Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.886293

54 (2015) 616–623
April

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Performance evaluation of the electrolysis process for waste sludge stabilization in decentralization practices

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Received 24 June 2013; Accepted 16 January 2014

ABSTRACT

This study was undertaken to evaluate the potential use of electrolysis process for waste sludge stabilization in decentralization practices by focusing on the operating parameters such as sludge composition, detention time, and electric voltage. The laboratory batch scale results show that the sludge extracted from a packed bed biofilm reactor can reach the minimum concentration of 659 mg/L volatile suspended solids (VSS) merely within 5 h detention time at an applied voltage of 2 V, whereas the most identical level is obtained from activated sludge by 7 h with 3.6 V. The soluble COD in the supernatant phase of the former process would be increased to 297 mg/L by means of 27% VSS reduction. The economical pre-estimation indicates that electrolysis is more sustainable if stand as a preconditioning stage of biological digestion by 70% capital and operating cost reduction. This configuration can also cause occupying 54% lesser footprint area of aerobic digestion with total average reduction of 56% VSS within 77 h. The biological assay on digested product was also determined with reference to the growth of *Phragmites* sp. plant. This study recommends the electrolysis-pretreated conditioning waste sludge followed by aerobic digestion incorporating with attached growth biological systems as a valuable process in decentralization.

Keywords: Electrolysis process; Aerobic digestion; Waste sludge; Stabilization; Bioassay

1. Introduction

Human activities intensively generate huge amount of wastewater which has resulted in natural resource pollution [1]. The safe and efficient disposal of wastewater is considered as a formidable environmental issue faced globally [2]. The aerobic biological treatment technologies are extensively introduced for urban wastewater treatment and offer an on-site effective solution in areas with low population densities, especially in residential complexes sectors. Meanwhile, these systems have been associated with unavoidable drawbacks of waste sludge production [3,4]. The excessive sludge as an extreme bacteriological hazard is formed by biomass growth in the bio-oxidation mechanism of pollutants [5]. The characteristics of these biowastes considerably depend on the type of wastewater and elimination process. The treatment and disposal of biosolids provide adequate reasons to increase the operational costs up to 60% in

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biological wastewater treatment plants [4–7]. In that order, the effective degradation process can create a sustainable approach by providing safe disposal in land application or reuse [6]. Therefore, the waste sludge management has been a complex challenging area due to regulating, economic, and environmental factors [4].

The aerobic digestion is a promising alternative for the excess sludge stabilization since it mainly offers a reliable, flexible, and simple operation [8]. This biological practice can be assured by the oxidative decomposition of waste biomass in the presence of oxygen. The phenomenon is attributed to the oxidation of microbial protoplasm and releases the energy required to maintain vital cell functions [9]. Nevertheless, the aerobic digestion system tackles with the disadvantage of high capital cost, energy consumption, and possible soluble organic concentration in the supernatant phase thereof. The hydrolysis of large organics presented within microbial cells has been established as a rate-limiting step [8,10,11]. Thus, it is significantly important to give an impression to shorten the digestion period and increase the effectiveness of the process; although it is influenced by biosolids composition as a result of wastewater origins and treatment processes [12–15].

In recent years, various methods including ultrasonic, mechanical, chemical, and thermal have been used for biosolids disintegration and enhancement of biological sludge stabilization [16–23]. The electrochemical is accordingly considered as a powerful means of clean technique for pollution control by means of versatility, high removal efficiency, and environmental compatibility [8]. Sludge is a typically multiphase medium, containing water, mineral, and organic substances. The latter covers high accumulation of bacterial cells which can be burst by the electrolysis process [24]. This practice is introduced as a firm technology for biosolids destruction to create an aggressive reaction condition in advance of the digestion process through the solubilization of intracellular substances; although the relevant literature is rare and it surely requires more investigations [8,24–26].

Therefore, the present scientific approach aimed to examine and review the potential future use of the electrolysis process for waste sludge stabilization in decentralization practices. In this study, an effort was made as well to consider the feasibility of incorporating electrochemical advantages with aerobic digestion. Moreover, the experimental investigations were initiated by evaluating the influence of sludge characteristics on accelerating the aerobic digestion and electrolysis processes, while ending with the possibility of treated effluent reuse.

