Renewable Energy 143 (2019) 501–511

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Evaluation of liquid and solid phase mixing in Chinese dome digesters using residence time distribution (RTD) technique

A.O. Jegede*,[1], G. Zeeman, H. Bruning

Sub-Department of Environmental Technology, Wageningen University and Research, Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 30 March 2018
Received in revised form
12 February 2019
Accepted 30 April 2019
Available online 8 May 2019

Keywords:
Residence time distribution (RTD)
Chinese dome digester (CDD)
Mixing
Liquid phase
Solid phase

ABSTRACT

The Residence Time Distribution (RTD) technique was applied to evaluate mixing of liquid and solid phases in laboratory scale Chinese dome digesters mixed via hydraulic variation. To achieve this purpose, six laboratory scales digesters with different mixing modes and two total solids (TS) concentrations using appropriate tracers were studied over a theoretical hydraulic retention time (HRT) of 30 days. The three different mixing modes were impeller, unmixed and hydraulic mixing, each at influent concentration of ca. 7.5 and 15% TS concentrations. The mode of mixing strongly affected the effective or actual residence time (t_a) and directly influenced the percentage of dead zones. The Chinese dome digesters had more dead volumes than the impeller mixed reactors and less than the unmixed reactors. This implied that mixing was more efficient in the impeller mixed reactors followed by the hydraulic mixed reactors and then the unmixed reactors, irrespective of the TS concentration. There was a clear relation between the RTD results and anaerobic digestion performance viz. methane production. There is need to optimize the hydraulic variation in the Chinese dome digester to reduce dead zones while also optimizing the effective residence time (t_a).

1. Introduction

Energy shortage in poor rural households in the developing world leads to challenges such as inadequate fuel for cooking and lighting. This shortage frequently leads to sickness and a low standard of living, thereby making it difficult for students to do their schoolwork [1]. However, if rural dwellers in developing countries could access a renewable and clean source of energy for their cooking and lighting needs, poverty could be reduced and standards of living improved [2]. Anaerobic digestion, producing biogas for cooking and biofertilizer as end products from organic wastes, is an attractive technology for rural areas. Domestic (household) biogas technology is well suited for rural households because of availability of organic matter as feedstock, energy recovery, and economic benefits.

The Chinese dome digester (CDD) is the most popular domestic digester in developing countries in terms of number [3–6]. It is the design of choice for the Netherlands Development Organisation (SNV) biogas programmes because of the digester's reliability, low maintenance requirement and long lifespan [6]. CDD is usually constructed underground with a concrete or reinforced plastic hemispherical dome top. The digester is operated in a semi-continuous mode at a relatively low total solid (TS) concentration (TS < 7%) and a long hydraulic retention time (HRT), viz. between 40 and 90 days[7,8]; at ambient temperature. Mixing in a CDD is achieved via hydraulic variation during gas use and reactor feeding. Biogas is produced and stored at the upper part of the digester displacing some digester content into the extension chamber. During gas use for cooking, gas pressure decreases and the displaced content in the extension chamber flows back into the main digester. The applied long HRT and low TS concentration make household digesters unnecessarily big. The application of a high solid anaerobic digestion process (TS > 7%) in Chinese dome digesters may present a better alternative to the present norm because dilution with water could be substantially reduced without affecting the digestion efficiency [9–11]). The advantage of applying this method would be a higher organic loading rates (OLRs) and then a smaller reactor volume would be applied. In high solid anaerobic digesters, the biological (microbial kinetics) and physical (mass transfer) processes are interlinked [12]. It has been

* Corresponding author.
E-mail addresses: jegedeabiodun@yahoo.com, ajegede@cerd.gov.ng (A.O. Jegede).

[1] Centre for Energy Research and Development, Obafemi Awolowo University, Ile ife, Nigeria.

https://doi.org/10.1016/j.renene.2019.04.160
0960-1481/

shown that the rheological properties of digestate from anaerobic digesters are affected by the percentage of total solids [13–15]. Digestate from high-solid (>7% TS) digesters has been reported to be visco-elastic with high shear stress and obeys the power law $\tau = k\gamma^n$, where τ - shear stress (Pa); γ - rate of shear (s^{-1}); k - consistency coefficient (Pa.s^n); n - flow behaviour index [12,15,16]. Consequently, achieving adequate mixing based on these characteristics at TS > 7% could be challenging [17,12]; and indeed could be more difficult to achieve in Chinese dome digesters, which are only mixed intermittently about three times a day via hydraulic variation during gas use. Mixing is an important parameter in the anaerobic digestion process to disperse substrate, nutrients, microorganismsand to achieve equal temperature distribution in the digester [18]. In addition, mixing equipment, mixing mode and reactor geometry can make results of mixing vary significantly [19].

To the best of our knowledge, high solids (TS > 7%) in Chinese dome digesters have never been evaluated for liquid and solid macro-mixing in either laboratory or pilot scale experiments. Therefore, this study evaluated as our objectivethe hydrodynamic behaviour in relation to reactor efficiency at two different influent TS concentrations, viz. 7 and 15% in Chinese dome digesters using the residence time distribution (RTD) method. RTD experiments are frequently used to study the hydrodynamic behaviour of reactors with single liquid phase [12,20–22] and both liquid and solid phases [12,23]. RTD techniques make use of tracers to investigate the hydrodynamic behaviour of reactors within food, bioprocess, and environmental technology domains and many more. Several authors [24];12,25,26] have applied RTD techniques to investigate mixing in anaerobic digesters, but most of the studies focused on Anaerobic Baffled Reactors (ABR), studies on Chinese dome digesters are scarce [23].

In this study, appropriate tracers were applied to follow the liquid and solid phases of laboratory scale Chinese dome digesters to investigate the effect of influent TS content on macro-mixing of the reactors. To achieve this, the hydrodynamic behaviour of laboratory scale CDDs was compared with that of laboratory stirred and unstirred anaerobic digesters at two different TS influent concentrations, using RTD technique. The hydrodynamic behaviour was evaluated by determining the percentage of dead zone via estimation of the actual residence time in the three types of digesters i.e. the Chinese dome, stirred, and unstirred digesters. Lastly, the RTD results were linked with the results of biogas production in the digesters.

2. Materials and methods

2.1. Reactor design

The experiments were conducted in six laboratory digesters consisting of two mechanical (impeller) mixed reactors, two unmixed reactors and two Chinese dome digesters (CDD). The CDD were mixed via hydraulic variation during gas production and collection. A scheme of reactors is presented in Fig. 1 a, b & c. The working volume of each digester is 39 L. The CDDs have an additional 10 L extension chamber. The extension chamber is directly connected to the reactor and serves to accommodate the hydraulic variation (displacement of reactor content during gas production and collection) and acts as an outlet for the reactor. The extension chamber is not considered as part of the working volume of the Chinese dome digesters. The digesters were constructed from polyvinyl chloride (PVC). Each type of the digester was fed with cow manure at ~7.5 and ~15% total solids (TS) concentrations. In the impeller and unmixed reactors, influents were added from the top and effluents withdrawn from the bottom. The two mechanically mixed reactors were mixed intermittently at 55 rpm for 10 min/hour. Biogas produced in the impeller mixed reactors and unmixed reactors was directly collected in gas bags while the biogas produced in the CDDs was stored in the headspace creating pressure to displace some of the reactor content to the extension chamber. Biogas was collected in a gas bag once a day before feeding. Consequently, some of the digestate in the extension chamber did flow back to the main reactor. In the CDDs, effluents were extracted from the extension chamber.

