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Studies of mixing in anaerobic digesters with CFD and future applications of nanotechnologies

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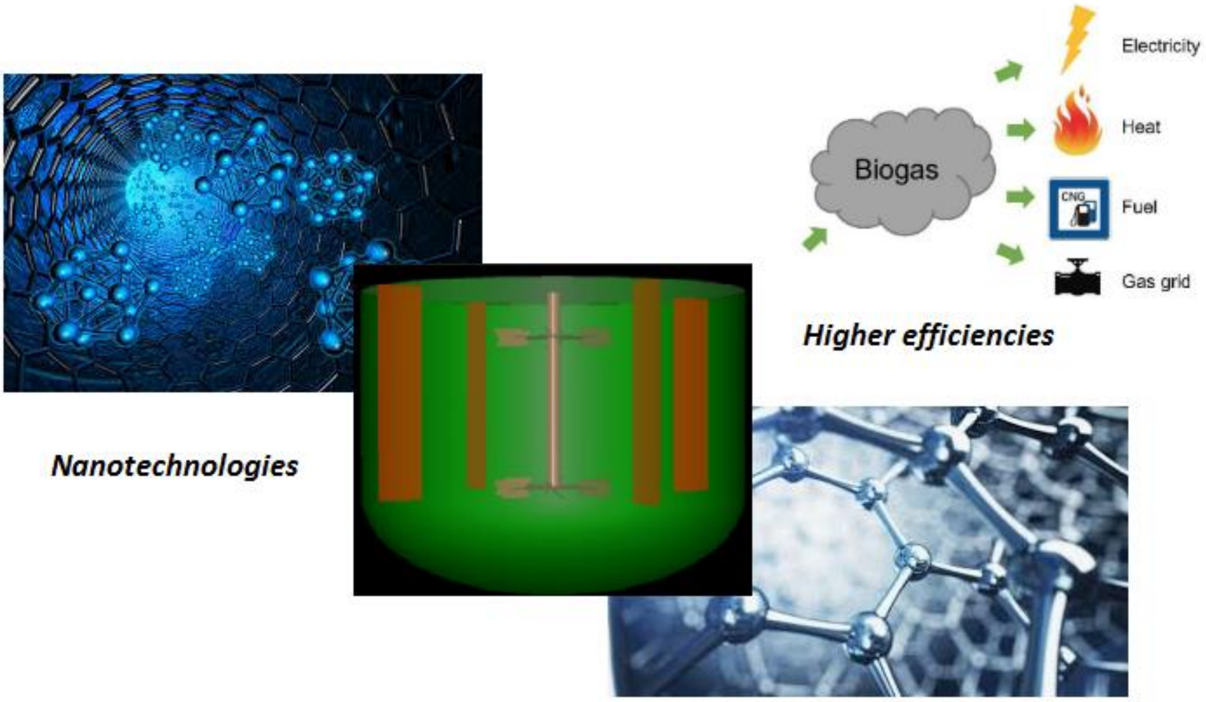
Abstract

Anaerobic digestions are extensively used for the treatment of wastewater. The impacts of nanoparticles, such as silver, zinc oxide, titanium dioxide, and copper oxide within the activated sludge wastewater treatment systems is recently discussed in the literature. Furthermore, in some cases, different conclusions are drawn from studies investigating the impacts of nanoparticles on the microbial activity during anaerobic digestion.

For a detailed analysis of this system a computational fluid-dynamic analysis can be used. In fact, fluid-dynamic analysis is generally used to evaluate the mixing of anaerobic digesters and different systems can be used: mechanical pumping, mechanical agitation, recirculation of biogas or slurry, pneumatic mixing. An important parameter to evaluate mixing inside digesters is the uniformity index. In general, fermenters for bio-hydrogen production, anaerobic digesters with perfect mixing, photo-bioreactors, bio-film reactors are studied by fluid-dynamic analysis, as shown with the reported literature works of this review.

However, more studies should be developed regarding the application of nanotechnologies in anaerobic digesters to evaluate the heat and mass transfer during mixing using the computational fluid-dynamics analysis. This can be an important research for the next future.

Keywords: anaerobic digesters, nanoparticles, computational fluid-dynamics, mixing, biogas production.



Statement of novelty

The work is timely for a review because a similar work is not present in literature. It is an interesting research study that would provide bases for future research regarding anaerobic digestions, showing what is already done. Nanotechnology is suggested as an important aspect to improve the efficiency of anaerobic digesters.

1. Introduction

The anaerobic digestion allows the degradation of organic matter by micro-organisms that not require oxygen and is the most developed technology for the treatment of sludge from wastewater treatment plants. The process produces a gas stream, called the biogas mainly constituted by methane and carbon dioxide. The current line of research is aimed at maximizing the recovery of energy and therefore the produced biogas is sent in a cogeneration or tri-generation system: the electrical energy produced by these systems can be recovered for the operation of the same biogas plant.

In particular, the system consumes electricity for mixing, that has an important role inside the anaerobic digestion process. Consumes of electricity for mixing are reported in literature.

Regarding to this, Kissel et al. [1] report that in ten pilot plants the consumed electricity for mixing inside an anaerobic digester is equal to 25% of all consumed electric power in the first fermentation stage, varying from 6% to 58% in the remaining digesters.

Then mixing is required for these processes.

An excellent mixing for an anaerobic digester is a basic condition for an efficient operation of the system: the need of an efficient mixing system for an anaerobic digester is emphasized in many technical literatures [2] and experimental studies [3, 4, 5]. However, most of the obtained results are empirical correlations between the rotational time and the destruction of the chemical oxygen demand (COD) or the methane production. In fact, an efficient anaerobic digestion depends on many factors: the characteristics of the substrate, pH, temperature, redox potential, hydraulic residence time and mixing [6].

If mixing system is inadequate, digestive efficiency is reduced [7, 8, 9, 10]. The first objective of mixing system is homogenization [11], followed by other processes that control material and heat transfer [11], chemical reactions [12] and structural changes [13].

Mixing target changes with the complex rheological characteristics of fluid, for example the non-Newtonian fluid, that are present in food, pharmaceutical, cosmetic and polymers industries. In these industries, mixing is focused to obtain a product with specific rheological properties rather than a homogenized product. Therefore, it is necessary to develop different mixing systems to satisfy the particular requests.

Mixing is important also for special industrial applications as industrial fermentation processes. In this context, Bezzo et al. [14] find that the lack of an adequate mixing leads to a partial stabilization of the raw sludge, insufficient methane yield, an increase in energy and capital costs.

Moreover, an efficient mixing process is also necessary to ensure a good homogenization of soluble compounds, to standardize pH, temperature, thus ensuring a physical, chemical and biological uniformity [15, 16, 17]. It also prevents stratification, phenomena of short circuits, formation of foam while the biogas production is maximized [18]. Also, several research groups emphasize the importance of mixing to avoid dead volumes, low methane production, damage due to stress of microorganisms [2, 19, 20, 21]. The quality of mixing influences the hydraulic residence time of feed, the homogeneity of suspension, biogas yield.

The mixing effect on biogas production is evaluated by several authors [21, 22, 23]. However, the effect of mixing on biogas production is not clear, because different conclusions are drawn also considering the composition and type of biomass, the size of digester, the bacteria concentration, the type of mixers and operating mode [21, 24].

Recently, in any cases, the importance of mixing in the efficiency of substrates conversion during anaerobic digestion is underlined by many researchers: it improves the distribution of microorganisms to the substrate, heat transfer, reduces the substrate size and improves the gas separation from the substrate [21, 25]. The importance of mixing in order to achieve a good conversion of the substrate is reported by many researchers [21, 26, 27, 28]. Mixing in anaerobic digesters is important for the transfer of the substrate to microorganisms that takes place with mechanisms of convention and diffusion. The contact between the microorganisms and the solid organic material is increased and prevents the sedimentation of solid particles that have a different density respect to digestate.

However, the use of problematic substrates or inconvenient mixing intervals may lead to some problems.
New researches are conducted to optimize mixing system for less common substrates and higher organic loads: the importance of mixing and the effect of operating conditions on cell growth and productivity is also well documented [29]. Mixing is important to solve problems related to the bad anaerobic digestion of lignocellulosic crop stalks, thus improving the production of bio-methane [25, 30].
In addition to lignocellulosic, mixing is studied for anaerobic digesters feed by sewage, food wastes, municipal solid wastes and rice straw [31].
In this context, as introduced before, although the importance of mixing system in anaerobic digester is clear in many studies, its effect on the performance is not yet defined [21, 32, 33]. Some studies report that the performance decreases with a greater mixing due to the spatial juxtaposition of microorganisms causing an excessive shear stress [25, 34]. In fact, mixing produces a direct impact on the structure of the biomass, destroying the membranes and eventually killing the microorganisms, animal and plant cells. However, other studies suggest that the performance of anaerobic digester improves [21, 32, 33, 34, 35, 36] because the non-uniformity, dead spaces and short circuits are minimized. These conflicting ideas highlight the importance of achieving an appropriate level of mixing: inadequate mixing determines a failure of the anaerobic digester.
The main factors that influence mixing are the intensity, duration, type of mixing, input and output of the system. However, in literature there are contradictory information about the intensity and the mixing time on the performance of anaerobic digesters [37, 38, 39]. Considerations about unmixed and continuously mixed conditions are discussed by Chen et al. [40], Ho and Tan, [41] and Fluent®Hashimoto [42]. On the other hand, Dague et al. [43], Mills [44] and Smith et al. [45] recommend intermittent mixing. It is noted that a rapid mixing disrupts the structure of flocs inside a biological reactor disturbing the syntrophic relationships between organisms, thereby adversely affecting the reactor performance [26, 46, 47, 48].
Also, researches on laboratory scale suggest that a minimal and gentle mixing before feeding is advantageous compared to a vigorous agitation with a high inoculum substrate ratio [3, 49, 50, 51].
Although mixing is studied with different perspectives of dead volume, mixing intensity and short circuiting, information regarding the time required for the mixing are missing. However, the time required for the homogenization varies with the shape of the digester, type of mixing, intensity, characteristics of the sludge. To quantify the time required for mixing also allows to have different intermittent feeding strategies for the optimization of the process. Typically, digesters fed in continuous are considered ideally mixed assuming that the substrate is homogenized as it enters the digester. Liew et al. [52] show that deviations from the ideal mixing behavior (i.e. non-ideal mixing phenomena) may lead to losses in yield and physiological changes in the microbes.
Overall, improvements of the performance and reduction of the required energy for the bio-methane production may also be obtained with the optimization of the digester configuration, operating conditions and mixing, characterized by the agitator flows model that depends on the geometry of impeller [53]. The design of an efficient agitation system, the improvement of an existing agitation system and the combination of existing systems is required by industries.

