Comparison of an Upflow Anaerobic Sludge Blanket and an Anaerobic Filter for Treating Wheat Straw Washwater

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Abstract: The study compared the performance of upflow anaerobic sludge blanket (UASB) reactors and anaerobic filters (AF) for the treatment of wheat straw washwater (WSW) which has a high concentration of Potassium ions. The trial was conducted at mesophilic temperatures (37 ^{o}C). The digesters were started up over a 48-day period using a synthetic wastewater feed and reached an organic loading rate (OLR) of 6 g COD L^{-1} day^{-1} with a specific methane production (SMP) of 0.333 L CH_4 g^{-1} COD. When the feed was switched to WSW, it was not possible to maintain the same loading rate; the SMP in all reactors fell sharply to less than 0.1 L CH_4 g^{-1} COD, with the AF affected more than the UASB. On reducing the OLR to 3 g COD L^{-1} day^{-1} the reactors recovered to produce 0.21 L CH_4 g^{-1} COD_{added} and exhibited 82% COD removal. A discrepancy between the COD consumed and the methane produced could be accounted for through increased maintenance energy requirement of the microbial community for osmo-regulation as K^{+} was found to accumulate in the sludge and in the UASB reached a concentration of 4.5 mg K g^{-1} wet weight of granules. Overall, anaerobic digestion of WSW was found to be one of the promising techniques in generating clean energy as one tonne of wheat straw would approximately generates 4148 L of CH_4.

Keywords: *Anaerobic digestion, osmotic stress, chemical oxygen demand, specific methane production.*

1. Introduction

Straw from cereal production has attracted attention for many years as a potential biomass fuel source, and there is interest in using it as a combustible fuel in both large and small-scale plant for heat and power production. The abundance of straw, its short rotation period and intensive culture systems have led to considerable interest from researchers in exploring efficient methods for its utilization as an energy source (He et al., 2008). Wheat straw is a major potential source of waste biomass for renewable energy production, but its high salt content causes problems in combustion. In the UK, according to Defra Statistics: UK Cereal Production Survey (accessed 18 May 2012), of 12.2 million tonnes of straw (wheat, barley, oats and oil seed rape), more than half is from wheat which comprised 7.7 million tonnes. Based on the findings from Biomass Futures project, it is estimated that in the UK more than 5 million tonnes of straw (dry matter), equivalent to approximately 15 million tonnes wet weight, will be available by year 2020 (Elbersen et al., 2012). Nevertheless, the major problem associated with the use of straw in thermal energy production is the low fusion temperature ash which can cause fouling during the combustion process. The high salt content, particularly K and Cl, can also give rise to acidic gases with associated boiler corrosion problems.

Pre-treatment techniques such as washing can improve the quality of the straw for thermal processing by reducing the concentrations of the salts K and Na as well as Cl (Jensen et al., 1997). Sander (1997) reported that the leaching process allows rapid removal of K because it is not associated with the structural components of plants. Although salts can be removed from straw in a relatively simple process, the saline wheat straw washwater (WSW) obtained requires treatment before disposal since in addition to the leached salts, it is also rich in organic matter. Anaerobic digestion (AD) has been identified as an option for treatment of this washwater, since it has a low operating cost, low sludge production, and the methane produced could be used as an energy source. Several studies have looked at the application of anaerobic treatment

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for the removal of organic pollutants in highly saline wastewaters, including the treatment of tannery wastewater, seafood processing effluent, fishery and fish farm wastewater effluent. The presence of excessive amount of salts, particularly Sodium, has been revealed as inhibitory for anaerobic wastewater treatment at concentrations of more than 10 g L^{-1} due to the effect of osmotic shock (Lefebvre and Moletta, 2006a). The toxic effect of high Na concentrations has been reported by many researchers, but little attention appears to have been given to the effects of high concentrations of K, which is the salt most likely to contribute to salinity in straw washings. Kugelman and McCarty (1965) and Mouneimne et al. (2003) investigated the toxicity of K in an acetate batch assay test, while Fernandez and Foster (1994) demonstrated the threshold of K inhibition using glucose feed substrate in batch study. Habert et al. (1997) demonstrated the treatment of inuline effluent using UASB at 10 g l^{-1} of salt at OLR of 23-32 kg COD m^{-3} day^{-1} and achieved 65% - 85% of COD removal rate.