2.2. Substrate characteristics

Cow manure was used for all experiments and was collected at Obafemi Awolowo University farm, Ife, Osun, Nigeria. The manure was prepared by screening, blending to reduce particle size variation, and water dilution into two total solids concentrations 7.5% TS and 15% TS, and applied in each type of reactor as shown in Table 1.

2.3. Biogas measurement

The generated biogas was collected in gas bags and measured daily using a Schlumberger Lab wet gas meter. Biogas composition was determined in terms of carbon dioxide (CO_2) and methane (CH_4) contents. The CH_4 content was indirectly measured by measuring the concentration of CO_2 viz. CO_2 absorption using NaOH in the gas bag once a week. Specific biogas and methane yields were expressed as daily methane produced, divided by the amount of VS daily fed to the digesters, and used to monitor the digestion efficiency of the digesters.

2.4. Residence time distribution (RTD) technique

Liquid and solid phase macro mixing were experimentally investigated by using the Residence Time Distribution (RTD) method. In this study, a stimulus response technique was applied to investigate the mixing in the liquid and solid phases. A pulse input signal method was applied in all reactors at time $t = 0$, by injecting a known number of tracers to the influent. The tracer amount was then measured daily in the reactor outlet during effluent withdrawal. Benbelkacem et al. [12], described the selection of tracers for biochemical reactors as critical and the tracer should fulfil the following criteria:

- The tracers should not impact the biochemical reaction process and not converted to another phase;
- The tracer must possess similar physical characteristics as the phase being studied;
- The tracers should be easily and accurately be detectable and measurable.

In this study, fluorescein was selected as a tracer for the liquid phase. Fluorescein is a dye soluble in water with a chemical formula $C_{20}H_{12}O_5$ that is frequently used in biochemical research [27,28] both to trace blood stain in serology and in dye tracing. The fluorescein concentration was measured in the effluents using an ultraviolet (UV) spectrophotometer, Helious Omega 479 Mb, Thermo Scientific at 488 nm. The effluents were centrifuged at 10,000 RPM for 20 min, filtered using 0.45 μm membrane filter and diluted before measurement using UV.

Polystyrene (PS) was selected as the tracer for the solid phase. Polystyrene with a density of 1.04 kg/Lwas selected. Polystyrene has a similar density as Bioflow 9®, a solid plastic tracer applied by Benbelkacem et al., [12]; for evaluating the macro mixing in the solid phase. 300 pieces of the PS tracers, with diameter 0.7 cm, were injected into each of the six reactors via influent addition. The PS tracers were detected and counted manually by separating them

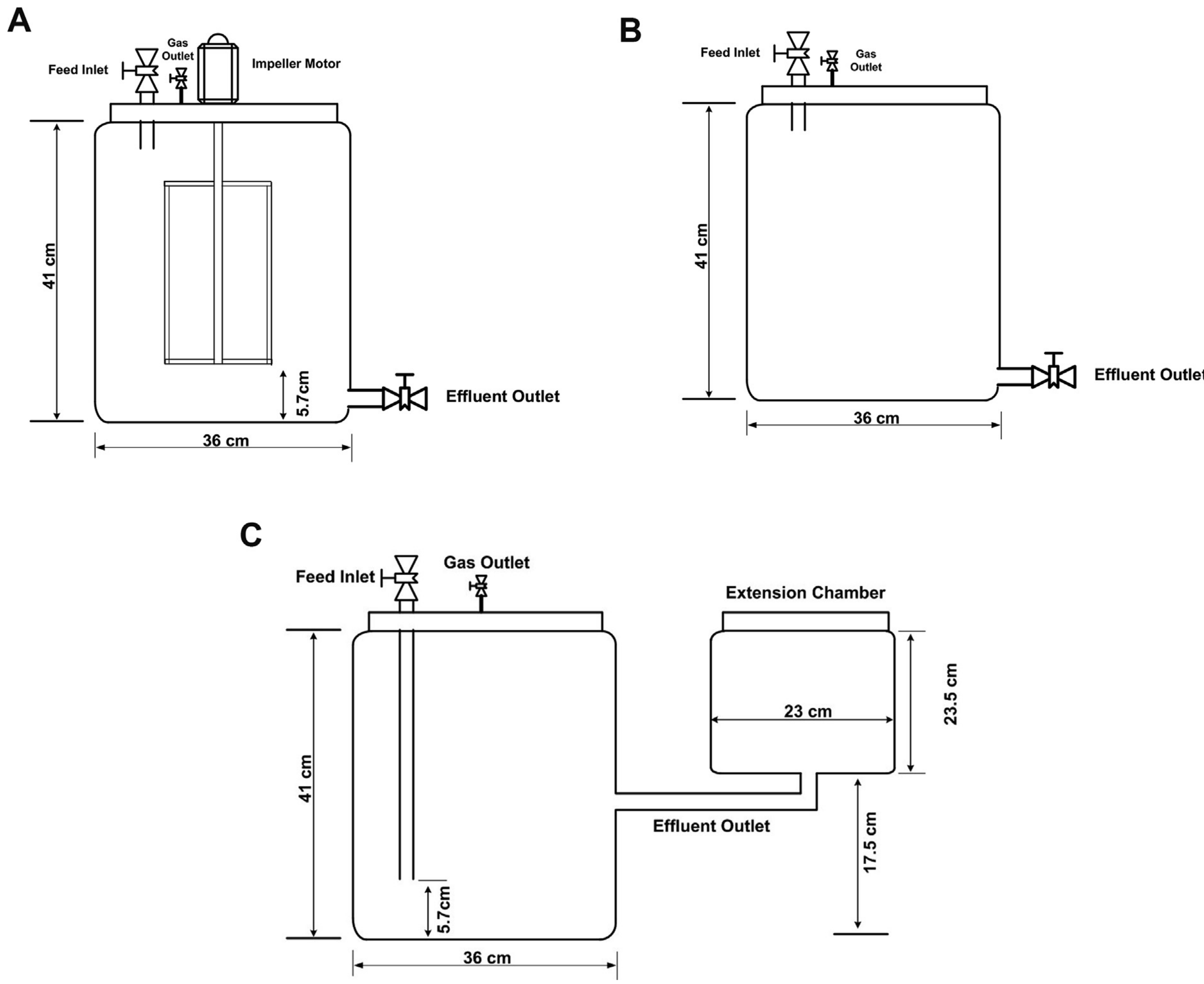


Fig. 1. (a) impeller mixed. (b) Unmixed. (c) Chinese dome digesters

from the digester effluent during effluent withdrawal

The liquid and solid tracers were injected into the digesters after achieving steady-state conditions[2] in all the reactors, and the duration of the RTD experiments were 2.2 times the theoretical hydraulic retention time, *t* in *days*, defined by Eq. (1)

$$t = \frac{V}{Q} \quad (1)$$

The concentration of the fluorescein C_i for the liquid phase was measured from the effluent daily.

2.5. Liquid phase modelling

Many authors have worked on the interpretation of RTD curves [12,21,22,29]. The liquid phase macro mixing was modelled using a simplified model assuming continuous operation, continuous mixing and simplified geometry. The model applied in the study is schematically shown in Fig. 2. Each of the digesters investigated was represented by tanks in series from 1 to n. Each tank or stage had three compartments. The top compartment was ideally mixed and materials entering the top stage was exchanged with the second compartment. The second compartment could be interpreted as either a semi-dead volume that had limited exchange with the bulk or solid matter to which the tracer adsorbed and desorbed. The third compartment was the complete dead zone, without exchange of materials with the other compartments.