Designers aim to optimize mixing in order to minimize costs and the environmental impact, without compromising the production of biogas. Some digesters are mixed for five minutes in one hour without affecting the biogas production, although others must be constantly mixed to have the same biogas production. In this context, a mathematical model can often be useful to explain the connection between mixing and kinetics of anaerobic digestion. Due to the complexity of biological processes it is difficult to develop a mathematical model that reflects the reality, then some simplifications have been established. The assumption of a completely ideal mixing may be valid in some cases, when due to the small scale of the used experimental reactors, the perfect mixing could actually be reached or when the constants related to the characteristic time for the kinetic parameters are quite more than the time constants related to the mixing and material transfer

[60]. However, the difficulties in achieving the complete mixing increase with the size of the reactor determining an increase of the costs, loss of efficiency for the equipments, etc.
There is a need for further researches and improvement of models to establish the link between real reactors configuration and the mixing model as well as its experimental verification. Further researchers should be carried out to improve the efficiency of the process and in this context nanotechnology with nano-fluids (produced by dispersing nanoparticles in the basefluid) are a valid solution.

Researchers are studying, in particular, the heat and material transfer coefficients during mixing process inside the anaerobic digestion with these new fluids. Computational fluid dynamics analysis (CFD) is also used to this purpose, defining continuous, momentum and energy equations in which all energy or force interactions of particles) are introduced.

In particular, different models can be considered to describe the fluid-solid flow in conjunction with the CFD model. In these cases, the fluid flow field has been solved implementing CFD principles, while the solid particles has been modelled by discrete element model (DEM), or by discrete phase model (DPM) or by PBM (population balance model). [54, 55, 56].

DEM can simulate the movement behavior of single particle and the collision process between particles, such that the velocity and position of particles at any time can be obtained [55]. PBM is useful to model size change taking place in the system [54]. DPM, unlike DEM, can predict only the trajectories of the particles, in particular for a group of particles of equal sizes [56]. Then according to the aim of the study, these different models for the solid particle can be considered.

Also, different forces can be evaluated in the DEM-CFD model. In Kloss et al. [57] a DPM parcel is subject to gravity, drag force, pressure force, Magnus force, virtual mass force and Saffman force. However, in Hosseini et al. [58] the same model considers gravitational acceleration, pressure, drag force, Buoyancy force, lift force, and virtual mass force. In Amiri et al. [59] the DEM-CFD model for a solid fluidized bed reactor considers the gravity acceleration, the exerted drag force to the particle, the exerted lift force to the particle, the exerted Magnus lift force to the particle and the fluid particle interaction force per unit volume. Then it is possibile to underling as gravity, drag force, pressure force, Magnus force are the most considered forces in this kind of model.

2. Anaerobic digesters

Anaerobic digestion (AD) is a well-known process for renewable energy production, which converts organic degradable material into the biogas inside anaerobic digesters. This biogas mainly consists out of methane (60-70%), carbon dioxide (30-40%) and other impurities and is mostly used for thermal and electrical renewable energy production by combustion in combined heat and power plants. Then, the overall result of anaerobic digestion is a nearly complete conversion of the biodegradable organic material into methane, carbon dioxide, hydrogen sulphide, ammonia and new bacterial biomass [60]. It is the most promising biological technologies for treating a wide variety of organic wastes with high treatment efficiency.
Commonly used substrates are wastewater, manure, energy crops and the organic fraction of municipal solid waste. Generally, substrates can be grouped into five different categories: (i) sewage sludge (SS), (ii) animal manures, (iii) food industry wastes, including slaughterhouse waste, (iv) energy crops and harvesting residues, including algae, and (v) organic fraction of municipal solid waste (OFMSW).
According to the type of feedstock, there are different biogas yields and methane concentrations as reported in table 1. The process is very complex due to four process stages, (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) each requiring different optimal process variables, as shown in figure 1. The anaerobic

digestion depends on various factors as pH, temperature, C/N ratio, etc. It is a relatively slow process and the lack of process stability, low loading rates, slow recovery after failure and specific requirements for waste composition are some of the other limitations associated with AD.

The digestion can take place under psychrophilic (< 20 °C), mesophilic (25-40 °C) or thermophilic (50-65 °C) conditions, although biodegradation under mesophilic conditions is the most common, because enables higher destruction of pathogens.

AD plants are either continuous stirred tank reactor (CSTR) or up flow anaerobic sludge blanket (UASB) reactor, which are utilized for particulate and soluble organic streams, respectively [61].

Different approaches have been applied to enhance digesters biogas production in anaerobic digesters such as: (i) co-digestion to increase the digester organic loading rate (OLR), (ii) pre-treatments to increase the biodegradability of the wastem (iii) improvement of the reactor configuration and operation conditions, and (iv) dose of additives to stimulate microbial activity and/or reduce the concentration of inhibitory agents. Several bibliographic reviews addressing these techniques already exist in the literature; however, these publications are mainly devoted to pre-treatments and anaerobic co-digestion, while less attention has been paid to the introduction of additives to the digester medium [62].

(See fig 1)

(See table 1)

3. Anaerobic digestion and nanotechnologies

Nanotechnology is one of the most advanced process for wastewater treatment and in recent years, nanoparticles (NPs) are used for anaerobic digestion. These kinds of materials are classified into three categories: (1) metal oxides, (2) zero-valent metals, and (3) nano-ash and carbon-based materials. The metal oxide NPs such as CuO, ZnO, CeO_2 and in some cases Ag are mainly used.

The effect of nanoparticles on the anaerobic digestion process and consequently on the biogas yields is an active area of research. Literature reports that nanoparticles produce a contaminant effect on anaerobic digestion process and inhibitory/toxic effect on microbial community. In particular, as compared with other tested nanoparticles (e.g. TiO_2, Al_2O_3, SiO_2, Ag, Au NPs), cerium oxide and zinc oxide nanoparticles show greatest inhibition of anaerobic digestion [63, 64].

The type and concentration of NPs, and dissolution of metal ions from NPs are the main factors influencing this behavior.

The negative effects of these NPs on biogas and methane production values depend on their concentrations. On the other hand, no system perturbation has been reported for NPs such as TiO_2, SiO_2, and Al_2O_3 in AD processes, showing that these NPs do not seem to pose any inhibitory/toxic effects on the microbial activity, at least for the concentration levels studied.

Table 2 reports the principal nanoparticles that are used for an anaerobic digester and the produced effects. The effect of nanoadditives on the anaerobic digestion process and consequently on the biogas yield is an active area of research.

(See table 2)

From the above analysis, the future directions may include the following:

- the use of bioactive nano-metal oxides to avoid the negative effect on bacteria caused by the toxicity of currently used materials.
- screening of nano-zero-valence metals (NZVM) with a wide range of concentrations, particle size and shape.

- the use of mixtures of ash and NZVM with different proportions to get the benefits of both components.
- anaerobic photo-fermentation reactors using visible-light photoactive metal oxides to increase the amount of hydrogen produced and consequently the methane production. It will be a great advantage to use photoactive/biocompatible metal oxides.

Nano fluids produced by dispersing nanoparticles in the base fluid have been paid wide attention due to the reported superior thermophysical properties which probably lead to a strongly promising potential application.

For this reason, it is important to study the mixing of anaerobic digestion, which importance is already suggested, through computational fluid dynamics analysis when nano-fluids are present inside the anaerobic digester.

4. Different systems of mixing for anaerobic digesters

4.1 Analysis of the systems using for mixing

Mixing inside the anaerobic digesters can be obtained in different ways: mechanical pumping, mechanical agitation, the recirculation of biogas or slurry, hydraulic, pneumatic [21]. In general, the type of mixing depends on the used digester and solids present in the feed.

Advantages and disadvantages of these methods are reported in literature. In Germany, the mechanical agitation is dominating the market for agricultural substrates [65]. A national study conducted in Germany shows that all completely agitated anaerobic digesters are equipped with fast-rotating submersible mixers. The mechanical agitation produces the homogenization of the substrate in the digester easily and therefore is widely used in industrial operations that use solid-liquid flow [23, 66, 67]. It is used for the mixing of crop stalks substrates especially when the content of total solids in the slurry is relatively high [68]. The mechanical mixing is also the most efficient mixing system in terms of consumed power per unit of volume [69] and in terms of consumed power per gallon mixed [36]. In particular, it is the most efficient in terms of input energy and performance related to mixing [70]. However, the internal fittings and equipments are not accessible for maintenance during the operating phase. Generally, this reliability can be achieved in systems that circular biogas or liquor, in which there are no moving parts inside the digester [71].

The configuration of the agitators in the digester, number, position, height of installation and alignment in accordance with the volume of the digester is in many cases based on the experience of the manufacturer and in other cases only on specific knowledge. The increase in the number of impellers can significantly improve the mixing performance and triple impellers are suggested for the mixing of rice straw. The most recommended axial mixers for anaerobic digestion have four or six blades with an inclined angle between 15 ° and 45°.

Other works in the literature report that the biogas recirculation systems are the most efficient for the mixing of anaerobic digesters [72, 73, 74].
Lee et al. [75] study the mixing of anaerobic digester in a pilot plant and find that the recirculation of the biogas is much more efficient than a mechanical stirring system. The mixing using biogas is found to be the simplest and cheapest compared to the rotors and to the slurry recirculation systems, but have not yet been optimized to maximize the yield of biogas.
The digesters with recirculation of the biogas, known as gas lift, are becoming popular and many studies in this regard are reported in literature [21, 33, 72, 73, 74, 76]. Many parameters can influence the mixing efficiency: the amount of the recirculated biogas, the shorter distance of the mouthpiece, the slope of the hopper bottom, the ratio of the draft-tube diameter of the reactor, the solids loading, the bottom clearance of the draft tube, the position of the biogas injection (sparger) and solids loading rate [77, 78].