The use of non-halophilic groups in an upflow AF has been demonstrated by Guerrero et al. (1997) during the treatment of seafood processing effluent at 15 g l^{-1} of salts and revealed 83% of COD removal at COD influent of 34 g l^{-1} and OLR of 2.8 kg COD m^{-3} day^{-1}. Furthermore, Boardman et al. (1995) also reported on the treatment of seafood processing wastewater using UASB and discovered 77% of COD removal at 7.7 to 26.3 g l^{-1} of salt. The OLR applied in the study was at 13.6 kg COD m^{-3} day^{-1} and COD influent of 1.7 g l^{-1}. Anaerobic digestion has not worked well in all such cases; however, and there are reports of saline wastewaters being inhibitory in AD systems when employing non-halophilic methanogens. Mosquera Corral et al. (2001) investigated the efficiency of a Hybrid Anaerobic Sludge Bed Filter in treating seafood processing effluent which contained 1-1.5 g l^{-1} of influent COD concentration at OLR of 1.5-2 kg COD m^{-3} day^{-1}. The findings showed about 70%-90% of COD removal at HRT of 18 hrs. Application of an Upflow Anaerobic Sludge blanket at OLR of 0.5 kg COD m^{-3} day^{-1} has also been reported by Lefebvre et al. (2006b) during the treatment of tannery wastewater at 71 g l^{-1} of salts and found 78% of COD removal at COD influent of 2.3 g l^{-1}. Vidal et al. (1997) investigated the performance of AF in treating seafood processing wastewater at salt concentration of 30 g $l^{-1.}$ This study revealed the COD removal efficiencies remained at 70% with an Organic Loading Rate (OLR) ranging from 1 to 15 kg COD m^{-3} day^{-1}.

Idrus et al. (2012) assessed biogas potential from wheat straw washed water using UASB. This study confirmed that the organics washed from wheat straw were to a large extent biodegradable in UASB digesters with a specific methane yield of 0.29 l CH_4 l^{-1} COD_{added} and 84% COD removal. Nevertheless, the achievement was only temporary when both specific methane yield and COD removal dropped to 0.12 l CH_4 l^{-1} COD_{added} and less than 50%, respectively. Studies on the treatment of saline wastewater indicate that salt concentration is not the main indicator in determining the level of inhibition. Apart from pre adapted sludge and population of the bacteria, the presence of other cations and OLR also need to be considered. These statements are supported by Feijoo et al. (1995) who noted that performance in treating saline wastewater in AD system depends on nutrient in the feedstock, previous adaptation of the sludge, antagonistic or synergistic effect (due to the presence of other cations) and lower substrates to biomass ratio used. Numerous studies on saline wastewater have highlighted the role of Na in contributing to inhibition in AD systems. The effect of other salts, particularly K, has been given relatively little attention. Microorganisms accumulate cations, including ionic K, and/or low-molecular-weight organic compounds known as compatible solutes from the surrounding medium to achieve an osmotic equilibrium. Most cells also maintain [K+(in)] >> [K+(out)] (Schönheit et al.,1984; Sprott et al., 1985). Inhibition or dehydration occurs when K+ in the extracellular solute concentration exceeds K+ in the cell cytoplasm (Lai and Gunsalus, 1992).

Fernandez and Foster (1994) investigated the threshold of K inhibition using glucose feed substrate (batch study) and observed that low concentrations of K (less than 400 mg l^{-1}) facilitated performance in both the thermophilic and mesophilic conditions, while at higher concentrations (greater than 2500 mg l^{-1}) toxicity of K was significant. Mouneimne et al. (2003) investigated the toxicity of K in an acetate batch assay test and found the toxicity threshold to be 0.43 mol l^{-1}. Kugelman and McCarty (1965) reported that 5.87 g l^{-1} of K caused 50% inhibition of acetate utilizing methanogen. Most of the K toxicity thresholds which have been reported were conducted in batch studies, which implied that further investigation is required in continuous system. Idrus et al. (2012) reported on potential of biogas production from WSW in a continuous system of UASB, and the aim of this study was therefore to compare the potential of biogas production from UASB and AF in treating WSW at higher OLR and to establish the highest methane production that could be achieved in either of these types of digesters.