2. Experimental methods

2.1. Laboratory investigations

The experiments were performed for 10 months to evaluate the electrochemical cell and subsequently in combination with aerobic condition for waste sludge stabilization. The extensive investigations were carried out in a single rectangular polypropylene compartment with an effective volume of 500 mL (internal dimension of 14 × 4 × 12 cm). The electrochemical cell consists of an anode and a cathode of 117 cm^2 active area with a gap length of 30 mm as shown in Fig. 1. The former is made of titanium and coated with a mixed metal oxide of Ruthenium and Iridium, while the latter is a stainless steel electrode. A magnetic stirrer bar was used to avoid sludge settling, making sludge contacts with electrodes.

This type of anode generically refers to a stable and not vulnerable to the leaching by applying current; it converts high biopolymer substances into low molecular weight products [8,26,27]. The electrodes connected to a 5A 30V DC current stabilizer in order to supply a constant current. The trace amount of 100 mg/L sodium chloride (NaCl) was taken as a supporting electrolyte to increase the conductivity of the mixture since it is a strong electrolyte, completely ionize when dissolved in the sewage sludge and easily accessible [28]. The low level of NaCl used because the anodic oxidation of organics in the presence of NaCl lead to the chlorination of some organics; this can potentially increase the toxicity and the environmental hazard associated with wastewater [29]. The

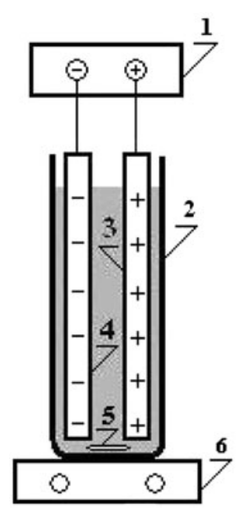

Fig. 1. Schematic appearance of bench scale electrochemical process (1—DC power supply, 2—electrolysis cell, 3—cathode, 4—anode, 5—bar stirrer, and 6—magnetic stirrer).

variables such as sludge composition, electric voltage, and required contact time were verified in order to identify the most favorable condition in biosolid minimization. The instantaneous current efficiency (ICE) was calculated as per standard practices [30]. The electrochemically treated sludge was then aerated by completely mixed aeration to remove the low molecular weight products [8]. All experiments were carried out with raw sludge, at ambient temperature, without any pH regulation by five time repetitions.

2.2. Bioassay determination

The final degradation product was examined on *Phragmites* sp. as a bioindicator of land application due to its high productivity, rapid growth, and wide distribution [31]. The plant was collected from a marshy land and transferred to the laboratory in soilless cylindrical media with a void capacity of 2 L in the presence of vegetation. The experiments were done after acclimatization through the exposure of a final degraded product till good plants growth was observed visually over a period of 40 d. In that order, the morphology of acclimatized macrophyte in terms of, number and size of the leaves and roots, dry and ash weight were analyzed every 10 d for a period of two months to monitor the morphological changes as per the standard practices [32,33]. Histochemical studies on the plant roots were also carried out according to the standard procedure [34].

2.3. Sludge sampling and characteristics

The biosolids were collected daily from two bench scales of aerobic biological processes treating residential wastewater i.e. conventional activated sludge and attached growth packed bed biofilm reactors. The samples were taken before and after the start of the trials and were analyzed pH, soluble chemical oxygen demand (SCOD), conductivity, suspended solids (SS), volatile suspended solids (VSS), and sludge volume index (SVI) as per the standard methods [9,35]. The SCOD was determined by the open reflux method, using COD digestion apparatus Model 2015 from Spectralab. The particle size analysis was carried out by laser diffraction method (Malvern Mastersizer 2000, UK). The characteristics of sludge samples are given in Table 1.

Table 1
The waste sludge characteristics from two biological treatment systems

Parameters	CASR	PBR
pH	7.11 ± 0.16	7.22 ± 0.13
SCOD (mg/L)	41 ± 6	34.2 ± 7
Conductivity (μS/cm)	631 ± 72	464 ± 81
SS (mg/L)	5,080 ± 286	2,568 ± 128
VSS (mg/L)	3,556 ± 234	1,130 ± 82
SVI (mL/g)	138 ± 18	62 ± 10
Particle size (μm)	40–550	10–50

Notes: CASR: Conventional activated sludge reactor.
PBR: Packed bed reactor.