Karim et al. [79], analyzing a draft tube digester, find that the majority of released gas is confined within the inner tube and is not present the hold-up of the gas in the annular zone. According to these observations, the mixing zones within the digester are simulated as a single stage by imposing the speed input into the draft-tube as a condition to contour. The obtained results are in agreement with those obtained by experimentations. Varma and Al-Dahhan, [80] use the technique and configuration shown by Karim et al. [79] to compare the hydrodynamic performance of two different spreaders and conclude that multi-orifice ring sparger is more efficient respect to a spreading device with only one orifice for digesters that use gas recirculation as mixing system.

Karim et al. [21] evaluate the effect of the amount of recirculated biogas and the height of the draft-tube on the performance of a mixed anaerobic digester with biogas recirculation, using six digesters at laboratory scale. The work volume of the digesters is equal to 3.73 L at a temperature of 35±2 °C. Biogas generated in each digester is collected in a Tedlar bag and is recirculated from the top of the digester by an air pump and draft tube arrangement, as shown in Fig 2. The fed sludge contains total suspended solids (TSS) of 66.13 g/L and volatile suspended solids (VSS) of 35.63 g/L. The volume of biogas is measured using wet gas test meters (GSA/Precision Scientific) and 150 µL samples for biogas composition are collected using a gastight syringe. The production of methane is equal to 0.4-0.45 L for liter of volume digester per day.

A greater production of methane is recorded for digesters that are not mixed, while the increase of the amount of recirculated biogas reduces the production of methane. This is found already by Ghaly et al. [50]. The production of methane is subjected to the analysis of variance (ANOVA) and a significant difference in the amount of the produced methane is evaluated at 5% of significance for four digesters with four different biogas recirculation. It is necessary to emphasize that the increase of the amount of the recirculated biogas increases the infiltration of air within the system.

4.2 The importance, effects and factors that influence in an anaerobic digester

Agitation of an anaerobic digester is vital to accomplish, primarily, the supply of substrate to be distributed uniformly, secondly, to keep continuous contact between the microorganisms and sludge, tertiary, the concentration of end product and prohibited biological intermediates have to be maintained at minimum levels. In addition, mixing can boost the homogeneous distribution of nutrients and micro-organisms and can evade formation of surface crust and sedimentation.

Mixing has different effects such as on microorganisms, efficiencies of anaerobic digesters, crust and foam formation, hydraulic retention time (HRT)/solids retention time (SRT), volatile fatty acids (VFA), and biogas production, also depending on the nature of the fluid. In fact, mixing inside the digester changes with the physical properties.

(See fig 2).

In this context, in Karim et al. [21] digesters are fed with animal slurry at 5% and 10% of solids, providing a constant amount of energy per unit volume (8 W/m^3). The experiments are conducted in eight digesters at laboratory scale, each with a working volume of 3.73 L and at a controlled temperature of 35±2 °C. The hydraulic residence time is kept at a constant value of 16.2 days, resulting a total solids loading of 3.08 g/Ld and 6.2 g/Ld respectively at the 5% and 10% of solids. Results show that the unmixed and mixed digesters perform quite similarly when is fed with 5% manure slurry and produce biogas at a rate of 0.84–0.94 L/Ld with a methane yield of 0.26–0.31 L CH_4/g volatile solids. This is probably due to the low concentration of solids for slurry at 5%, in which the mixing created by the gas is sufficient to provide adequate mixing.

Digesters fed with 10% manure slurry and mixed by slurry recirculation, impeller, and biogas recirculation produce approximately 29%, 22% and 15% more biogas than unmixed digester, respectively. The deposition of solids within the digester is not observed in the case of slurry at 5% of solids, but becomes significant for slurry with a solids content of 10%.

Based on the findings of this study, it can be concluded that mixing becomes more critical with thicker manure slurries. Fig. 3 shows the different experimental set-up of anaerobic digesters studied in this research (digester 1 and 2 use biogas recirculation, digester 3 uses an impeller, digester 4 uses a slurry recirculation, digester 5 is unmixed, digester 6 uses an impeller, digester 7 is unmixed, digester 8 uses biogas recirculation, digester 9 uses an impeller, digester 10 uses a slurry recirculation).

(See fig 3.)

5. Types of impellers for mixing systems

The type of impeller is one of the main factors that determines the flow characteristics and allows to obtain mixing within the tank. The best type of mixer should be selected according to the established targets. The fermentation characteristics of the substrate, as the fiber content and rheology, and the design must be considered in the choice of the agitators [81]. In the tanks the performance of mixing generated by the impeller are mainly determined by their design. In fact, the mixing efficiency is influenced by the flow pattern which depends on the geometry of the agitator [53]. A calculation method that accurately provides the flow around the impeller of an arbitrary shape should be a benefit for the design and proper operation of agitated tanks [82, 83, 84].

In general, as the flow proceeds from the impeller and circulates within the tank, the main kinetic energy is converted into turbulent kinetic energy and the relative distribution at each position depends on the design of the impeller, tank and each other internal condition. Required by the industries is therefore the most efficient mixing system. . In fact chemical industries require efficient agitation systems which must be applied in a wide range. The mixing of fluids cause the formation of well mixed zones around the impeller (also known as caverns) while other are as stagnant zones [85]. The existence of such dead zones reduces the mass and heat transfer rates: it is necessary to eliminate them by designing a suitable stirring system [86]. Several experiments have been conducted to measure the size and shape of these caverns: dye method [87], hot film anemometry [88], X-rayphotography [89, 90], laser Doppler anemometry and tomography [91].

Generally, in mixing system, axial and radial impellers are used. Radial impellers are useful for liquid-gas, liquid-liquid applications, and other multi-phase dispersions. Axial impellers are used for mixing, heat transfer and solid suspensions [84]. However, the design of an efficient axial flow impeller are quite difficult to model due to the complicated shape, twist and curvature of the blade.

In mechanical mixing, the A310 propellers and helical ribbon can be used. The A310 is an axial impeller and it is considered as a hydrophobic impeller at high efficiency with minimal energy dissipation near the impeller [92]. It is designed for turbulent fluids and is well suited for mixing solid-liquid, miscible liquids, blending. The helical ribbon impeller, always axial impeller, is typical for industrial applications where viscosity is greater than 25,000 Pas [93]. In fact, mixing in highly viscous systems is difficult because the turbolent vortices are not present to help the distribution of components.

In particular, the helical ribbon impellers are recognized to be the most efficient system applied in polymer industries. Since HSAD is a high viscous and shear sensitive system, the application of helical ribbon impellers might improve the distribution of enzyme and microorganism into the substrate. Rivard et al. [94] compare mixing at high viscosity conditions (TS>15%), carried out by the helical ribbon impeller and the A310 impeller. Calculations of the energy input for helical ribbon in HSAD system are performed based on Rivard's minimal mixing requirements. Of the two impellers the power number is also calculated: this decreases as the Reynold number increases [95].

In this context, Kumaresan and Joshi, [82] evaluate the effects of various types of axial impellers (blade angle, number of blades, blade width, blade twist, etc.) on flow fields and mixing time. When the impellers are compared to an equal power consumption, the narrow blade hydrofoil impeller with a blade twist of 15° yields the maximum flow number.

Bugay et al. [90] analyze the flow field in a stirred tank, induced by an axial impeller Lightin A310 using the technique of particle image velocimeter (PIV) with an emphasis on turbulence (production, transport, and dissipation rate of turbulent kinetic energy).

Agitator turbines can be also used to provide both radial and axial flow.

Ankamma and Sivashanmugam, [97] find that for the modified agitator turbines the consumed power is less than conventional turbines. However, the pumping capacity for the energy-saving turbine agitator is not taken into account. The standard pitched blade turbines (PBT) impellers are simple but provide a reduced efficiency.

Ge et al. [98] evaluate the effect of a modified pitched blade turbine (m-PBT) impellers with down-pumping mode using the particle image velocimetry (PIV) and CFD analysis. Three different types of 45° pitched-down blade axial flow impellers, i.e., m-PBT45, PBT45-3, and PBT45-4 are compared. The simulations show that a small change in the shape of the blade influences the distribution of the velocity, increasing the value of the velocity near the impeller, and that the m-PBT impeller has a higher pumping efficiency than the other. Comparing the axial and radial mean velocity profiles at different axial positions (below and above the blade, i.e., z=90 and 130 mm), it is noted that there is a different trend for PBT45-3 and PBT45-4 impellers.

Bakker et al., [99] model the agitation of a turbine pitch-blade impeller for non-Newtonian slurry (the model is according to the law of Hershele Bulkley fluids with a stator starboard foil located in the vicinity of the impeller).

Ascanio et al. [100] experimentally characterize the performance of an ARI impeller (axial radial impeller), for Newtonian fluids and not Newtonian fluids in terms of consumed time and power. Their results show that this impeller is favorable for applications where a good dispersion at low power is required.

Cabaret et al. [101] report that the mixing of Newtonian viscous fluids can be improved by the combination of axial and radial impellers. They find that mixed impellers are more efficient than single axial or radial impellers.

In any cases, Ding et al. [102] demonstrat that different types of rotors at different velocity generate different flow patterns and therefore offer different efficiencies. The optimization of the impeller can ensure a better distribution of velocity inside the digester with a lower speed of rotation. In this way, a higher production of hydrogen and biogas are obtained and less time to the strat-up is necessary.

Reactors with an optimized impeller have obtained a yield of biogas equal to 24.3 L/d at low rotation velocity and require less time to reach the steady state. The peak in the yield of biogas is achieved with a velocity equal to 70 rev/min.

In the presence of biological inactive zones, determined by a non adequate mixing, intermediate will be distributed inside the digester. Through a non-invasive method in the "Unterer Lindenhof" of Hohenheim University, the effect of mixing with different agitators on nutrient distribution within the digester is studied by Lemmer et al. [103].