The dynamic mass balance for the top compartment is given by

$$(1-\beta)V\frac{dC_i}{dt} = Q(C_{i-1} - C_i) + \alpha Q(C_{di} - C_i) \quad (2)$$

where:

(1-β) V = Volume of the top compartment
t = Time (d)
Q = Flow rate through the system (L/d)
C = Tracer concentration in the top compartment (C_1, C_2, C_n) (mg/L)

Table 1
Total solid concentrations in reactors.

	Reactor design	Total solids (TS) %
1	Impeller mixed	7.5
2	Impeller mixed	15
3	Unmixed	7.5
4	Unmixed	15
5	Chinese dome (hydraulic)	7.5
6	Chinese dome (hydraulic)	15

[2] Steady state is defined as period when biogas production varies less than 15%.

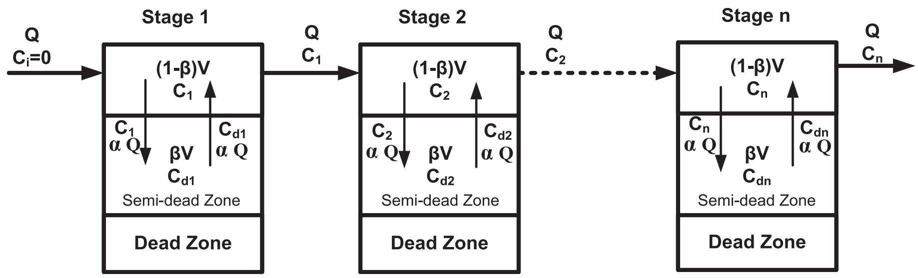


Fig. 2. Schematic diagram of the non-ideal model applied for the liquid phase.

C_i = Ingoing tracer concentration, either from the inlet or the previous stage (mg/L)
C_d = Tracer concentration in the second compartment (semi-dead zone) (mg/L)
α = Dimensionless exchange rate, relative to the flow rate Q, between top and second compartment. A value of $\alpha = 0$ means a true dead zone, a large value of α means no semi dead zone at all.
n = Number of tanks in series

The dynamic mass balance for the second compartment is given by

$$\beta V \frac{C_{di}}{dt} = -\alpha Q (C_{di} - C_i) \tag{3}$$

where:

βV= Volume of the second compartment (L)
$\beta = 0$ means no semi dead zone at all, similar to a large value of α

In the implementation of the model, V and Q are grouped as one parameter V/Q – the one stage HRT. The Runge–Kutta midpoint method was used for the integration and fitting of the model to the experimental data applying the least square method, where, Q = flow rate (L/d), V = Volume of reactor (L), C_o = initial concentration of tracer (mg/L), as shown in Table 2.

The exit time distribution for the pulse-input methods represents external RTD, *E(t)* and could be defined by Eq. (4).

$$E(t) = \frac{t_{a.}\ C_{fit}}{\sum C_{fit}\ \Delta t} \tag{4}$$

The actual mean residence time (t_a), unit *(d)* was determined from Eq. (5).

$$t_a = \frac{\sum t C_{fit} \Delta t}{\sum C_{fit} \Delta t} \tag{5}$$

where, C_{fit} is the concentration of the best fit.

The percentage of dead zone was estimated using Eq. (6)

Table 2
Residence time distribution (RTD) operational parameters.

TS %	7.5	15
Q (L/d)	1.3	1.3
V (L)	39	39
C_o (mg/L)	50	50

$$\text{Dead Volume } (\%) = \frac{t_a}{V/Q} \tag{6}$$

2.6. Solid phase modelling: Sedimentation

For the sedimentation evaluation, the standard analysis method used for the liquid phase could not be applied because the number of solid particles was only 300 pieces. This implies that the amount of tracer collected from each reactor was small and the quantities in a sampling volume each day were not as explicit as the concentration of the soluble tracers and not statistically applicable [12]. On the other hand, it was possible to determine accurately the quantity of the Polystyrene (PS) coming out the reactor by just separating them from the digestate and counting at a given time using Eq. (7).

$$N(t) = \sum_{i=0}^{t} N_i \tag{7}$$

where: N_i is the number of PS tracers counted in the effluent volume at time t_i.

The fraction of PS tracers staying in the digesters shorter than the retention time *t* was determined by Eq. (8)

$$F_{PS}(t) = \frac{N(t)}{N_{total}} \tag{8}$$

where, N_{total} is the total number of PS tracers added.

The *F*-function was determined by fitting the cumulative $F_{PS}(t)$, data using Eqs. (9) and (10).

$$F(t) = 1 - (1 + t^* p(t))^* e^{-a*t} \tag{9}$$

$$p(t) = a_o + a_1^* t + a_2^* t^2 \tag{10}$$

The E-curves were calculated from the *F*-function using Eq. (11)

$$E(t) = \frac{dF}{dt} \tag{11}$$

Excel solver was used to determine the best fits for the cumulative $F_{PS}(t)$ data, thereby finding the best values for a, a_o, a_1, and a_2.

The actual mean residence time t_a *(d)*, was then calculated using Eq. (12),

$$t_a = \int_0^1 t\ dF = \frac{a^3 + a^{2*}\ a0 + 2^*a^*a1 + 6^*a2}{a^4} \tag{12}$$

3. Results and discussion

The results of the macro mixing of both the liquid and solid phase of the six different anaerobic digesters are presented in this section (see Table 3).

3.1. Mixing characterization of the liquid phase

The mixing of the liquid phase was investigated for six reactors with three different mixing modes and two total solids (TS) influent concentrations.. For all six reactors, the actual (experimental) mean or average residence times (t_a) were lower than the theoretical residence time (HRT). The actual mean residence times (t_a) were 27.05, 25.12, 23.57, 20.31, 25.47, and 23.20 days for reactors 1 to 6 as shown in Table 3, meaning the active volume of the reactors were lower compared to the reactors volume.

Best fits were obtained by two tanks in series for the mixed digesters and three tanks in series for the unmixed and Chinese dome digesters as seen in Table 3. The mixed digesters and the CDDs had semi-dead zones. In the mixed digesters, there was no semi-dead volume at the first stage, but there was at the second stage for both digesters. In the CDDs, there were dead volumes in both digesters at stages 2 and 3. The dimensionless exchange rate relative to flow rate (α) between the second (semi-dead zone) and top compartments are also shown in Table 3. The α values imply that there were exchanges between the top and second compartments (semi-dead volume) in the mixed reactors at stage 2, and the Chinese dome digester at both stages 2 and 3. However, in the unmixed digesters there was no semi-dead zone but main and large dead volumes.

The percentage of semi-dead and dead zones in the reactors depended on the mode of mixing and applied TS concentrations. The dead zones were estimated from the actual mean residence time. . It was observed that the impeller mixed reactors had the lowest dead zones, 9.83% and 16.28% for reactors 1 and 2 respectively. This to some extent could be due to the accumulation of digester content. Reactor 2 had a higher dead volume than reactor 1 because reactor 2 was fed with higher TS content (15%), but same mixing intensities were applied to both reactors. The unmixed reactors had the highest dead zones mainly because no forced mixing was applied and biogas production in the reactors was not sufficient to establish mixing in the digesters at the operated TS concentrations (7.5 & 15%). The Chinese dome reactors (hydraulic mixed) had a lower dead volume compared to the unmixed digesters but higher than the impeller mixed digesters as shown in Table 3. The hydraulic variation achieved in the Chinese dome digesters during gas collection improved mixing, compared to the unmixed digesters but not enough to achieve similar results as in the impeller mixed reactors.