3. Results and discussion

The aerobic digestion has been resulted in major restrictions of long retention time and high energy consumption [8,17]. Thus, this study highlights the electrolysis potential in waste sludge disintegration and obligatory applied electrical current intended to overcome certain limitations of aerobic condition. Transfer of electrons at the cathode produces hydroxide ions and hydrogen gas. The electro-oxidation takes place at the anode surface through generation of physically adsorbed active oxygen i.e. adsorbed hydroxyl radical, OH. In the presence of chloride, oxidation of organic compounds can also mediated by active chloro-species. The possible reactions at the electrodes are as follows:

(1) Cathode (reduction): $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode (oxidation): $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

Overall reaction: $2H_2O \rightarrow 2H_2 + O_2$

(2) Cathode (reduction): $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode (oxidation): $2Cl \rightarrow Cl_2 + 2e^-$

Overall reaction: $2H_2O + 2Cl \rightarrow H_2 + Cl_2 + 2OH$

3.1. Effect of sludge composition

The quantity and composition of waste sludge can play an important role to assist the process of aerobic digestion [34]. The initial experiments of 2 L waste sludge under aerobic condition show that the biowaste from packed bed biofilm reactor requires a considerably lower digestion period of 7 d to drop VSS concentration from an average of 1122–705 mg/L, whereas VSS of activated sludge reduced from 3563 to 1707 mg/L in within 16 d detention time (Fig. 2). The hydrolysis of waste sludge is the bottleneck during aerobic digestion due to recalcitrant nature biological cell wall and membrane [36]. Unlike conventional activated sludge (suspended growth system), the packed bed reactor provides a large internal surface area for the growth of micro-organisms leading to a longer sludge age and elevated dynamics of sludge mineralization [37]. This phenomenon can reduce the biomass concentration and particle size of biowaste, causing a shorter digestion period (Table 1). The long detention time for organic stabilization in the activated sludge is due to the higher organic fraction.

The impact of wastage sludge characteristics on the operating voltage can probably be marked as a considerable parameter in electrochemical process [8]. Accordingly, the electrolysis cell was operated under electric voltages from 1–4 V/L at various reaction times. The biowaste from the attached growth system shows an efficient VSS reduction at a lower voltage power of 2 V where ICE was 0.03 (Fig. 3). These results indicated that the organic matter solubilization increased with increasing electrical voltage of waste activated sludge (ICE ~ 0.17). This can be concluded by the composition of SS; a small fraction of organic matters is hydrolyzable by applying voltage power owning to refractory organic compounds [8]. The same phenomenon is comparable to the electrolyte constitution during electrolysis performance. The variation of total dissolved solids has an impact on the electric power request profile wherein the sludge composition can play a similar role in the voltage requirement [8]. The high VSS–SS ratio of activated sludge signifies the long detention time or else high voltage power requirement (Table 1).

Thus, the wastage biomass from the packed bed reactor by applied voltage of 2 V was selected for the subsequent studies.

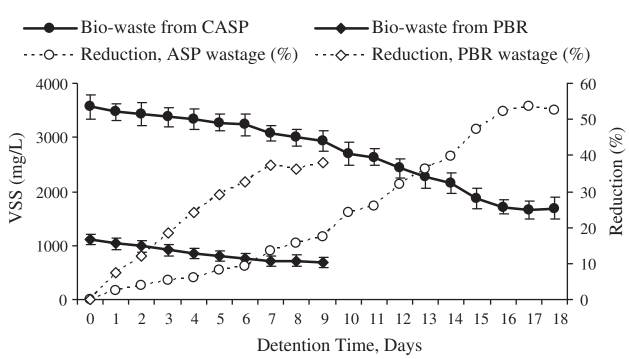

Fig. 2. The compression of VSS reduction under aerobic condition.