Results demonstrate that using only a submersible motor mixer the demand for electrical energy is reduced from 32.5% to 12.5% compared to other types of agitation. A reduction from 79% to 75% could be achieved using only the incline propeller mixer. The highest demand for electricity is measured using the combination of both the agitators, but as a result a lower nutrient content in the fermentation substrate is measured. The submersible motor mixer and the incline agitator differ widely in the consumed electricity energy but do not show a significant difference in the quality of mixing described by the distribution of nutrients.

Impellers can be also coaxial: a combination of central impeller and anchor.

Studies show that coaxial mixers are more effective for fluids with a complex rheology [104]. These studies are carried out only in the last ten years finding a correletion to predict the total consumed energy and the mixing time [105, 106, 107, 108, 109, 110, 111, 112], and to evaluate the flow [113, 114, 115, 116, 117, 118]. Pakzad et al. [111] use an electrical resistance tomography (ERT) and the computational fluid dynamics to evaluate the performance of different impellers. The new impeller called ASI (a combination of axial impeller A200 and radial impeller Scaba) is compared with impeller Rushton (radial), impeller ARI (axial) and impeller A200 (axial) for the consumed energy and dimensions of caves. This impeller provide better performance for the mixing of pseudoplastic fluids. Caves with higher dimensions can be obtained with higher velocity of the impeller, increasing the consumed power and producing a minor uniformity with dead zones in the bottom of the bioreactor. These problems can be solved using coaxial mixers. Results suggest that the anchor impeller ASI is the mixing system more efficent for consumed energy compared to other systems.
However, Pakzad et al. [116] find that the combination of axial-radial impeller called ARI is the most efficient system that use radial impeller Rushton or axial impeller A200, especially for Non-newtonian fluids.
But, in another work, Pakzad et al. [117] evaluate the performances of five anchor coaxial mixer configurations used for the mixing of pseudo plastic fluids considering the energy of mixing. Results show that the ARI-anchor coaxial mixer with radial axial flow central impeller is more efficient compare to other mixing system for non-newtonian fluid.

6. Application of the computational fluid dynamics analysis in anaerobic digesters and bioreactors in general

Computational Fluid Dynamics is a numerical method for simulating physical and biological processes. Traditionally, it is used in aerospace and mechanical engineering, to simulate the forces that act on an airplane and the combustion phenomena occurring in the motors. The use of computational fluid dynamics to bioengineering, with the goal to develop a model that integrates physical and biological processes is still at the beginning. Simulators currently used in the study of bioreactors using the computational fluid dynamics software are: ANSYS-Fluent®, ANSYS-CFX®, Star-CFD®, PHOENICS®, OpenFOAM® and Comsol®. The advantages that the CFD analysis allows for the study of bioengineering are the following:

- To define the rheological characteristics of materials because they have an important role in the study of material and heat transfer and mixing.
- To simulate turbulent systems through DNS, LES and RANS methods. The first is the most accurate but is also the most expensive method of calculation. The RANS approach is most commonly used and includes the standard k-ε model (used to study the mixing in bioreactors), the RNG k-ε, the feasible k-ε, the standards k-ω and the Reynold's efforts (tested for specific applications). However, these models are not appropriate for the study of heterogeneous turbulent system. The LES method has more attraction, but has many limitations in engineering applications for high computing costs.
- To define multiphase models, because bioreactors treat multiphase systems: gas-liquid, solid-liquid, gas-liquid-solid. The first is used in systems that use the gas mixing. If it is necessary to study solid particles in suspension, the second multiphase model can be used.
- To define models with porous systems, which can be used to simulate the hydrodynamics in anaerobic reactors biofilms, even if information regarding their application are not yet available.
- To study heat transfer by identifying the components that contribute to heat transfer in the studied system.
- To study material transfer, for which it is important to define the material transfer coefficient.

In bioengineering the CFD analysis emerged in the 2000 to predict the yield of bio-methane in an artificial anaerobic basin. Since then, numerous studies have been conducted on various bioreactors for the production of biomethane, biohydrogen, including artificial anaerobic lagoons, plug flow digesters, perfect mixing digester, anaerobic biofilm reactors and photo-bioreactor.

As an important point, for them, the computation fluid dynamics is used to simulate heat and material transfer and light. The biochemical kinetics are also simulated.

Actually, the CFD analysis offers a new approach to evaluate the hydrodynamic behavior and the design of new reactors [119, 120, 121, 122, 123]. It is used to evaluate the hydrodynamic turbulent shear stress in plant cell culture bioreactor [124], to evaluate the hydrodynamic analysis of trickle bed reactors, to optimize the internal structure of photobioreactors for the growing seaweed [125, 126], to design the sparger in bubble column bioreactor [126], to design the impeller in the agitated tank [102], to optimize the diameter ratio in bubble columns [126]. Cao et al., [127] report that computational fluid dynamics contribute to the design and construction of the reactors.

In addition, the computation fluid dynamics has the possibility to simulate complex flows in real conditions and is often used in the industry for the scale-up or the design of many types of bio-reactors [128].

It can be used to predict the mixing characteristics where correlations are not available [129], as in the past, several researches are carried out [6, 130, 131, 132, 133, 134].

Large-scale digesters are studied by several researchers using CFD analysis [67, 134, 135, 136]:
the computation fluid dynamics allows to evaluate the flow fields, to measure where can not be experimentally. Actually, researchers aim to minimaze the provided energy for mixing and maximize yields to increase the production of energy from renewable resources.

Generally, for a bioreactor, in particular, the modeling of the movement of a impeller may be performed using different methods. In addition to the Moving Reference Frame (MRF) and its simplified method a more accurate but difficult method is the Sliding Mesh Model (SMM). Kritzinger, [137] compare the MRF and SMM method and find that the first provides results in a very less time (the MRF method allows solutions at steady state conditions while the SMM method is mainly used for transient state conditions). Wu, [138] and Bridgamn, [67] use a MRF approch in ANSYS Fluent® to model the rotation of the impeller.

Regarding studies about mixing, Keshtkar et al. [139] characterize mixing in a reactor using two parameters that represent the stagnant and crossed zones by a flow. The performances of anaeribic digesters are evaluated by connecting the mixing model in the two zones to a kinetic model related to enzymatic and hydrolysis phase..

A group of researchers from Washington University (St. Louis) launche an extensive research on the mixing of a digester in laboratory scale through CFD with non-invasive techniques as CARPT (radioactive tracer particles computer automated) and CT (computed tomography) analyzing three mixing mode (pumps and gases recirculation, blades).

Interesting application of CFD analysis are done for anaerobic digesters.

Table 3 shows the works reported in the literature about the simulations of anaerobic digesters at perfect mixing with the CFD analysis [140].

(see table 3)

Vesvikar et al. [141] model mixing within a digester through gas recirculation in order to display the flow lines. The simulation results show a reasonable agreement with the experimental data obtained from CARPT. An increase in the diameter of the spreader and the use of a conical bottom of the digester reduces dead zones. Wong [132] conducts experimental and numerical studies for the treatment of wastewater in a digester with an egg form and a mixing tube for the mechanical stirring. In the simulations, instead of characterizing the rotation of the impeller, the author links the flow stream to mixing tube in order to significantly reduce the calculation

of the meshes. Due to the complex geometry and the high volume (9000 m^3), 101258 tetrahedra meshes are generated to arrive at convergence in two months. This work is the first application of CFD analysis to study the mixing of the digester at large scale, although the excessive computing time determines limitations in the industrial application.
Wu and Chen, [133] develop a model to simulate the mixing of a digester in a laboratory scale with pumps recirculation: Newtonian and Non newtonian fluids lead to a different flow patterns.
Wu, [142] make a comparison of four different mechanical mixing systems in a digester: mechanical pumping with two helices of 10 HP placed in two outer tubes, mechanical agitation with two inner helices of 10 HP, mechanical pump with a single-helices of 20 HP placed in an inner tube, mechanical agitation with helices of 20 HP placed in the top of the digester. Results suggest that the mechanical agitation without tubes is more efficient than mechanical pumping with tubes.
Subsequently Wu, [143] develop a simulation model in two stages to determine the mixing time of four systems and find that the mechanical stirring with a single helices allows to have a mixing in less time. Studies conducted by Wu, [136] find that the shape of egg of the digester could ensure more efficient mixing than the cylindrical shape.

Wu, [144] uses a Eulerian model to characterize the gas mixing in a digester and suggestes that the k-ϖ model with low Reynold number can be used to simulate the gas and non-Newtonian two-phases flow. In this work, a quantitative comparison of two mixing methods showed that the confined gas mixing was less efficient than the unconfined gas mixing at TS = 0% and 2.5%, whereas the confined gas mixing was more efficient than the unconfined gas mixing at TS = 5.4%.

Wu, [145] evaluated 12 turbulence models for single-phase non-Newtonian fluid flow in a pipe, and recommended find that the k-ϖ model with low Reynold number may be also used to simulate the mixing within a digester with pumped circulation.

Generally, the k-ϖ model is superior to the k-ε model for several reasons. For instance, it achieves higher accuracy for boundary layers with adverse pressure gradient and can be easily integrated into the viscous sub-layer without any additional damping functions. In addition, k-ϖ model is much more accurate for free shear flows and separated flows.

However, Wu, [146] identify six turbulence models for mechanical agitation of a non-Newtonian fluid in a digester and among these, k-ε and k-ϖ models give the best results.

The k-ε model behaves very in predicting turbulent shear flows, in many applications of engineering interest. However, this model is unable to predict accurately flows with adverse pressure gradients and extra strains (streamline curvature, skewing, rotation). As a result it yields poor results for separated flows, whilst it is rather difficult to be integrated through the viscous sublayer. Despite the above shortcomings, the k-ε model is recommended for an at least gross estimation of the flow field. Generally, this model is suitable for flow away the wall. The Reynold number of this model is typically between 1500-5000.

Wu, [147] carry out large eddy simulation (LES) of mechanical mixing in digesters (Fig. 4), and compared three subgrid scale (SGS) models (Smagorinsky–Lilly model, wall-adapting local eddy-viscosity model and kinetic energy transport model). The results indicated that all the SGS models produced excellent impeller power and flow numbers, and that a LES performes better than a Reynolds-averaged Navier–Stokes (RANS) simulation in predicting turbulent flow.