The dimensionless retention time distribution (RTD) graphs (E curves) are presented in Fig. 3. The E curves for each type of digester are similar but differ in magnitude based on TS concentrations. This implies that the type of digester in relation to mode of mixing plays an important role in the established RTD curves. Digesters 1 and 2 produced similar E curves but different magnitudes, with early peaks and then a gradual exponential decay. Digester 3 and 5, having the same TS concentrations, produced broader peaks and quick decays while 4 and 6 produced higher peaks. The impeller mixed reactors have the sharpest peaks followed by the Chinese dome digesters and then the unmixed reactors. The peaks trend relates to the actual residence time (t_a) of the reactors. None of the digesters produced symmetrical curves or peaks close to mean residence time ($\theta = 1$). All peaks appeared between $\theta = 0.5$–1. The peaks clearly showe that a certain amount of tracer was removed from the reactors before the mean residence time of the reactors. Mixed reactors and CDDs reactors have E curves with long tails which is consistent with the results in Table 3. The size of the tails varies, which is an indication of the fraction of the semi-dead zone and an exchange of particles occurring between the semi-dead zone and the active volume.

The applied model described was also used to investigate the mixing of the liquid phase with respect to the number of tanks (or stages) connected in series. The number of reactors (n) in series (Table 3) was adjusted to fit the experimental data. The best fit curves were determined for all the reactors and shown in Appendix 1. All the models were in a good agreement with the experimental data and the coefficient of determination (R^2) are 0.90, 0.86, 0.96, 0.95, 0.93, and 0.85 for reactors 1–6. The number of reactors (n) applied in the models differs based on the mode of mixing and reactor type. For the impeller mixed reactors, $n = 2$ for both 7.5 and 15% TS concentrations, while the unmixed and Chinese dome digesters $n = 3$ for both 7.5 and 15% TS. The dimensionless exchange rate relative to flow rate between bottom and the semi-dead zone compartment (α) for the reactors 1–6 are 0.43, 0.27, 0, 0, 0.6, and 0.7. This together with the percentage dead zone, the unstirred reactors have true or higher dead zones compared to the stirred and Chinese dome digesters. Consequently, based on the number of reactors applied in the model and shape of the E (curves), the liquid phase macromixing in the impeller mixed reactors is close to two Continuously Stirred Reactors (CSTRs) at both TS contents with semi-dead volumes. The unmixed reactors modelled with 3 CSTRs with no semi-dead volume, but large dead zone approached a plug flow reactor. The CDDs at both influent TS concentrations were modelled with three tanks with a very small first stage according to values of V/Q, and no semi-dead volume shown in Table 3 are close to three CSTRs in series. This implies for the CDDs, inlet mixing is prominent in these reactors.

Table 3
Results parameters for the non-ideal model.

	Reactor/ % TS	α	β	n	t_a (day)	Dead volume (%)	Volume (%)/Stage
1	**Impeller 7.5**	0	–		27.0		50
		0.43	0.53	2		9.8	50
2	**Impeller 15**	0	–		25.1		50
		0.27	0.47	2		16.3	50
3	**Unmixed 7.5**	0	–		23.6		33.3
		0	–				33.3
		0	–	3		21.4	33.3
4	**Unmixed 15**	0	–		20.3		33.3
		0	–				33.3
		0	–	3		32.3	33.3
5	**CDD 7.5**	0	–		25.5		9.66
		0.60	0.86				45.2
		0.60	0.86	3		15.1	45.2
6	**CDD 15**	0	–		23.2		3.35
		0.73	0.94				48.3
		0.73	0.94	3		22.7	48.3

N.B. stage also means number (n) of tank, if $\alpha = 0$, β has no meaning.

3.2. Mixing characterization of the solid phase

Fig. 5 and Table 4 present the fraction of the extracted solid tracer particles for the six reactors.. The model data fit well to the experimental data given in Appendix 2. It can be seen that the *F*-curves have the same trend in all the reactors because the type of applied tracer material, is same in all reactors and have the same densities. This is consistent with the findings of Benbelkacem et al. [12], on solid sedimentation of four different tracers' materials having different densities: 0.95, 1, 1.14, and 2.5 kg/L. Their results

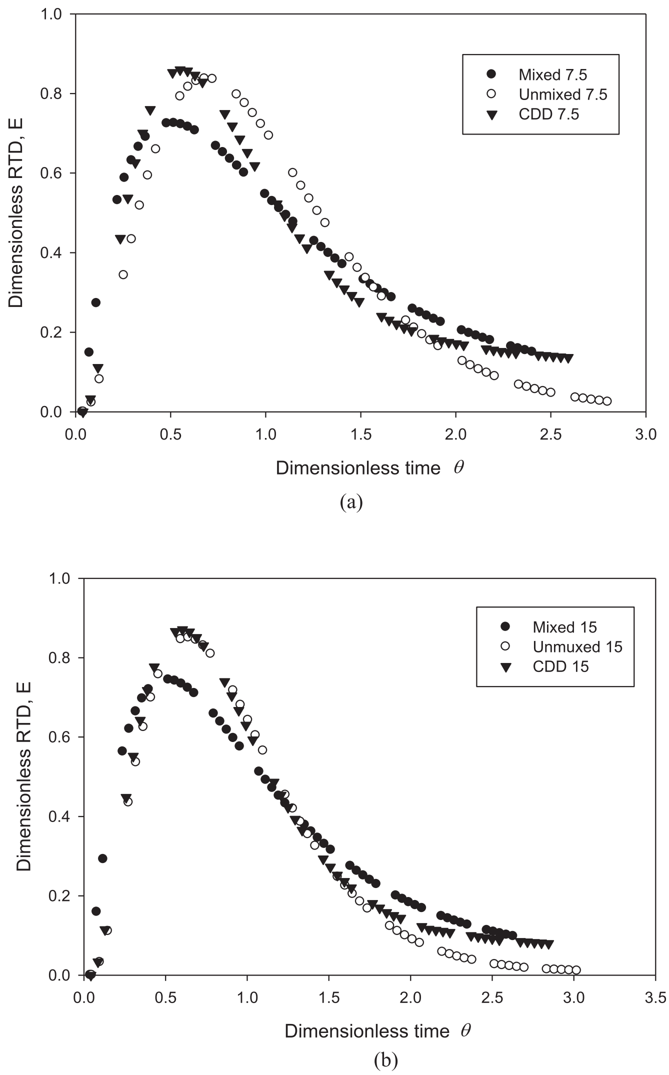


Fig. 3. The dimensionless retention time distribution (RTD) E, plotted against the dimensionless (θ) time, for the liquid phase of digesters (a) 1, 3 and 5 (b) 2, 4, and 6.