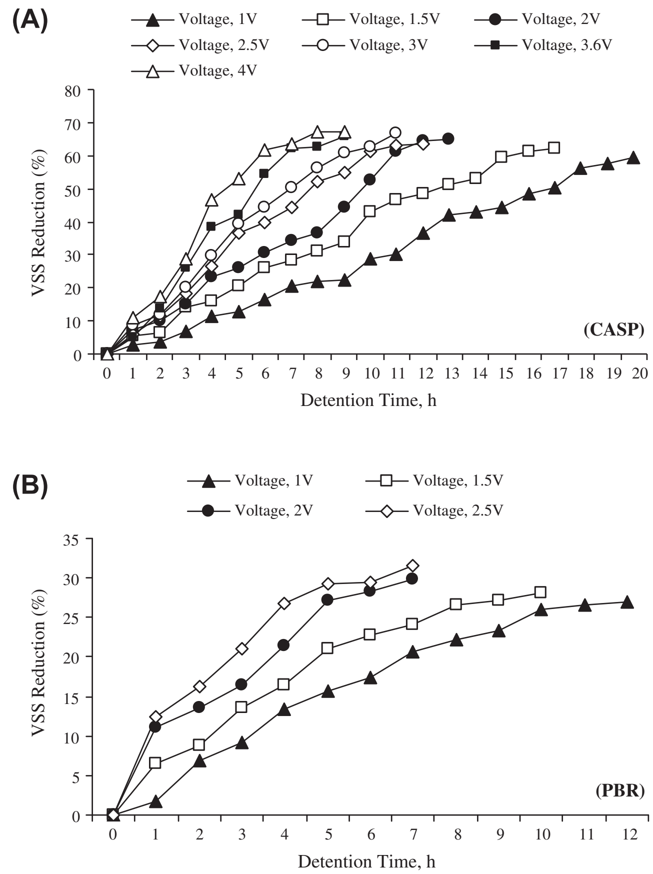

Fig. 3. The percentage of VSS reduction under applied currents of electrochemical process (A) Biowaste from CASP, (B) Biowaste from PBR.

3.2. *Electrolysis effect on the solubilized organic matters*

It is noteworthy to say that the potential of electro-oxidation reaction thoroughly depends on an adequate contact time of the process parameter [38]. In that order, the electrolysis time at an electric voltage of 2 V was examined to evaluate the decomposition rate of solubilized organic matters from PBR waste sludge; soluble COD was introduced as a primary indicator in the process (Fig. 4). The results show that the 5 h electrochemical treatments can gradually increase the soluble COD in the supernatant phase of sludge sample by 90% as a result of sludge floc breakage, cell lysis, and releasing intracellular materials into the solution [26]. The slow rate of soluble COD decomposition can be recognized above this reaction time (ICE ~ 0.01); although the complete oxidation is achievable within approximately 20 h. Furthermore, the 27% VSS reduction would be achievable to reach a constant level beyond 5 h; leads a portion of the biodegradable organic matters into the supernatant phase (Fig. 3).

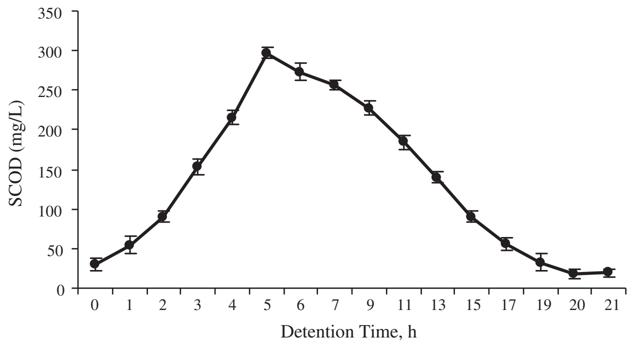

Fig. 4. The profile of soluble COD concentration at different detention time under applied voltage power of 2 V.

Correspondingly, the proportion between the degradation to solubilization rates was obtained to be 0.3–0.4.

3.3. *The assessment of electrolyzed sludge under aerobic condition*

The aerobic condition was performed after the electrolysis preconditioning step of biowaste from PBR to assess the overall performance of the stabilization process (Fig. 5). The results showed that 28% VSS reduction can be achieved merely within an optimal 72 h detention period of aerobic condition. Correspondingly, high expression levels of soluble organic matters were degraded readily to reach the approximate of 109 mg/L, which can be appreciated in proportion to the relevant literature [11]. As a result of the comparison with data presented in Fig. 2, the stand-alone aerobic digestion could remove 37% VSS content of the waste sludge from PBR over a 7 d period, whereas the total VSS reduction by electrolysis-aerobic digestion was 56% within a shorter time (3.21 d in total). This is probably due to the sludge disintegration and cell lysis resulting more homogeneous