(See fig 4)

Meroney, [134] studies mechanical draft tube mixing numerically in four full-scale anaerobic digesters where a fan boundary condition is used to specify mechanical pumping, and then calculates digester volume turnover time, mixture diffusion time, hydraulic retention time and velocity gradient. The unique characteristic of this study is to present first-hand information for practical design, construction and operation of anaerobic reactors through CFD simulations. Similar to Wong [138], the major concern is that the CFD model does not characterize the impeller rotation.

Terashima et al. [6] evaluate the efficiency of mixing within a digester with a form of egg through the homogenization time (miximg time) and the index of uniformity. The first index is more efficient because it is related to mixing process, but requires a greater difficulty in the resolution due to the transport equation of the transient species.

Mendoza et al. [148] utilize the CFD analysis to simulate the mixing of cylindrical digesters with jet mixing to find mixing and dead zones and use the law of Stock to calculate the sedimentation velocity of the biomass and examine the effect of a jet angle on the flow fields.

Bridgeman, [67] simulate the mechanical agitation of digester at laboratory scale fed by sewage sludge. The author evaluates the average velocity, the velocity gradient and the influence of the solids content and the velocity of rotation on dead volumes. Through fluid dynamic simulations, results show that for a sludge with a solids content equal to 2.5% the biogas yield is not affected by the mixing. In addition the work shows that to increase the yield of biogas is necessary to reduce the input energy to prevent the deposition of solids rather than optimize the mixing energy. Thi is the most important information also for future works. In the work, the selection of a turbulence model and a test of the grid density as well as non-Newtonian rheology are considered, and it is found that the Reynolds stress model combined with the multiple reference frame method that characterizes the impeller rotation is the most appropriate modeling strategy through comparisons of five turbulence models.

Karim et al. [149] use the finite element method to study the digesters where mixing is obtained with the gas recirculation and compare the obtained results with and without the presence of diaphragms. In the latter case, better efficiencies are obtained. Wu and Chen [133] conduct an extensive review of non-Newtonian fluids in anaerobic digesters and emphasiz through numerical tests that the behavior of Newtonian fluid is completely different in laboratories scale.

Table 4 shows the studies carried out by the CFD analysis in fermenters for the production of biohydrogen [140]. Ding et al. [102] simulate a mechanically stirred fermenter for the production of biohydrogen, and find that the rotation velocity must be between 50 and 70 rpm to obtain the maximum production of biohydrogen. Wang et al. [150] use the CFD to study the scale up of the fermenter designed by Ding et al. [102] founding the velocity and the dead volumes that have to be optimized in a reactor at industrial scale.

(see table 4)

Table 5 shows the studies about the biofilm reactors carried out by the CFD analysis. Lima et al. [151] apply a symmetric boundary condition in the simulation of a biofilm reactor for the production of methane. The simulation is conducted in two dimensions, in steady state conditions and with three phases (waste water, sludge and biogas). Results show that pressure values obtained from the simulation are in agreement with the experimental data. Wang et al. [152] simulate a biofilm reactor for the production of biohydrogen in three phases (waste water, hydrogen and mud): the velocity of the liquid phase is crucial for the optimization of biohydrogen production. Wang et al. [153] develop a model that links the hydrodynamic to the reaction kinetics in the simulation of a bioprocessing tri phase system, highlighting advantages and disadvantages.

(See table 5)

Table 6 shows the studies carried out in photobioreactors, used mainly for alghae production. The turbulence in these cases is used to keep algaes in suspension and to ensure the growth with light. Pruvost et al. [154] examine the effect of hydrodynamic conditions on the growth processes of algaes for packed bed reactor: crops grow faster with vortical flow than axial flow.

(See table 6)

Pruvost et al. [155] simulate an agitated mechanically packed bed reactor for microorganisms and compared axial average velocity values with the velocity measurements of some particle image. Wu et al. [156] through simulations performed with Fluent® find that photobioreactor with a spiral configuration is better compared to a tubular configuration for the cultivation of microalgaes. Sato et al. [157] study a virtual photobioreactor for the production of microalgaes using a two-phase model and the photosynthesis dynamic model with the effects of the flash of light developed by Yoshimoto et al. [158]. Pruvost et al. [159, 160] study numerically and experimentally the flow in a toroidal reactor agitated with blades at helis marine and characterize the curvature effects on whirling motion with the swirl number defined by Gupta et al. [161].

The use of the computational fluid dynamics analysis in digesters at high solids content is still limited. Hoffmann et al. [54] simulate a digester, stirred with an impeller A310, treating slurry with a solids content less than 5% w/w. Under these conditions for the simulations, the slurry is considered as a Newtonian fluid, with constant viscosity. However, for a more solids content, numerous experimental tests are carried out to determine the rheological properties of the fluid and thus to have simulations with more accurate results. Other works are present in the literature about anaerobic digesters with different configurations and with different aims in their developed research, even if it is related to miximg system.

Recently Wasewar and Sarathi, [162] use the computational fluid dynamics to determine the optimum geometry of the nozzles of an anaerobic digester treating slurry. They use Fluent® 6.2 software subdividing the domain in 50,000-80,000 tetrahedral cells, using the calculation algorithm SImple and PISO and the standard model turbulent k-ε. The simulations faithfully reproduce the experimental tests of each studied case when the Reynolds number is greater than 10000.

Yu et al. [135] use a mechanical mixing using an axial flow impeller and a helical ribbon. Their non-Newtonian fluid is a sludge modeled by a power law whose coefficient is determined by rheological experiments. Bridgeman, [67] simulates an agitated cylindrical digester with two six-blade paddles, using the same properties of slurry of cow's milk of Wu, [138].

Wasewar and Sarathi, [163] use the CFD technique to determine the optimal geometry of the nozzle. A commercial Fluent® 6.2 is used, with 50,000-80,000 tetrahedral and hexahedral meshes, SIMPLE and PISO algorithms for steady state and transient pressure-velocity coupling, and the standard k-epsilon turbulence model. Simulations reproduce the experimental data when the Reynolds number inside the draft-tube is greater than 10000.

More generally, Wu and Chen, [133] use the CFD analysis to simulate the mixing flow of a fluid in a cylindrical reactor continuously fed. The volume of the five digesters at laboratory scale is between 1 and 5 m^3, while for the pilot scale digester the volume is equal to 40 m^3. The hydraulic residence time varies from 4s for digester in laboratory scale and 4000s for the pilot-scale digester.

Meroney and Colorado, [163] use the computational fluid dynamics to simulate the characteristics of the mixing of four different circular anaerobic digesters (with a diameter of 13.7, 21.3, 30.5, and 33.5 m) equipped with single or multiple draft tube. Rates of step mixing and slug injection of tracers are calculated from digester volume turnover time (DVTT), mixture diffusion time (MDT), and hydraulic retention time (HRT). Washout characteristics are compared to analytic formulas to estimate any presence of partial mixing, dead volume, short-circuiting, or piston flow. The obtained results show that all configurations allow to have an excellent mixing without any evidence of a short circuit, dead volumes, partial mixing or areas in plug flow.

Vesvikar and al-Dahhan, [1131] performe through the CFD analysis an internal airlift loop reactor (ALR): cylindrical with a central draft tube. The numerical predictions are compared with those obtained from an experimental ARL treating municipal sludge at 5% solids content. Vesvikar and Al-Dahhan consider regions with velocities less than 5% of the maximum velocity to be dead or stagnant; according to this definition the dead space occupies from 25% to 59.7% for digesters with a conical base. The experimental and numerical results are in good agreement, even if the water is used in the CFD simulations.

Different parameters for mixed digesters can be also evaluated. Kaiser et al. [164] use the fluid dynamics computation to determine characteristics such as mixing time, input power, transferred oxygen inside a Mobius Cell ready bioreactor with a volume of 3L. The marine impeller within the bioreactor produces a loop of directed movement 25° above a horizontal plane, with the velocity of the fluid dominated by its radial component. A tinned area characterized by values of average velocity negligible are observed at the drain inlet, leading to sedimentation and accumulation of cells in the region.

Rihani et al. [165] conducte numerical simulations of the fluid operating in a milli torus reactor as an air lift without agitation. The numerical software Fluent® 6.2.16 is used and unstructured meshes are used to predicte the gas hold up. A model Eulerian-Eulerian multi-fluid approach is used with a k-ε turbulence model. The diattrito forces between the phases are considered. For a simplification of the solution, the dimesions of bubbles inside the reactor are taken of the same size. The gas hod up is calculated comparing the experimental data and a good response is obtained with unstructured mesh

Karim et al. [79] characterize the mixing within a digester gas lift that contains mixed primary and secondary sludge, using non-invasive flow-sensing techniques, as the computer automated radioactive particle tracking (CARPT) and the computed tomography (CT). Results through the CFD simulations show that the non-mixed zones can not be reduced with the increase of the gas recirculation from 28.32 l/h to 84.96 l/h.

Karim et al. [166] use a finite element method to simulate the mixing of gas within a gas lift digester and compare the flow fields with and without the presence of baffles. In their model the sludge is treated as a non-Newtonian fluid and the effects of the gas phase are simplified considering only one velocity at the exit of the tube.

Wu, [142] extende the non-Newtonian model to simulate the mechanical agitation in an anaerobic digester. A single phase and not the phase interactions are considered.

Different mixing systems are compared. Wu, [138] find that the gas mixing is much more efficient than the pumped circulation, however, is less efficient than the mechanical mixing. The simulations are conducted using the k-ω model with shear flow correction.

Khopkar et al. [167] evaluate the gas-liquid flow generated by a pitched-blade turbine through the CFD methods and find that the standard k-ε turbulence model can model correctly each flow field.

Other anaerobic digester typologies are considered. Fleming, [130] develope a 3D model of a digester lagoon. This complex model incorporates the process of bulk fluid motion, sedimentation, mixing bubble, bubble entrainment, advection, biological reactions, and heat transfer. The model is validated using the experimental data of a digester in North Caroline.