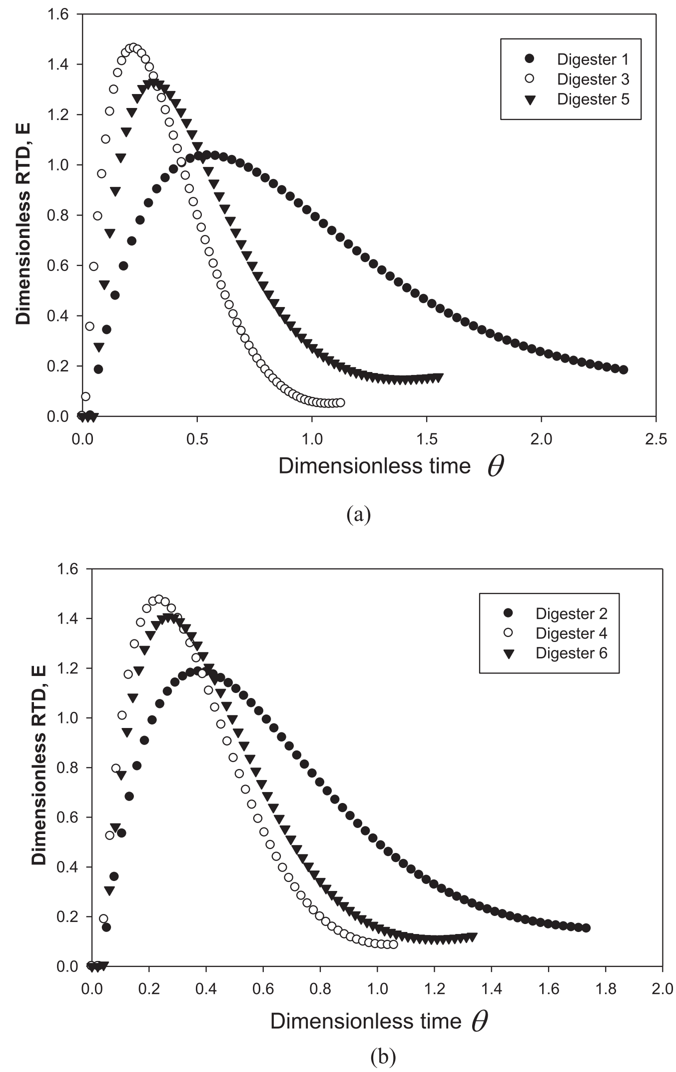


Fig. 4. The dimensionless retention time distribution (RTD) E, plotted against the dimensionless (θ) time, for the solid phase of digesters (a) 1, 3 and 5 (b) 2, 4, and 6.

showed that the tracers segregated according to their densities. However, the total number of particles extracted from the reactors at the end of the experiments differed according to the mixing mode and geometry of the reactors. As shown in Fig. 4 and Table 4 after two hydraulic retentions times ($\theta = 2$), the stirred reactors (1&2) have the highest percentages of tracers extracted (75 and 71%), followed by the Chinese dome reactors, 5 (68%) and 6 (66%). The unstirred digesters have the lowest numbers of tracers extracted 64 and 63% for reactors 3 and 4 respectively.

The dimensionless residence time, E, presented in Fig. 4, was estimated by differentiating the *F* functions over time and similar to the E-curves of the liquid phase. All peaks appeared before the first HRT, however, the mixed reactors have broader peaks while the unmixed and CDDs have sharp peaks.

The actual or effective retention times calculated from the fitted model for all the reactors differ according to their mode of mixing. After two hydraulic retention times, the effective mean residence time *(t_a)* are: 49.98, 54.34, 64.61, 53.26, 54.38, and 58.40 days for reactors 1–6. On the average, the mixed reactors have the lowest retention time followed by the Chinese dome, and lastly the unmixed. t_a, the fraction of particles extracted in relation to the mean residence time is an indication of degree of sedimentation or segregation of solid particles in the reactors. In the unmixed digesters, the fraction of particles extracted is lowest compared to other reactors. These results corroborate the results of the liquid phase modelling where the unmixed digesters have the largest dead volumes with no semi-dead volumes. This therefore implies the fraction of particles trapped or extracted is directly proportional to the percentage of the dead zone in the reactors.

3.3. Reactors and biogas production

The Chinese dome digesters, which were mixed by hydraulic variation, exhibited a considerable percentage of dead zones and a high solid retention, which in fact affected the reactor performance and digestion efficiency. The fraction of the digester volume occupied by the dead zone is a proof of digester performance. The semi-dead and dead zones are regions in the reactor where flow velocities during mixing are very low, and fluid is delayed in these zones. These zones will reduce the actual reactor volume or create zones of non-uniform concentrations and temperature. Dead zones are results of poor mixing or absence of mixing. However, there is a debate and divergent views about the role and extent of mixing in anaerobic digesters. The need for biogas reactors to be adequately

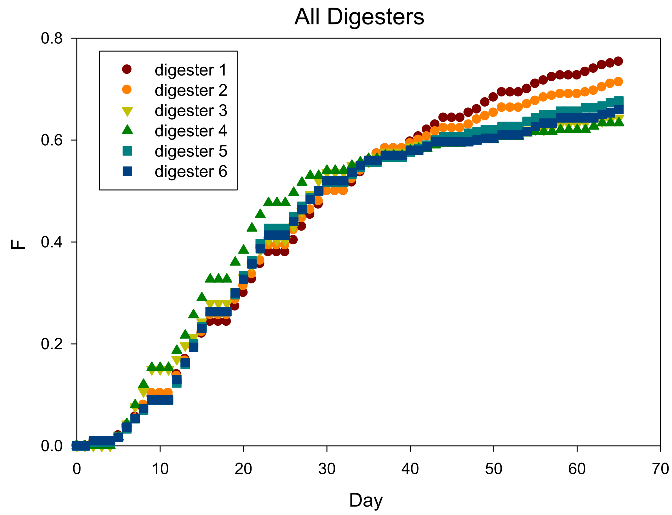


Fig. 5. Fraction of the extracted particles, (F) function for the solid phase.

mixed has been supported by many authors [30,31], while challenged by others [32–35]. In fact, some authors [36,37]) reported similar biogas production when comparing continuously mixed and intermittently mixed reactors. While others [32] reported similar biogas production between intermittently mixed and unmixed reactors. Unfortunately, these studies didn't evaluate hydrodynamic behaviour of liquid and solid phases of the reactors using RTD to compare with the biogas production. However, in this study, results of the liquid phase presented earlier, it can be seen that mixing is important compared to non-mixing but an optimal mixing point to achieve optimal reactor performance is yet to be established.

The mode of mixing and geometry of the bioreactors play an important role in the RTD. The RTD results of the macromixing of the liquid and solid phases in the study showed that the impeller mixed reactors performed best, followed by the Chinese dome digesters and then the unmixed digesters. Similarly, the results of methane production at steady state are consistent with this trend. Table 4 presents the average methane production from all the reactors. The high methane production in the impeller mixed reactors compared to the CDD and unmixed reactors is attributed to the forced mixing via impeller, which minimizes stratification in the reactors. This is consistent with the calculated dead zone in the RTD study where the impeller mixed reactors exhibited the lowest dead regions. Biogas release in the liquid phase in intermittently mixed reactors has been reported to increase during mixing regimes as compared to non-mixed periods [38,39]. This means gas release may be hindered in unmixed digesters and mixing increases the chances of mass transfer liquid phase to gas phase. The Chinese digesters produced more methane than the unmixed digesters as reported. They also have slightly higher methane content compared to the unmixed digesters. This could be attributed the differences in

Table 4
Fraction of extracted tracer particles from rectors after two HRT, actual residence time t_a of solid particles and specific methane production.

Reactor	Extracted particles (%)	t_a (day)	CH_4 L/g VS
1	75	49.98	0.16
2	71	54.34	0.15
3	64	64.61	0.1
4	63	53.26	0.09
5	68	54.38	0.13
6	66	58.4	0.12

the HRT viz. the uneven mixing created during the hydraulic variation during gas collection or gas “use”. Volumetric biogas production rates increased with increase in TS concentration, nevertheless, specific methane production and methane content in the ‘double fed digesters’ (impeller 2, unmixed 4, and CDD 6) were lower compared to impeller 1, unmixed 3, and CDD 5. This might imply higher volumetric biogas production in the double fed digesters does not improve mixing compared to single fed digesters. One major reason for this is that the rheological properties, especially viscosity of manureincreases at higher TS concentration. The viscous property of the reactor content coupled with the reactor type and mode of mixing did not improve specific methane production. This also means that at higher total solid concentration (TS) loading, the organic fraction could not be optimally utilized at the applied HRT and mesophilic temperature range.

