to be most problematic and would require a robust system for disposal. The presence of the sludge is also associated with problems related to odor and fly-related issues. For the aerobic digesters used in this study of waste sludge digestion, however, regardless of their low investment costs, simpler operation and ease of management and control, the present study has revealed that the aerobic sludge digestion processes for waste sludge generated from an activated sludge process (ASP), moving bed bioreactor (MBBR) and packed bed biofilm (PBBR) are not a feasible application for a small community, as these required large space due to very high digestion times. Despite the unsuitability of these techniques, PBBR showed a better digestion time (seven days), compared with the others. Therefore, further studies are needed in order to identify a more suitable method for waste sludge management.

Author Contributions: S.A. conceived and designed the experiments; S.A. and I.K. performed the experiments; S.A. and M.T. contributed reagents /materials/analysis tools; S.A. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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