Luo and Al-Dahhan [168] use a CARPT and study the dynamics of multiphase flow in a draftube air lift reactor. In their works, details as the turbulent kinetic energy and the fluid velocity are reported: the turbulent kinetic energy in the top and bottom of the digester has high values.

Van Baten et al. [169] work about the hydrodynamics of two air-lift configurations that operate with an air-water system: develope a CFD analysis for the interior of the reactor, validated with experimental data.

Moraveji, [170] evaluates the hydrodynamics of a concentric draft tube airlift reactor in 3D operating with an air-water system with different gas velocity. The values of velocity are changed between 0.018 and 0.108 m/s (with respect to the cross sectional area of the riser). Investigations are carried out using computational fluid dynamic with Eulerian descriptions of the gas and liquid phases. A comparison between the experimental data (which are made from the magnetic tracer particle method and pressure drop in monometer) and the simulated date is performed.

Wu, [136] models a mechanical mixing through draft-tube in an egg-shaped digester. The simulations are conducted with an impeller speeds between 400 and 750 rpm, assuming the sludge as a Newtonian and non-Newtonian fluid depending on the solids content. The power number and flow is validated by experimental results. Mechanical draft tube mixing may function either an up- or down-pumping mode, which can be accomplished by the propeller being operated in either clockwise or counterclockwise direction. In the up-pumping mode the propeller rotation produces a closed-loop circulation that drives the fluid up the tube, flowing out from the upper disc to the tank, and then drawing back into the tube through the lower splash disc. Conversely, the down-pumping mode yields a circulation loop in the opposite direction. From the qualitative and quantitative analysis it is found that the up pumping system is much more efficient compared to the down pumping system for Newtonian and not fluids.
In addition to a digester with a egg shape, a cylindrical digester with a working volume of 4888 m^3 is used to evaluate the effect of mixing on the shape of the digester. The main dimensions are the diameter tank: 20.1 m, cylinder height: 14.86 m, cone height: 1.65 m. The other dimensions are the same for the egg-shaped digester. Comparing the mixing energy, results show that the system mixing for the egg-shaped digester is much more efficient than cylindrical. For the egg-shaped digester for TS=0, 2.5, 5.4% the mixing energy levels are: 2.97, 3.25, 3.99 W/m^3 respectively. For the digester in a cylindrical shape instead for the same solids concentrations levels of 6.6, 6.95, 7.4 W/m^3 are respectively.

Brehmer et al. [81] combine the CFD analysis with experimental methods and show at laboratory scale that the incorrect position of the submersible mixers can lead to a considerable stagnation zones and to the collapse of the bulk flow. Also the authoris find that the position and geometry of the agitator as the composition of the substrate and its rheology influence the characteristics of the mixing and the mixed volume of the digester, as well as the jet width of the agitators.
Vesvikar et al. [141] study the flow pattern and the hydrodynamic parameters of an airlift loop anaerobic reactor with the help of the CFD and CARPT. Regarding the flow, position of dead zones, and trends in the velocity profile, the CFD predictions show a good qualitative agreement with experimental data. Results show areas in the absence of flow and with low velocity in 11%-58.3% of the volume, classified as dead or stagnant. A decrease in the digester performance is caused by an increase of pH and temperature in the unmixed regions.

Wu, [145] presents an Eulerian multiphase flow model to characterize the gas mixing in an anaerobic digester. In the developed model the slurry is assumed to be water or a non-Newtonian fluid which depends on the concentration of solids. The results obtained from the simulations are validated by experimental found in literature [79]. Comparing two different gas mixing inside the digester is found that the intensity of mixing is insensitive to the solids content in confined mixing gases, whereas there are significant decreases with the increases of TS to unconfined gas mixing. However comparisons between the three mixing methods indicate that the mixing gas is more efficient than the pumped circulation, while it is less efficient than mechanical mixing. The used digester is of cylindrical shape with a conical bottom with a working volume of 79129 m^3, a diameter of 12 m, the cylinder height 6.7 m, height of the cone tank of 0.9 m, the pipe diameter 0.66 m, height 6.1 m. Using the equations 26 and 29 in Binxin Wu [138], the mixing energy levels for mechanical agitation and circulation pumps are predicted as 4.11 and 5.9 W/m^3, respectively. Then the gas mixing system is much more efficient than the pumped circulation, although it is less efficient the mechanical mixing.

Shen et al. [30] improve the mixing for a higher biogas production in an anaerobic digestion of rice straw through the CFD, used to determine the best blade type, number of impellers and the agitation intensity. For

the simulations a CSTR reactor with a diameter of 0.2 m height 0.3 m, with a volume of 8 L is used. Three typical impellers are evaluated: pitched blade (PB), the high efficiency blade (HEB) and the discmounted flat blade (DFB). The impellers have the same blade diameter 0.17 m and a thickness of 1 cm. The performances of the different impellers are measured at different rotation ranging between 0-0.36 ms^{-1}. The distribution of the solid fraction can directly reflect the efficiency of the mixing in the digester: a greater volume of the solid fraction produce a better performance in the mixing.
Li et al. [110] and Pan et al. [151] analyze the field flows in a dual rushton turbine stirred tank using the CFD analysis and PIV: the results obtained using CFD are in agreement with those obtained from experimental PIV measurements.
Manea et al. [172] determine the optimal parameters for the mixing process: the simulated values are compared with those obtained from an anaerobic digester at laboratory scale. According to the results obtained through the simulations, the authors are able to match the central recirculation capacity of the mixer to the needs of the anaerobic digester to produce biogas.

Mendoza et al. [148] model the fluid dynamics inside a digester to identify the mixing zones and areas without and with little mixing as dead zones. The analyzed digester is installed in Quart-Benager, Valencia, Spain. The stirring system used is the dinomix: it is a mixing device using a jet, causing a flow in the digester slowed by the viscosity. The sizes of the digester are 30.50 m in diameter and 8.8 m in height with a total volume of 6504 m^3. Results show that one of the most important parameter that influences the internal speed of the digester is the geometry at the entry angle of flow. This is defined α if viewed by the top of the digester and β when viewed from the right side of the digester. Four simulations are carried out, as shown in Fig. 5: simulation 1, with $\alpha=30^o$ and $\beta=11^o$; simulation 2, with $\alpha=0°$ and $\beta=0^o$; simulation 3, with $\alpha=\beta=22^o$ and 30^o; simulation 4, with $\alpha=15^o$ and $\beta=0$.

(See fig 5)

All configurations provide a good result even if they have some differences. In the simulations 1, 3, 4 the streams follow the geometry of the digester and with a continuous downward movement. In simulation 2, the flow present a different behavior, as the shock front is sweeping flow from the middle of the digester which begins in the nozzle exit, crossing a distance of roughly the distance from the radio and returns. In the simulation 1, at 0 m and 0.7 m of height, the 85% of zones are mixing and at 4 m and 7.8 m the 94%. . The more mixing zones are in the vicinity of the walls. Dead zones are at the center in the bottom of the digester. In the simulation 2 the values of the mixing zones are the 96% at 0 m, 98% at 0.7 m of height and at 4 m and 7.8 m the 95%. . This simulation has less dead zones in the center and on the bottom of the digester. In the simulation 3, the 94% of mixing zones are at 0m and 0.7m of height, and 95% for 4m and 7.8m of height. . The dead zones are localized in certain areas of the digester. In the simulation 4, the mixing zones mixing zones are the 66% at 0 m, 83% at 0.7 m and to 4 m and 7.8 m the 100%. . The results underline the importance of considering the mixing in the anaerobic digester simulations.

Today, anaerobic digesters at high solids content are made in laboratory, pilot and commercial scale and the mixing is a key factor [173]. In this case, researches about mixing with the CFD will provide theoretical support for design, optimization, and scale-up of digestersFor digesters at high solids content the mixing is an important parameter to improve the diffusion processes and therefore the reaction kinetics [168, 169].

Garcia-Bernet et al. [176] report that a digester with a high solids content have a visco-elastic nature and a yield strength greater than 200 Pa. This parameter increases exponentially with the solids content and also depends on the physico-chemical characteristics of the solids (particle size, biomass of origin, etc.). For this reason, mixing is difficult to achieve [6, 177]: in the pilot plant such digesters are generally mixed in a sequential manner, with a great equipment and with an excessive consumption of energy.

Karim et al. [71] show that in such conditions the mechanical stirring is the most efficient in terms of supplied energy and the mixing performance. The mechanical agitation of a low solids content sludge is simulated by Hoffman et al. [48]: the use of CFD analyis allows the reduction of a third of the volume of the digester treating the fluid as Newtonian.

Vesvikar and Al-Dahhan, [131] apply the CFX software to simulate a digester in laboratory scale with the gas recirculation in which the manure contains 5% solids. The simulation results with a single point scatterer show that there are no significant effects of the gas flow, of the draft-tube height on flow fields, however, an increase in the diameter of the draft-tube results in higher liquid phase velocities outside the tube. Hoffman et al. [48] simulate the mechanical mixing of sluge with low solids content (<5%) composed by slurry of animals regarded as Newtonian fluids.

For slurry with solids content greater than 5%, many experiments to evaluate the rheological characteristics are carried out [178, 179].

Bridgeman, [67] uses the CFD to simulate the mechanical mixing of sludge in anaerobic digesters at laboratory scale. The generated flow fields are analyzed to evaluate the stirring performance: the mixing efficiency and the design of digester are linked to the yields of biogas. Digesters with volume of 6 l with diameter of 160 mm and height 305 mm are used continuously fed and continuously agitated by two, six-blade paddles, which are positioned on the bottom and in the hill top of the digester. The rotational speeds are between 20 and 200 rpm. Results show that in the digesters there is a reduction of the average velocity with the increase of the solids content at a fixed mixing velocity. This is due to the increase of the viscosity of the sludge and hence to the greater required energy to achieve the mixing. Therefore, maintaining a constant mixing velocity (and therefore a constant input energy) determines a reduction of the velocity in the tank. Fig. 6 shows the trajectory of 100 particles: the increase of the solids content reduces the ability of the particles to move, and then to mix. There is a clear reduction in the lack of movement of the particles with the increase of the solids content.