3.4. Mixing in Chinese dome digesters

The Chinese dome digesters can be described as three CSTRs in a series based on the RTD results of the liquid phase. The Chinese dome digester complex geometry i.e. the addition of the extension chamber, which helps to provide the natural hydraulic variation and also serves as the outlet of the reactor. The mixing in the CDD reactors has been poorly investigated in literature with little or no information available about the reactor hydrodynamics. The suspected dead zones and sedimentation in the reactors are primarily at the bottom of the reactors, which is the region below the effluent pipe that connects the main reactor to the extension chamber. During the hydraulic variation, there are possibilities that these regions are poorly mixed because only low velocities would be achieved by the downward movements and flow of the reactor contents during these hydraulic variations.

Future research should focus on how to reduce the dead zones and large sedimentation at the bottom of the reactor. One of the possible methods is increasing the number of naturally occurring hydraulic variations in the reactor. To achieve this, special approaches are required to increase the mixing circles naturally, such as using the pressure created by the biogas produced in the reactor without the use of any internal mechanical or electrical devices. This is required because any addition or inclusion of any of these devices will increase the installation and maintenance cost of the Chinese dome digester.. It is worthwhile to note that, the Chinese dome digesters are primarily used by poor people mostly in developing countries with little or no access to electricity and limited access to skilled technicians for maintenance. To this end, an innovative approach that will require the use of advanced modelling methods such as computational fluid dynamics (CFD) to study and to optimize the velocity flow fields in the reactor should be investigated to optimize the reactor performance via improving the mixing frequency and subsequently reduce dead zones and sedimentation.

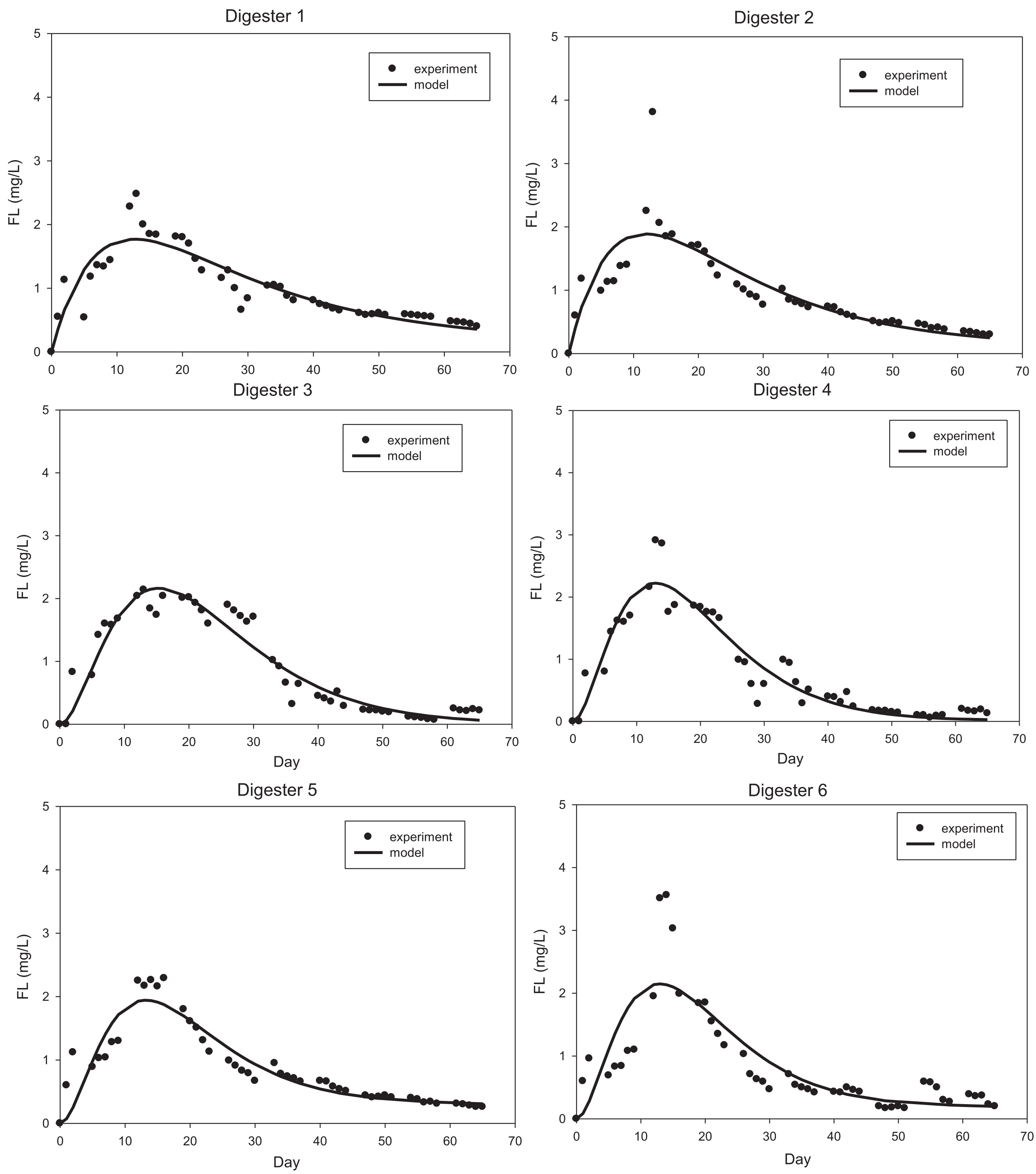
4. Conclusion

The residence time distribution (RTD) technique was applied to study the hydrodynamic behaviour of three types of reactors: impeller mixed, unmixed, and the hydraulic mixed (CDD) reactors at two different TS concentrations. The impeller mixed reactors have the lowest dead zones followed by the hydraulic reactors, and lastly the unmixed. The reactors performance in terms of biogas production is directly related to the percentage of dead zones in both liquid and solid phases. The reactor type and mixing modes had direct impact on reactor hydrodynamic and eventually biogas production. At both TS concentrations, the CDDs had considerable dead zones, implying the mixing achieved by the hydraulic variation is inadequate at TS > 7.5%. The CDD digester therefore needs to be optimized for improved hydraulic variation to achieve optimized mixing cycles to achieve higher biogas production without use of moving parts.