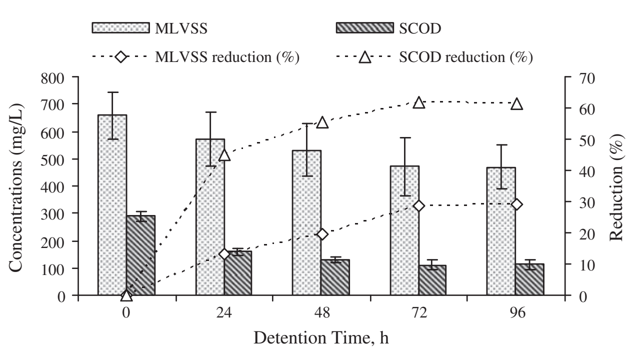

Fig. 5. The variation of VSS and SCOD concentrations during the aerobic digestion of electrolyzed sludge.

dispersion of the sludge flocs. [39]. Therefore, the electrochemical pretreatment can significantly promote hydrolysis step and enhance aerobic digestion efficiency.

Based on the literature review findings, it should be recognized that, the degrees of biosolids disintegration during electrolysis pretreatment can increase with the increasing of pH under alkaline condition or the decreasing of pH in acid range; subsequently, effects the performance of aerobic digestion [8,10,40]. The high pH hydroxyl anions can destroy floc structures and cell walls, causes natural shape losing of proteins, saponification of lipid, and hydrolysis of RNA. The low acid condition resulted in the modifications of the organic matter composition of sewage sludge.

3.4. *Pre-estimation of capital and operating costs*

The financial analysis is a valuable factor describing a sustainable technology [41]. The pre-estimation of capital and operating costs have been initiated for complete oxidation of 1 m^3/h waste sludge in a single unit based on results generated by bench scale trials (Fig. 4). The cost examination was also done for identical capacity of biowaste at 5 h. The results of these analyses indicated that the electrochemical method is economically impracticable as a stand-alone solution for the complete decomposition practice, unless it is used for a preconditioning stage to accelerate the

Table 2
Pre-estimated capital and operating cost of electrochemical process for 1 m^3/h waste sludge degradation

	Electrolysis application	
Components	Single unit	Pre-conditioning unit
A. Capital cost		
Reactor volume, m^3	20	5
Anode area, m^2	24	6
Cathode area, m^2	24	6
Reactor tank cost PE, US $	1,334	338
Anode cost, US $	9,648	2,412
Cathode cost, US $	3,072	768
Total A, US $	14,054	3,518
B. Operating cost		
Current	3 A	3 A
Current density	125 mA/m^2	500 mA/m^2
Voltage	2 V	2 V
Watt	6 W	6 W
Time	20	5
Kwh/m^3	120	30
Total B, US $	9	2

digestion processes with substantially lower cost at 5 h detention time (Table 2). The purpose of this pre-estimation is merely to verify the advantage of electrolysis pretreatment prior to the aerobic digestion process. The detailed cost analysis of this technology has to be evaluated in the subsequent pilot and field experiments.

The literature reported that the application of electrochemical pretreatment is feasible and can be a cost-effective process when compared to conventional aerobic digestion unit as a stand-alone solution [8]. The overall footprint area for an estimated capacity of 1 m^3/h wastage sludge, based on the detention time, shows that the application of electrochemical process as a preconditioning stage could lead to occupy 54% area less than a single aerobic digestion unit in stabilization process; making minimization more sustained (Fig. 6(A)). A comparative evaluation on the percentage biomass removal at 3 d detention time also confirms that the electrochemical pretreatment can lead to a higher rate of biowaste degradation under aerobic condition (Fig. 6(B)).

3.5. Bioassay of stabilized sludge

The sewage sludge land application can be accounted as a bottleneck for the environment [42]. The biological determination was carried out to assess the impacts of the electrochemical protocol as a preconditioning stage of aerobic digestion on the fertilizer value of the sludge for land application. The study on morphological aspects of *Phragmites* sp. indicated that the final digested product has no detrimental effect on plants growth as their yield were increased which could verify the sludge value for soil application (Table 3 and Fig. 7). This might be caused by nutrient concentration; although, this calls for further detailed investigation [43]. The histochemical study illustrates that the vegetation absorb nutrients through the epidermal regions and vascular bundles to transport upwards to the plant [44].