(See fig. 6)

The solids content influences the presence of dead zones inside the digester, calculated at each rotation speed. Bridgeman, [67] settle that if the velocity is less than 5% of the maximum speed in the digester, the area is considered stagnant. A fixed relationship between the dead volume, velocity and solids content is described by a polynomial of second order, as shown in Fig. 7 and 8.

(see fig 7 and 8)

To evaluate the effect of mixing on the yield of biogas, a cumulative gas production is measured in the laboratory by means of different experiments in a 11-day period. A sludge with 2.5% solids is processed in four identical tanks. One is not mixed, one mixed at 20 rpm, one at 60 rpm and one at 100 rpm: there is no impact on the biogas yield varying the mixing velocity (Similar results are obtained for 20 and 60 rpm).

(See fig. 9)

Yu et al. [135] apply the non-Newtonian fluid theory to model the mechanical mixing of a fluid with high solids content. The theoretical model is validated by experimental data present in the literature [60] in which the experiments are conducted with a digester at laboratory scale with a wet volume of 4.5 L. Computer Automated Radioactive Particle Tracking is used for the flux field measurements. The flow field, the pumping capacity of the impeller, shear stress and power of the A310 impeller with a high solid content (TS=10%) are compared with a solids content of TS <5%.

There are several ways to improve the energy efficiency of mixing, such as improving the rheological properties of the substrate. Undoubtedly, the apparent viscosity of the lignocellulosic biomass is expected to increase with the content of total solids [180, 181]: a greater energy for mixing must be developed. The reduction of the substrate size also reduces the apparent viscosity [181, 182]. Also, rheological properties of the slurry, as the coefficient of consistency (K), apparent viscosity (l), have a negative correlation with temperature [183]. Carreau et al. [184] report that improving the rheological properties of the lignocellulosic biomass is possible to improve the performance of the anaerobic digestion and optimize the energy input for mixing. Similar considerations can be made for the corn stover substrate. Theoretically the improvement of rheological properties may reduce the consumption of energy for mixing. According to this, the rheological properties of corn stover can be improved by reducing the size and increasing the temperature especially for high solids content. In this case, the equations developed by Nagata, [185] are used to calculate the theoretical power for mixing.

Tian et al., [186] evaluate the rheological properties of corn stover to evaluate the energy of mixing for different reduction of solid content. The effect of particle size and temperature on the rheological properties and the related energy reductions are evaluated. The results indicate that the corn stover exhibits pseudo plastic characteristics with a solids content between 4.23% and 7.32% and is well described by the law of power. However, when the solids content increase to 7.32%, there is a 10.37% reduction in the shear stress and 11.73% of reduction due to the increase of temperature from 25 to 55 °C.

At this point it is possible to underline that different rheological models can be used to describe the anaerobic digestion: Bingham, Ostwald (de Waele), Herschel Bulkley, Casson, Sisko, Cross, Carreau, Ellis [187].

The computation fluid dynamics can be also used to evaluate the shear stress. The mixing characteristics have a direct impact on the structure of the microbes in the anaerobic digester. Microbial cells are susceptible to mechanical forces [188], that destroyes cell membranes. Continuous shear, in particular, negatively affects microbial flocs [48]. CFD data on sheare stress, sheare rate and Re are obtained for a A310 impeller in a digester with a solids content of 5% and 10%, while it is difficult to measure the maximum stress and sheare rate on the impeller experimentally.

The calculated results show that a small increase in shear stress and shear rate with the increase of Re, is observed with values of Re minor of 10000 with sludge at 5% solids and 100 in the sludge with 10% solids. In additions, the impeller maximal wall shear stress and shear rate of the 10% TS digester are much higher than that of the 5% TS digester due to the high viscosity.

7. Parameters to evaluate mixing inside anaerobic digesters

The computational fluid dynamics may assist in the study of mixing through numerical simulations of fluid in movement [87]. Its advantages are greater even in applications where it is difficult to determine the mixing parameters experimentally. Consequently, the CFD has actually been applied in an industrial area and not, such as aerodynamics of aircraft and vehicles, power plants, chemical process engineering, meteorology and so forth [189, 190].

The importance for developing indicators that establish the mixing performance is highlighted by Keshtkar et al. [139]. They propose two mixing parameters: the volume relating the flow-through region, and the ratio between the internal flow rate and the feed flow rate.

Vesvikar and Al-Dahhan, [131] carry out a 3D simulations of digesters in steady state to display the flow models and get the hydrodynamic parameters to measure mixing. Vesvikar and Al-Dahhan, [191] use computer automated radioactive particle tracking and computed tomography to see the flow fields and get the hydrodynamic parameters in anaerobic digesters.
In literature, a variety of other techniques are available for characterizing the mixing: mixing time, [17, 192, 193, 194, 195, 196], circulation time, [197, 198, 199], flow patterns, [17, 125, 199, 200].

The mixing time is an important feature of bioreactors and is used to validate the CFD. This is defined as the time required to obtain a certain degree of homogeneity in order to have a miscible fluid. The fluid dynamics shows that the increase in gas superficial velocity involves an acceleration of the working fluid, and then of the circulation time and mixing time. The shortest obtained mixing time is equal to 3.5 s for a superficial gas velocity of 0.085 m/s.
The effect of gas superficial velocity on mixing time is shown in the graph reported by Rihani et al. [165] and shown in Fig. 10.

However, from CFD the reduction of mixing time with the increase of gas superficial velocity is evaluated, observed especially in air-lift reactors [193, 201, 202]. In this case, the increase in gas superficial velocity produces an acceleration of fluid motion and therefore, the reduction of the recirculation time and mixing. The shortest mixing time of about 3.5 s is recorded for gas superficial velocity equal to 0.085 cm/s. The discrepancy between the predicted and experimental data is less than 12%.

Karamanev et al. [203] and Verlaan et al. [204] report that approximately 4-9 liquid cycles are necessary to obtain a full mixing in the digesters airlift. Rihani et al. [165] find that 3-5 cycles are required.

(see fig. 10 and 11)

Similar observations are obtained from Lu et al. [205], Guo et al. [206], Acien et al. [207].
In addition to figure 10, figure 11 shows the dependence of the recirculation velocity of the liquid phase from gas superficial velocity. In the range of tested values of Ug the hold-up of the gas phase also increases: this leads to an increase of the driving force. The liquid circulation velocity is controlled by the energy loss at the entrance of the air into the milli torus reactor. The overall liquid circulation velocities determined by CFD are in agreement with the experimental data.

Other several methods are used to assess the mixing time as pH tracer, tracer conductance and color change. The pH tracer is the most widely used because practical at all scales and easily conducted. Unlike intensive studies that have been conducted to determine the effects of probe lag on kLa calculation [208, 209, 210, 211], much less work has been published regarding the pH probe lag impact.
Zhang et al., [212] evaluate the impact of the pH probe response time on mixing time. The results indicate that there are two phases in the pH probe lag. One is the delay time due to the data transmission system, the other is the probe response time two to ion diffusion. The CFD is used to determine mixing time simulating the interaction of the liquid with the surface defined by the boundary conditions. The obtained results are comparable to experimental data.

The mixing time is also defined as the time when all four mass fractions are within 5% of the final steady-state concentration [213, 214].

Recently, regarind the evaluation of mixing time, the distribution of residence times (RTD) is used to study the hydrodynamic behavior of digesters with a high solids content, both for the liquid and solid phase. Benbelkacem et al. [215] find through the RTD analysis that an increase in solids content from 22% to 30%

w/w allows that the internal mixing is in plug flow conditions and in the liquid phase are not present in many dead zones. In previous work, [216, 217], the distribution of residence times is used for a single phase. The description of the distribution of residence times is useful for the characterization of non-ideal reactors or bioreactors [218, 219].
The analysis of two curves allows the use of different models available in the literature [218, 219]; the two most important are the average residence time and variance used to describe the macro and micro mixing.

Monteith and Stephenson, [220] measure the residence time distribution in two gas-mixed digesters through tracer analyzes, and reporte that 75% of the total volume of each digester is inactive and short-circuiting around the actively mixed zone accounted for 61% of the input flow in one digester. Smith et al. [221] use the tracer based on the same technique of Monteith and Stephenson, [219] to assess the mixing characteristics of an anaerobic digester in pilot scale. In one study they find that the dead and mixed volume are respectively 51% and 49% respectively, whereas the ratio of the feed flowrate to the flowrate of material flowing through the dead zone is equal to 3.
Bello-Mendoza and Sharratt, [222] develope a mixing model based on RTD measurements of anaerobic digesters simulated by mixing gases. The digester is simulated experimentally using 400 L, fed continuously with a central draft-tube. Compressed air provides the strength for mixing. The RTD studies are performed using tap water and a NaCl tracer. They find that the traditional multi-parameter model used for the RTD analysis results in a lack of physical meaning. They introduce a compartment-based mixing model composed of a mixed compartment in an ideal way to represent the area around the draft-tube and two cascade tanks to represent the recirculation flow rate to each of the draft-tube side. The model parameters are: ratio between the volume mixed in perfect way and total volume, number of cascade reservoirs, recirculation period.

Rivera et al. [113] evaluate the performance of a mixing in a tank that simulates an anaerobic digester considering the distribution curve of the residence times of the CSTR model with dead volume and the bypass flow, in order to obtain parameters to improve the mixing. The scale down of the tank rapresent the digester of the pilot plant for which the mixing is promoted by pumping and gassing. In the experimental conditions, pumping of 0.01 vvm is set; while gassing varies in the range of 0 to 0.01 vvm, using a Newtonian fluid with a viscosity of 0.001 Pas. Results show an average residence time, between 94 and 106.3 min to 0.00 vvm to 0.01 vvm, respectively. The variance of the time distributions suggests a completely mixed stirred tank behavior with both, segregation model and tank-in-series models. Dead volume is calculated as a parameter of a CSTR model with dead volume and by-pass: this parameter ranged from 11% at 0.00 vvm to 0.8% at 0.01 vvm.