2. Method

2.1 Feedstocks

A synthetic wastewater (SW) was prepared as a concentrate (Table 1) and diluted to the required working strength using tap water. The working strength was determined by the required organic loading rate (OLR) based on measured chemical oxygen demand (COD). The COD of the SW concentrate was approximately 50 g L^{-1}. Wheat straw leachate was prepared by chopping up wheat straw into approximately uniform length pieces which were placed inside the mesh drum of a reciprocating-action washing machine. A quantity of water in a known ratio to the dry weight of the straw was then added to the drum trough and the temperature was raised to 60 °C for 3 hours, afterwards the liquid was drained off.

Table 1 Composition of synthetic wastewater concentrate

Component	Unit	Quantity
Trace element solution (mg L^{-1}: Fe 10; Co, Mn, Ni and Zn 1; Cu, B, al, Mo, and Se 0.1)	mL	1
Yeast (block baker's form)	g	23
Urea	g	2.14
Full cream milk (UHT sterilised)	mL	144
Sugar (granulated white)	g	11.5
Dried blood	g	5.75
Ammonium phosphate	g	3.4
Tap water	Make up to 1 L	

2.2 Experimental set-up

The experimental work used two anaerobic filters (AF1 and 2) and two UASB reactors (U1 and 2), each with a working volume of 1.5 L and maintained at 37 ºC. The anaerobic filters were inoculated using salt-acclimated digestate from a laboratory-scale digester which had been fed daily on SW supplemented with a mix of Potassium Chloride and Sodium Chloride (KCl + NaCl). Three litres of this digestate was divided evenly between AF1 and AF2 and recirculated through the filter for 7 days using a peristaltic pump. The UASB reactors were each inoculated with 1 kg wet weight of granular sludge, which had been stored at ambient temperature and then brought up to operating temperature and maintained at this for 7 days, whilst the liquid fraction was recirculated through the granular bed. SW was then fed into each of the digesters using a variable speed peristaltic pump (Model 505S, Watson Marlow, UK), Feeding commenced at a low OLR and then gradually increased over a 48-day period reaching a final OLR of 6 g COD L-1. During this start-up phase the hydraulic retention time (HRT) was maintained more or less constant at 18-19 hours by gradually reducing the dilution of the SW. The effluent from the digesters was collected in a sealed container, which was connected to a gas sampling bag, allowing separation of the biogas generated from the liquid effluent stream. Biogas production was determined by measuring the quantity of biogas in the sample bag using a weight-type water displacement gasometer (Walker et al., 2009), and then subtracting the volume of effluent collected in the inter-connected receiver vessel. All gas volumes are reported at a standard temperature and pressure (STP) of 101.325 kPa and 0 ºC.

2.3 Analytical methods

Biogas composition (CH_4 and CO_2) was determined using a Varian star 3400 CX gas chromatograph (GC), calibrated with a standard gas of 65.12% CH_4 and 34.88% CO_2 (v/v). Conductivity was measured using a LF330 meter (WTW GmbH, Germany). pH was measured using a Jenway 3010 pH meter (Bibby Scientific Ltd, UK) with a combination glass electrode calibrated in buffers at pH 4, 7 and 9 (Fisher Scientific, UK). Suspended solids were determined according to Standard Method 2540 D (Environment Agency Q1 2007), using glass fiber filter discs (GFC) (Whatman, UK). COD was measured using a closed tube digestion and titration [put author surname here not a number as per JHER style]. Total Organic Carbon (TOC) was measured using a Dohrmann TOC (DC-190) based on Standard Method 5310 (APHA, 2005). Ammonia was determined using a Kjeltech block digestion and steam distillation unit according to the manufacturer's instructions (Foss Ltd, Warrington, UK). K, Mg, Na and Ca in leachate samples were analyzed by first filtering the sample (Whatman No 1) and then diluting it into 12.5% of nitric acid (HNO3). The acidified samples were analyzed using a Varian Spectra AA-200 atomic absorption spectrometer (Varian Ltd, UK), according to the manufacturer's instructions.

3. Results and discussion

3.1 Characterization of wheat straw leachate

The two batches of WSW had the following characteristics (mg L^{-1}): batch 1 - COD 4500; K 638; Na 28; Mg 352; Ca 367; Zn 43; Cl^- 432; SO_4^{2-} 484; PO_4^- 86; and conductivity 3554 µS cm^{-1}. Batch 2 - COD 2250; K 317; Na 9; Mg 112; Ca 123; Zn 14; Cl^- 136; SO_4^{2-} 182; PO_4^- 26; and conductivity 1114 µS cm^{-1}. The cation present at the highest concentration in the leachate was thus potassium, in agreement with the results of Jensen et al. (1997).