It can be summarized that the attached growth technologies offer greater characteristic of wastage biomass compare to the conventional activated sludge process. This fact by incorporating the advantages of

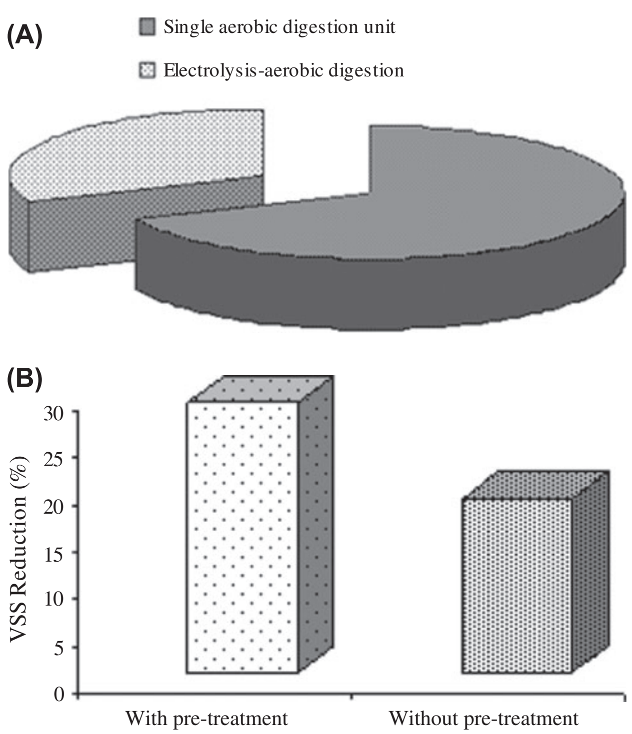

Fig. 6. Comparative evaluation on the necessity of electrolysis process as a preconditioning step of aerobic digestion (A) Overall footprint area requirement, (B) VSS reduction under aerobic condition at 3 d detention time.

Table 3
The morphological changes of the plants during the feeding of final digested product from electrochemical process flow by aerobic digestion

Botanical aspects	Initial	After 10 d
Number of leaves	5.4 ± 1.40	8.6 ± 1.14
Size of leaves (mm^2)	1,522 ± 198.54	1,556 ± 188.22
Number of roots	8.4 ± 1.14	22.2 ± 3.11
Longest root (mm)	113 ± 9.15	133.8 ± 9.12
Dry weight/g	0.59 ± 0.10	0.9058 ± 0.44
Ash weight/g	0.03 ± 0.007	0.0874 ± 0.036
New shoots germination	0	2 ± 0

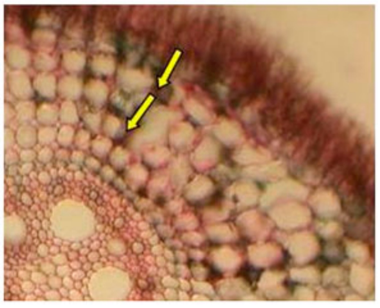

Fig. 7. Cross-sectioning of the *Phragmites* sp. root after experimental studies. ⇨ Translocation of nutrients upward to the plants.

electrochemical process and aerobic digestion is capable of being accepted as a true treatment process for small societies, especially wherever land use is restricted. Furthermore, the low soluble COD effluent in final degradation products of biowaste could discharge into soak pit, leach fields, and mounds or else reuse for irrigation.

4. Conclusions

The study extremely highlights the electrolysis as a prominent process enhancing biological digestion through disintegration of sludge flocs and microbial cell walls. It is shown that the waste sludge from the packed bed biofilm reactor can be identified with lower degradation period and applied electric voltage of 2 V. Meanwhile, the single electrochemical application would not be recommended due to economically impracticable for the complete degradation process. The preconditioning role in this process optimized at 5 h can lead to the reduction of the capital cost of aerobic digestion owing to low detention time and the footprint area requirement in comparison with the stand-alone aerobic unit. The biological assays on processed biowaste illustrated that it can be used to likewise land applicable products. The overall study reveals that the electrolysis-pretreated conditioning followed by aerobic digestion can consider as an efficient and effective technique for waste sludge stabilization. This process by incorporating with attached growth aerobic treatment systems may considerably offer an ideal framework in decentralization practices.

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