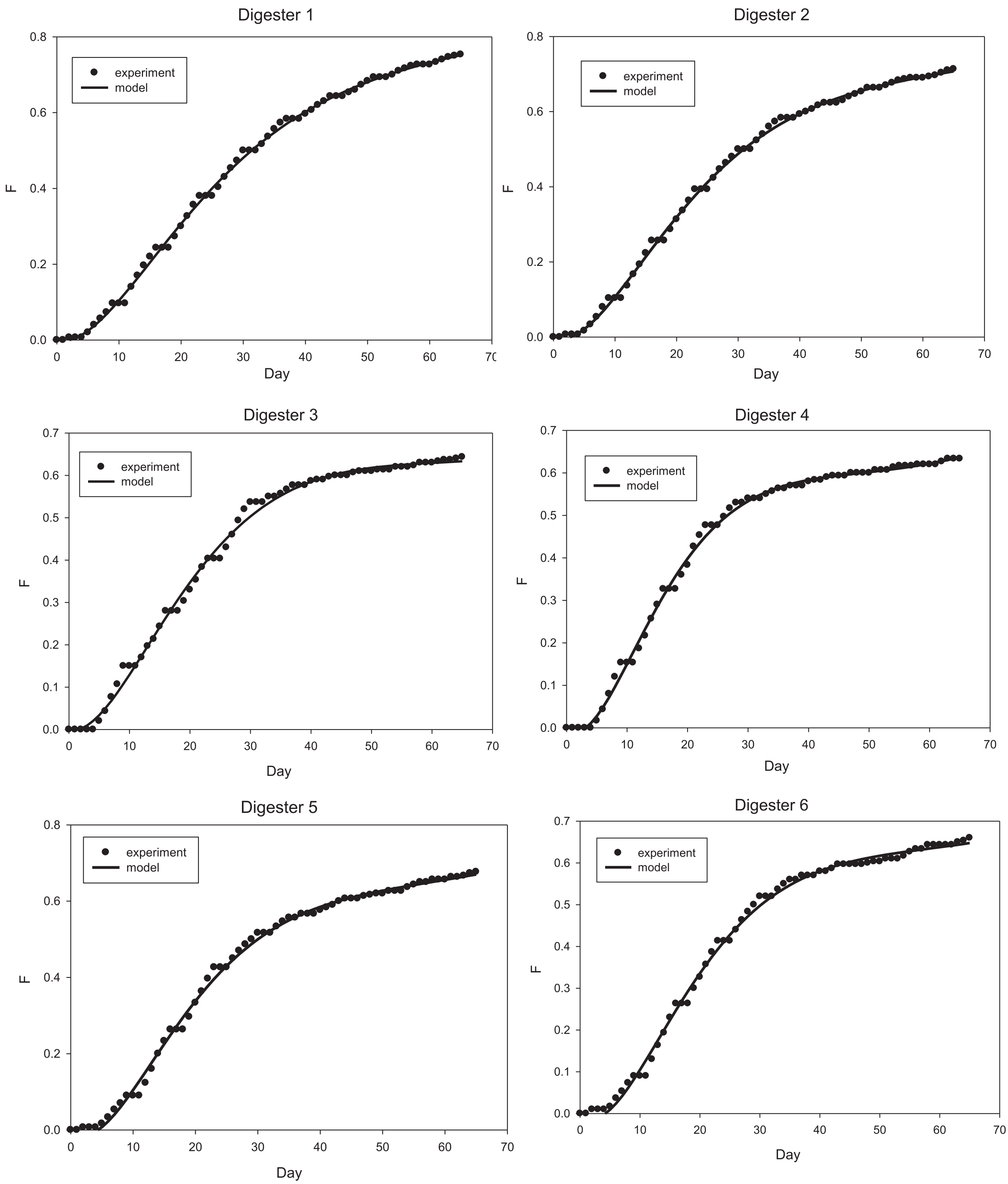
Acknowledgments

This work was funded by the Netherlands Fellowship Programme (NFP),The Netherlands. Special thanks to the analytic/lab support team at Sub-Department of Environmental Technology, Wageningen University, The Netherlands. Special appreciations to the management and support staff of Biochemical Engineering laboratory, Centre for Energy Research and Development, Obafemi Awolowo University, Ile-ife Nigeria for their support.

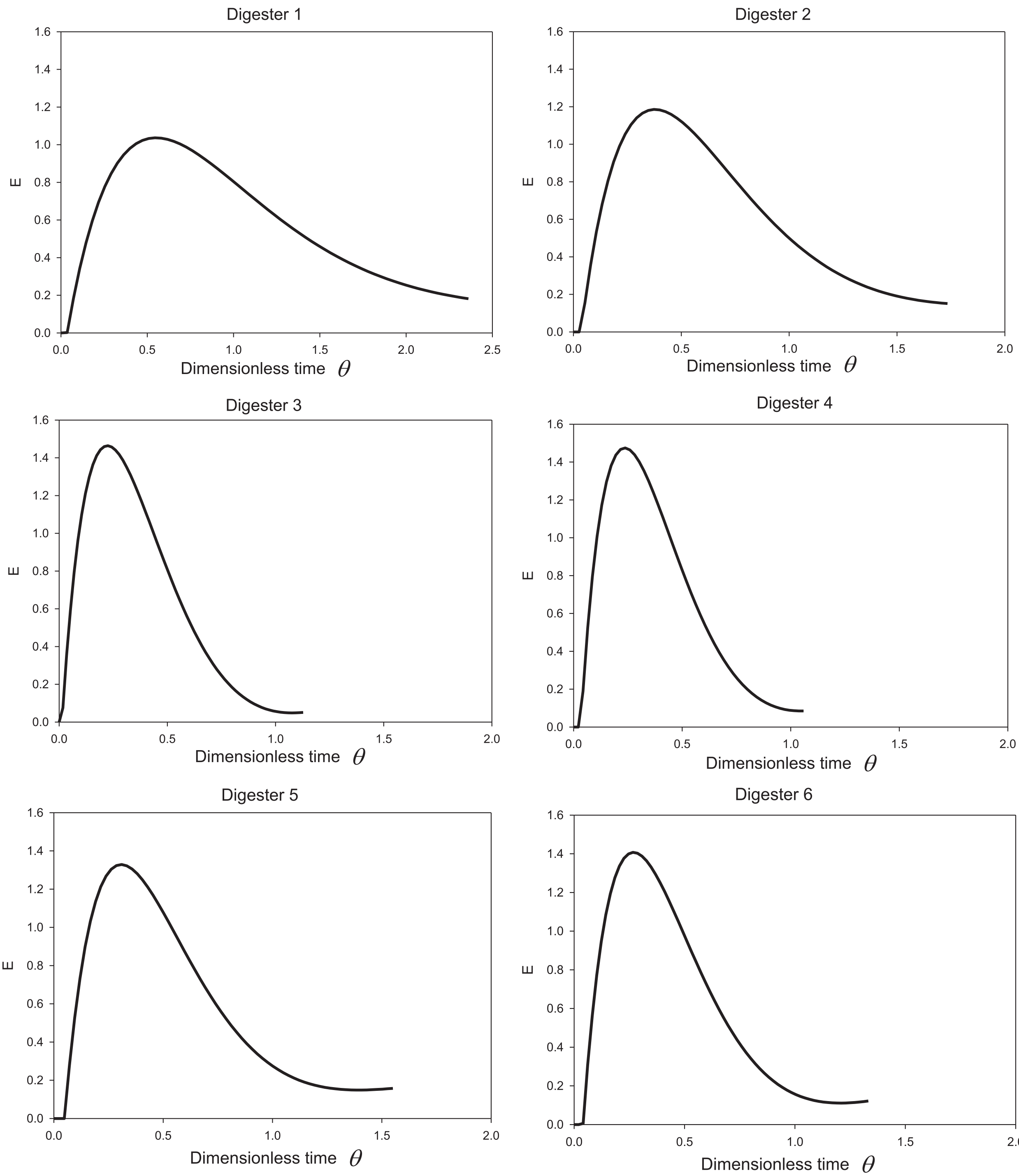
Appendix 1. Concentration of tracer FL (mg/L) against time in daysfor all digesters, experimental data and model for the liquid phase.