3.2 Digester start-up

Figure 1 shows the applied OLR for all four digesters. Minor fluctuations were due to slight variations in pumping rates. Specific methane production (SMP) in the AF was initially slightly lower than in the UASB reactors, indicating that the former needed some additional time for acclimatization, but by day 25, all digesters had achieved SMP values of around 0.32 l CH_4 g^{-1} COD_{added} (Figure 2), and COD removal rates of 95%.

All four digesters responded well to the rapid increase in OLR up to around 6 g COD L^{-1} day^{-1}, although U1, which received a marginally higher loading due to variability in pump flow rates, showed a marginally lower SMP. Between day 25-40 the pH in U1 and 2 dropped below 7, but recovered to around 7.4 by day 48 (Figure 2).

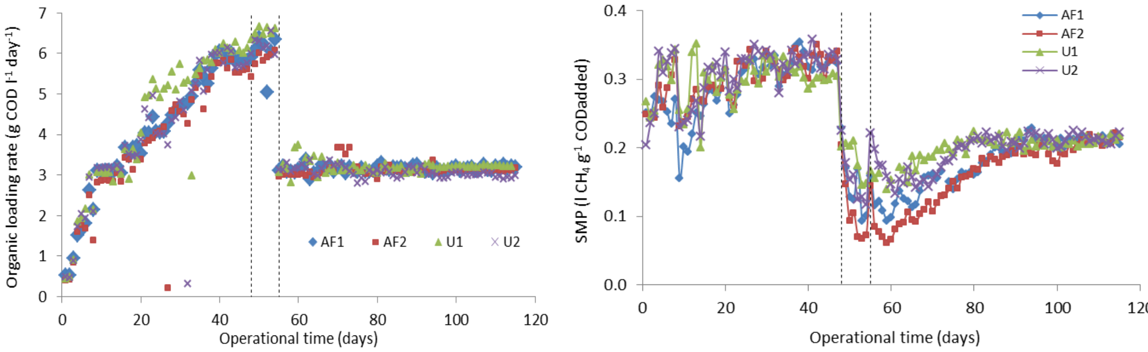

Figure 1 Applied OLR and SMP in UASB and AF digesters. Vertical dotted lines indicate the change from SW to WSW, and the OLR reduction from 6 to 3 g COD L^{-1} day^{-1}

3.3 Wheat straw leachate

On day 48, the feed was switched to WSW at an OLR of 6.0 g COD L^{-1} day^{-1}. As the organic strength of the WSW was greater than that of the SW, this involved reducing the volume added each day and increasing the HRT. At this point, the SMP fell sharply in all reactors (Figure 2), with the AF affected more than the UASB, and U2 more than U1. The effluent COD concentration also rose sharply to around 4 g COD L^{-1} in all the digesters, corresponding to a fall in removal rates to around 35% (Figure 2) although there were some signs of recovery in the following days. On day 55, the OLR was therefore reduced to 3.0 g COD L^{-1} day^{-1} by diluting the WSW with tap water to give an influent concentration of around 2.5 g COD L^{-1} and a HRT of around 26 hours: these values were fairly close to those for the SW feed. The SMP in both UASB reactors improved over the next 25 days, with U2 showing an immediate peak in gas production in response to the reduced load. The AF digesters responded more slowly, but by day 90 the SMP in all the digesters had recovered to around 0.21 l CH_4 g^{-1} COD_{added} with a biogas methane concentration of around 73%. By day 69, COD removal was close to 75% in all the digesters, and by the end of the run had stabilized at around 83%.

Effluent VFA concentrations (not shown) remained extremely low throughout the experimental run (measured values < 10 mg L^{-1}), indicating that any peaks in effluent COD consisted of unhydrolysed material and/or other intermediate products. Effluent suspended solids concentrations also showed little variation throughout the experiment (Figure 2). During the period of feeding on WSW, the pH in the AF was slightly higher and more stable than in the UASB, which operated at just below pH 7 for much of the time. The ammonia concentration in the effluent of all the four digesters stabilised at around 0.1 g N L^{-1} as shown in Figure 2, indicating that little buffering was available from this source.