Appendix 2. *F* function with the fitted data for the six reactors against time in days



Appendix 3. Dimensionless RTD, (E-curves) for the solid phase of all reactors



References

[1] G. Austin, J. Blignaut, South African National Rural Domestic Biogas Feasibility Assessment, Ministry of Development Co-operation, The Netherlands, 2008.
[2] V. Tumwesige, D. Fulford, G.C. Davidson, Biogas appliances in sub-sahara Africa, Biomass Bioenergy 70 (2014) 40–50.
[3] Y. Chen, G. Yang, S. Sweeney, Y. Feng, Household biogas use in rural China: A study of opportunities and constraints, Renew Sustain Energy 14 (2010) 545–549.
[4] I. Ferrer, E. Cadena, Perez, M. Garfi, Technical, economic and environmental assessment of household biogas digesters in developing countries, in: Proceedings of 13th World Congress on Anaerobic Digestion, 25-28 June 2013, Sandiago de Compostela, Spain, 2013.
[5] D. Fulford, Running a Biogas Programme: A Handbook, Intermediate Technology Publications, London, 1988.
[6] P.C. Ghimire, SNV Supported domestic biogas programmes in Asia and Africa, Renew. Energy 49 (2013) 90–94.
[7] B.X. An, T.R. Preston, Gas production from pig manure fed at different loading rates to polyethylene tubular biodigesters, Livest. Res. Rural Dev. 11 (1) (1999). http://www.cipav.org.co/lrrd/lrrd11/1/an111.htm.
[8] I. Ferrer, M. Garfí, E. Uggetti, L. Ferrer-Martí, A. Calderon, E. Velo, Biogas production in low-cost household digesters at the Peruvian Andes, Biomass Bioenergy 35 (2011) 1668–1674.
[9] A.K. Jha, J.Z. Li, L. Nies, L.G. Zhang, Research advances in dry anaerobic digestion process of solid organic wastes, Afr. J. Biotechnol. 10 (2011) 14242–14253.
[10] Y.B. Li, S.Y. Park, J.Y. Zhu, Solid-state anaerobic digestion for methane production from organic waste, Renew. Sustain. Energy Rev. 15 (2011) 821–826.
[11] O.P. Karthikeyan, C. Visvanathan, Bio-energy recovery from high-solid organic substrates by dry anaerobic bio-conversion processes: A review, Rev. Environ. Sci. Biotechnol. 12 (2013) 257–284.
[12] H. Benbelkacem, D. Garcia-Bernet, J. Bollon, D. Loisel, R. Bayard, J.-P. Steyer, R. Gourdon, P. Buffiere, Liquid mixing and solid segregation in high-solid anaerobic digesters, Bioresour. Technol. 147 (2013) 387–394.
[13] P. Battistoni, Pre-treatment, measurement execution procedure and waste characteristics in the rheology of sewage sludges and the digested organic fraction of municipal solid wastes, Water Sci. Technol. 36 (1997) 33–41.
[14] P. Battistoni, G. Fava, C. Stanzini, F. Cecchi, A. Bassetti, Feed characteristics and digester operative conditions as parameters affecting the rheology of digested municipal solid wastes, Water Sci. Technol. 27 (1993) 37–45.
[15] H.M. El-Mashad, W.K.-P. van Loon, G. Zeeman, G.P.A. Bot, G. Lettinga, Design of a solar thermophilic anaerobic reactor for small farms, Biosyst. Eng. 87 (3) (2004) 345–353.
[16] D. Garcia-Bernet, D. Loisel, G. Guizard, P. Buffiere, J.P. Steyer, R. Escudie, Rapid measurement of the yield stress of anaerobically-digested solid waste using slump tests, Waste Manag. 31 (2011) 631–635.
[17] M. Terashima, R. Goel, K. Komatsu, H. Yasui, H. Takahashi, Y.Y. Li, T. Noike, CFD simulation of mixing in anaerobic digesters, Bioresour. Technol. 100 (2009) 2228–2233.
[18] D. Deublein, A. Steinhauser, Biogas from Waste and Renewable Resources, Wiley-VCH Verlag GmbH& Co. KGaA, " Weinheim, Germany, 2008.
[19] J. Lindmark, E. Thorin, R.B. Fdhila, E. Dahlquist, Effect of mixing on the result of anaerobic digestion: Review, Renew. Sustain. Energy Rev. (40) (2014) 1030–1047.
[20] R. Escudie, T. Conte, J.P. Steyer, J.P. Delgenes, Hydrodynamic and biokinetic models of an anaerobic fixed-bed reactor, Process Biochem. 40 (2005) 2311–2323.
[21] O. Levenspiel, Chemical Reaction Engineering, J. Wiley and Sons, New York, 1972.
[22] A.D. Martin, Interpretation of residence time distribution data, Chem. Eng. Sci. 55 (2000) 5907–5917.
[23] M.A. Hamad, A.M. Abdel Dayem, M.M. El Halwagi, Evaluation of the performance of two rural biogas units of Indian and Chinese design, Energy Agric. 1 (1983) 235–250.
[24] A. Grobicki, D.C. Stuckey, Hydrodynamic characteristics of the anaerobic baffled reactor, Water Res. 26 (3) (1992) 371–378.
[25] X.L. Liu, N.Q. Ren, C.L. Wan, Hydrodynamic characteristics of a four-compartment periodic anaerobic baffled reactor, J. Environ. Sci. 19 (2007) 1159–1165.
[26] I.V. Skiadas, G. Lyberatos, The periodic anaerobic baffled reactor, Water Sci. Technol. 38 (9) (1998) 401–408.
[27] F. George Arsnow, A. Michael Vancil, P. Robert Schruber, N. Cristina Ramacciotti, Dye trace study: Trid and true method yields surprising results, Proc. Annu. Int. Conf. Soils, Sediments, Water and Energy 15 (2010) 26, in: http://scholarworks.umass.edu/soilsproceedings/vol15/iss1/26.
[28] J.E. Noga, P. Udomkusonsri, Fluorescein: A rapid sensitive nonlethal method for detecting skin ulteration in fish, Vet. Pathol. 39 (2002) 726–731.
[29] O. Sanchez, S. Michaud, R. Escudié, J.P. Delgenes, N. Bernet, Liquid mixing and gas–liquid mass transfer in a three-phase inverse turbulent bed reactor, Chem. Eng. J. 114 (2005) 1–7.
[30] J. Bridgeman, Computational fluid dynamics modelling of sewage sludge mixing in an anaerobic digester, Adv. Eng. Software 44 (2012) 54–62.
[31] M. Halalsheh, G. Kassab, H. Yazajeen, S. Qumsieh, J. Field, Effect of increasing the surface area of primary sludge on anaerobic digestion at low temperature, Bioresour. Technol. 102 (2011) 748–752.
[32] X. Gomez, M.J. Cuetos, J. Cara, A. Moran, A. Garcia, Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes-conditions for mixing and evaluation of the organic loading rate, Renew. Energy 31 (2006) 2017–2024.
[33] M. Ike, D. Inoue, T. Miyano, T.T. Liu, K. Sei, S. Soda, S. Kadoshin, Microbial population dynamics during startup of a full-scale anaerobic digester treating industrial food waste in Kyoto eco-energy project, Bioresour. Technol. 101 (2010) 3952–3957.
[34] M. Kim, Y.H. Ahn, R.E. Speece, Comparative process stability and efficiency ofanaerobic digestion: Mesophilic vs. thermophilic, Water Res. 36 (2002) 4369–4385.
[35] A.J. Ward, P.J. Hobbs, P.J. Holliman, D.L. Jones, Optimisation of the anaerobic digestion of agricultural resources, Bioresour. Technol. 99 (2008) 7928–7940.
[36] P.G. Stroot, K.D. McMahon, R.I. Mackie, L. Raskin, Anaerobic co-digestion of municipal solid waste and biosolids under various mixing conditions: Digester performance, Water Res. 35 (2001) 1804–1816.
[37] P.L.N. Karapaju, J.A. Rintala, Effects of solid-liquid separation on recovering residual methane and nitrogen of a digested dairy cow manure, Bioresour. Technol. 99 (2008) 120–127.
[38] H.K. Ong, P.F. Greenfield, P.C. Pullammanappallil, Effect of mixing on biometha-nation of cattle-manure slurry, Environ. Technol. 23 (2002) 1081–1090.
[39] S. Sung, R.R. Dague, Laboratory studies on the anaerobic sequencing batch reactor, Water Environ. Res. 67 (1995) 294–301.