In terms of performance parameters (SMP, COD and suspended solids removal), the two systems tested thus appeared to perform equally well. During the last 10 days of operation, the SMP was stable at 0.20 l CH_4 g^{-1} COD $_{added}$ and COD removal rate was 82% for all the digesters (Table 2). Comparisons between UASB and AF reactors have been carried out in the past, but not using wheat straw washwater. In a study by Hutnan et al. (1999), a synthetic wastewater with a COD of 6 g L^{-1} was used. The loading was successfully increased to 15 g COD L^{-1} day^{-1} and comparable COD removals were seen for the different reactor types. This loading is higher than that applied in this study, but the strength of the wastewater in [use surnames] was higher and the study was thus not affected by reductions in HRT which may become critical when dealing with lower strength wastewaters.

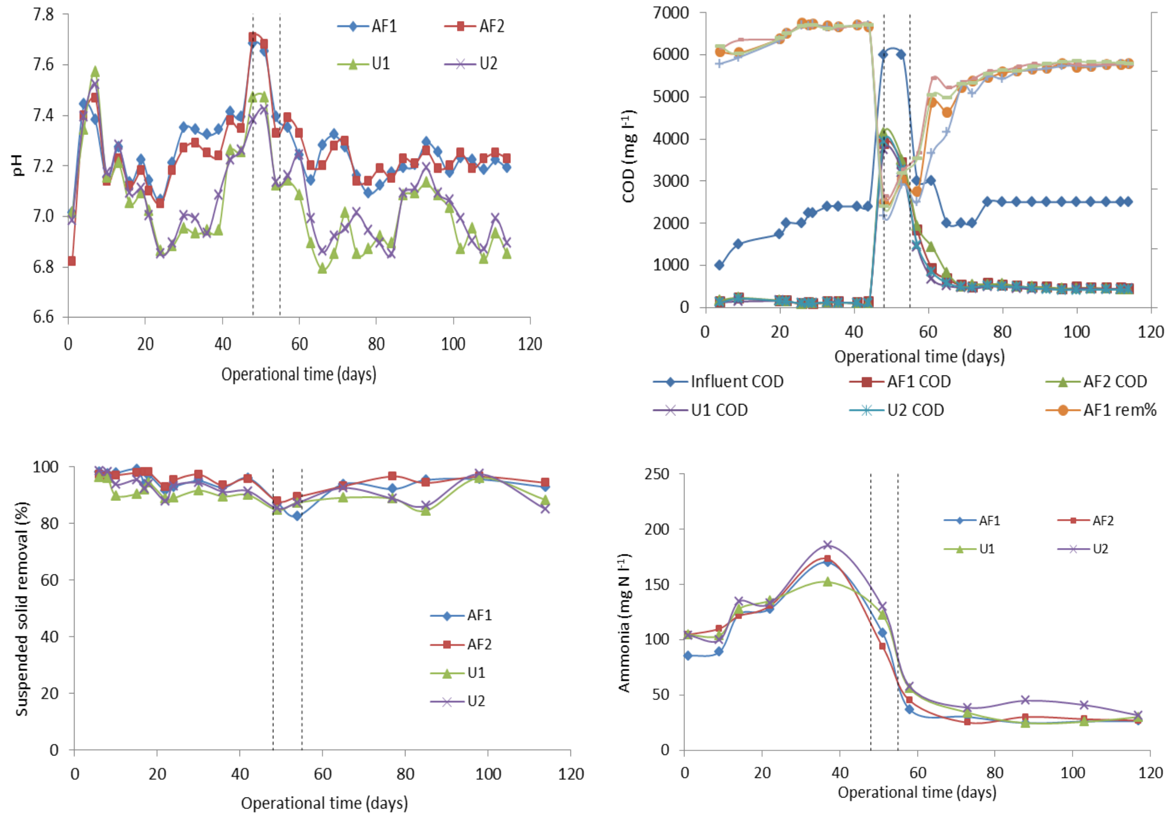

Figure 2 pH, COD and COD removal, suspended solids removal and ammonia concentrations in UASB and AF during experiment. Vertical dotted lines indicate the change from SW to WSW, and the OLR reduction from 6 to 3 g COD L^{-1} day^{-1}

Table 2 Average values for performance parameters in last 10 days of experimental run

Parameter	Unit	AF1	AF2	U1	U2
SBP	l biogas g^{-1} COD added	0.290	0.292	0.288	0.297
SMP	l CH_4 g^{-1} COD added	0.212	0.212	0.212	0.214
	l CH_4 g^{-1} COD removed	0.256	0.257	0.257	0.260
COD removal	%	82.5	82.2	82.4	82.2

3.4 Accumulation of K in digesters

Table 3 and Figure 4 show the accumulation of K in the digesters during the experimental period, calculated on a mass balance basis from influent and effluent K concentrations. At an OLR of 6 g COD L^{-1} day^{-1} rates of accumulation were around 0.3 g K day^{-1}. When the OLR was reduced by diluting the WSW, this rate fell dramatically to 0.033 and 0.034 g K day^{-1} in U1 and U2. Accumulation in the AF showed some variation with time, but in the last 35 days of operation, the rates in AF1 and AF2 were 0.024 and 0.031, respectively. The rates in the two reactor types were surprisingly similar, and showed no obvious sign of falling by the end of the run. The final values for K accumulation equated to an additional concentration of 4.5 mg K g^{-1} wet weight of granular sludge inoculum.

Osmo-regulation in Archaea has been previously described by Roberts (2004) and this group of organisms is known to be able actively to pump K^+ across the cell membrane. Under these circumstances, additional energy in the form of ATP is required to maintain osmo-regulation as reported by Mitchell (1973), Kashket (1985), Gober and Kashket (1986) and a small proportion of carbon is converted to meet this need reducing slightly the COD that can be metabolised to CH_4. In the current study the average SMP per g COD removed in the UASB reactors at the end of the experimental period was calculated to be 0.259 L CH_4 g^{-1} $COD_{removed}$. This corresponded to around 74% of the theoretical methane yield of the COD removed, or a shortfall of 0.029 L CH4 g^{-1} $COD_{removed.}$

Table 3 Accumulation of K in digesters

	AF1	AF2	U1	U2
K accumulated by day 56 (g)	2.35	2.52	2.73	2.78
K accumulated by day 115 (g)	4.46	4.74	4.74	4.92
K accumulated by day 115 (mg g^{-1} WW of original inoculum)	4.46	4.74	4.74	4.92
Accumulation rate at OLR 6 (g K day^{-1})	0.281	0.314	0.349	0.336
Accumulation rate at OLR 3 (g K day^{-1})	0.024*	0.031*	0.033	0.034

* Average for last 35 days

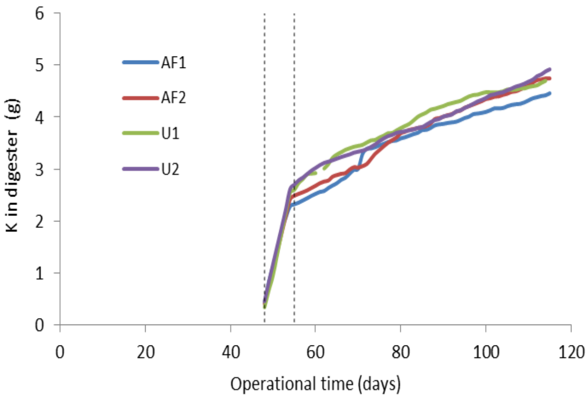

Figure 3 K accumulation in UASB and AF digesters. Vertical dotted lines indicate the change from SW to WSW, and the OLR reduction from 6 to 3 g COD L^{-1} day^{-1}

4. Conclusion

The comparison of a UASB digester with an anaerobic filter for the treatment of WSW showed no difference in the COD removal or the specific methane production for these two process types. An OLR of 6 g COD L-1 day-1 could not be maintained with WSW, and the highest steady loading achieved was 3 g COD L-1 day-1 at an influent concentration of 2.5 g COD l^{-1}, giving a HRT of around 26 hours. When fed on WSW the digesters accumulated K: the rate of accumulation and final amounts accumulated in both the UASB and AF were found to be very similar and had reached an additional concentration of between 4.5-4.9 mg K g^{-1} wet weight of granular sludge. The findings of this study will be useful in similar studies in other countries as it is also applicable for the other types of straw such as rice straw, barley straw, oat straw and soybean straw.

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