In the past, the mixing efficiency is determined through the use of tracers requiring time, equipment located inside the digester and expensive tests. A sludge injection with tracer (lithium chloride) is made and sludge residence time from measurements of the "washout" of tracer concentrations within the tank and at the outlet over extended times (up to 90 days) is inferred. The results are used to characterize the dead volume and short circuiting inside the digester [222, 223, 224]. Although tracer studies are conducted to assess the flows, the approach is intensive in resource and sometime may not be applicable at two full-scale plant to various operational constraints. The final results are expressed in terms of Dispersion Mixing Time (MTD), (time required for the sludge to mix throughout the digester so that the concentration of tracer in the output reaches a maximum value), the hydraulic residence time (HRT) associated with the time constant for the exponential decay of tracer, active volume (AV), ratio between the nominal tank volume minus dead or inactive volume and the nominal volume tank. AV is normally implied in the tracer washout tests by comparing actual decay of tracers at the digester exit to analytic or ideal decay rates [220].
Other parameters can be used to describe the mixing inside anaerobic digesters.

Some researchers develop parameters relating to the energetic mixing which combines the effect of the consumend dimensional mixing time (Ntm) and the specific power (P/V) to evaluate the efficiency of different mixing systems. The energetic level of mixing, expressed as the ratio E/V, with V the volume of the digester work and E total power supplied at the input can be used [225]. A statistical method is proposed by many researchers to quantify the mixing index in the agitated equipment [226, 227, 228, 229], referring to the relative normal deviation or the relative mean deviation.

The uniformity index, (Ui) used to describe the mixing, is defined with a statistical parameter through the relative mean deviation (RMD), according to the following relationship (See Eq. 1-3):

$$UI = RMD = \frac{\sum_{i=1}^{m}\{C_i - C'|V_i\}}{VC} \qquad (1)$$

$$V = \sum_{i=1}^{m} V_i \qquad (2)$$

$$C = \frac{\sum_{i=1}^{m} C_i V_i}{V} \qquad (3)$$

with V the digester volume in m^3, Vi the partial volume for a numerical calculation in m^3, C is the average concentration of the tracer in the digester in kg/m^3, Ci is the local concentration of the tracer in kg/m^3, UI is the index uniformity, and RMD is the relative mean deviation. The uniformity index takes values between 0 and 2. The maximum value is obtained when the concentrated tracer is present in small volumes of the digester, as occurs during feeding. Nulls value of uniformity index values are obtained when the concentration of the tracer in the digester is uniform. The minimum Ui value (Uimin) is estimated from the assumption that Ci=C in each volume of the mesh, and the maximum value of the uniformity index (Uimax) is estimated from the assumption that the tracer exists only in a single volume of the mesh (See Eq. 4-5).

$$Ui_{min} = \frac{\sum_{i=1}^{m}|C' - C'|V_i}{C'V} = 0 \qquad (4)$$

$$Ui_{max} = \frac{\sum_{i=1}^{1}\left|\frac{V}{V_i}C' - C'\right|V_i}{C'V} + \frac{\sum_{i=2}^{m}|0 - C'|V_i}{C'V} = \frac{C'V - C'V_1}{C'V} + \frac{C'V - C'V_1}{C'V} = \frac{2(V - V_1)}{V} \cong 2\ (V \gg V_1) \qquad (5)$$

Accodring to this new parameters, Terashima et al. [6] develope a mathematical model considering the rheological properties of sludge to quantify the mixing in a digester draft tube. In this model, the rotation of the propeller is included in the momentum equations, and simulation is conducted under laminar flow. The value of UI are evaluated at different mixing times for different sludge concentrations. For complete mixing (UI=0.02), the homogenization time for sludge concentration equal to 0, 19, 63 and 72 (kg/m^3) is estimated to be 1.1, 1.3, 2.2 and 2.7 (h), rispectively. The relationship between sludge concentration, homogenization time and internal recirculation time is evaluated. This increases with the increase of the concentration of solids in the sludge, due to the different viscosity of the sludge. The viscosity for low sludge concentration is about 20 times lower than that of high sludge concentration, resulting in much lower sludge viscosity. Velocity profile are also evaluated.

The authors also evaluate the UI to different mixing velocity equal to 8, 14, 19 and 24 (day^{-1}): UI increases as the mixing velocity increases.

Literature show that power numbers, flow number and shear rate/stress are parameters used to evaluate the performance relative to mixing of an impeller [95]. These parameters are evaluated for a A310 impeller in a digester with a solids content of 5% and 10% [230, 231].

8. Suggestions of the nanotechnology for anaerobic digesters

Some works are about the analysis of heat and mass transfer for nanofluids.
Pang et al. [232] provid a brief review of heat transfer characteristics in nanofluids.
Sheikholeslami and Ganji [233] investigate the problem of nanofluid hydrothermal behavior in the presence of variable magnetic field. The fluid contains different types of nanoparticles: Al_2O_3 and CuO. The effect of the squeeze number, nanofluid volume fraction, Hartmann number and heat source parameter on flow and heat transfer are investigated.
Hydrodynamic and mass transfer characteristics such as liquid velocity, gas holdup and gas-liquid volumetric mass transfer coefficient in the riser and downcomer of the gas-liquid-solid three-phase internal loop airlift anaerobic digester with nanometer solid particles are investigated by Wen et al. [234]. A mathematical model for the description of flow behavior and gas-liquid mass transfer of those reactors as also developed. The predicted results of this model agre well with the experimental data.

It is possible to notice that no works are reported in literature to analyze the beaviour of heat and mass transfert coefficient during the mixing of anaerobic digester with nanoparticles using computational fluid dynamics. Then future works should be about these fields and researchers.

9. Conclusions

Anaerobic treatment of organic wastes has already been proved to be an efficient technology for waste management practices and energy (biogas) recovery, if the process is carefully operated. In this regard, nanotechnology is one of the ideal options for advance wastewater treatment processes. Various nano-materials have been developed and investigated successfully for wastewater treatment. However, different conclusions are drawn from studies investigating the impacts of nanoparticles on the microbial activity during anaerobic digestion. The positive effect depends on the concentration, time and typology of nanoparticles.

A computational fluid dynamic analysis can be used to study the anaerobic digestion. This allows to evaluate mainly the mixing, the biogas production and the heat and mass transfert inside the anaerobic digestion. Then in this work, after an analysis of different mixing systems, a review of the principal works regarding the application of CFD on anaerobic digesters tp study the mixing is carried out.

However, researches regarding the CFD analysis are focused mainly about the mixing system and not about the presence of nanoparticles. Mixing is very important for an anaerobic digester because it is related to the efficiency of the process. Then, future works, should use the CFD analysis to study the effect of nanotechnology on the anaerobic digestions and in particular on the evaluation of heat and mass transfer during mixing.

Moreover, further work is required on developing a cost effective methods of synthesizing nano-materials and testing the efficiency at large scale for successful field application.

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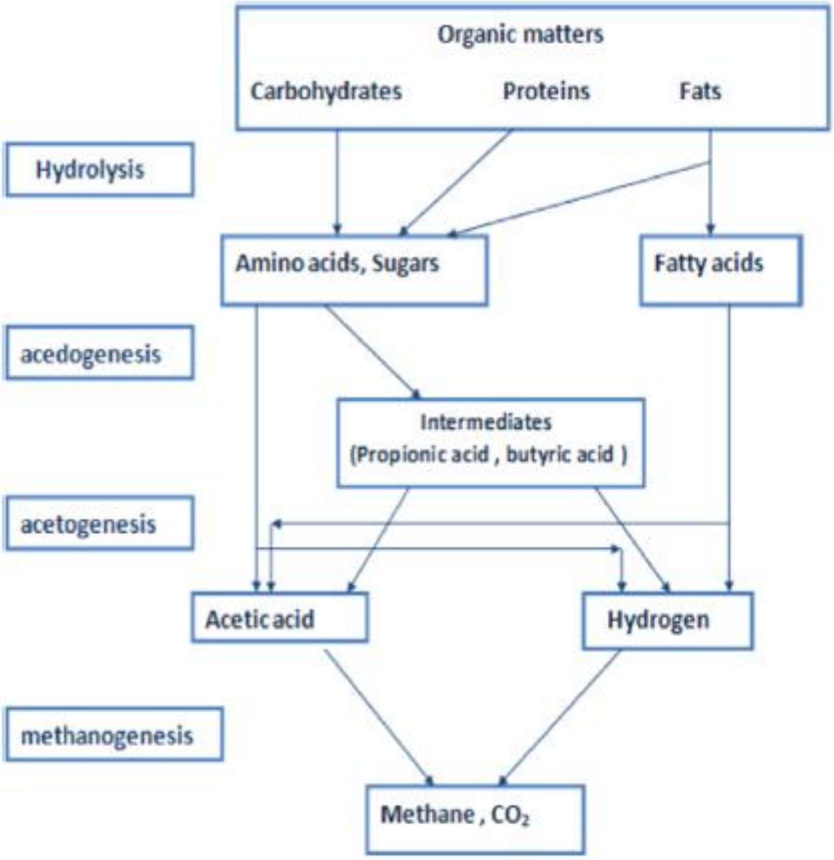


Figure 1 The anaerobic digestion stages [234]

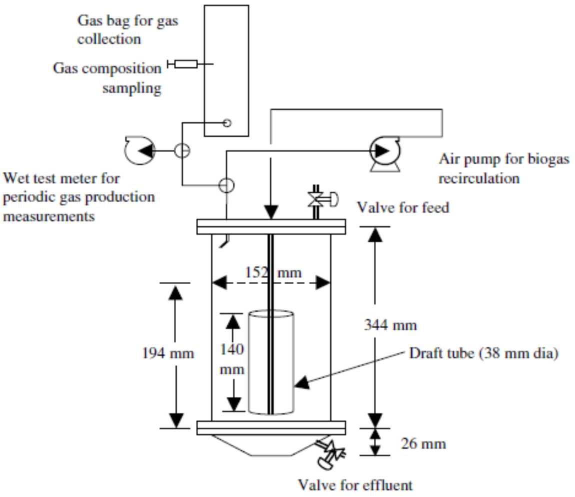


Figure 2 Schematic diagram of the experimental set-up of the anaerobic digester [71]

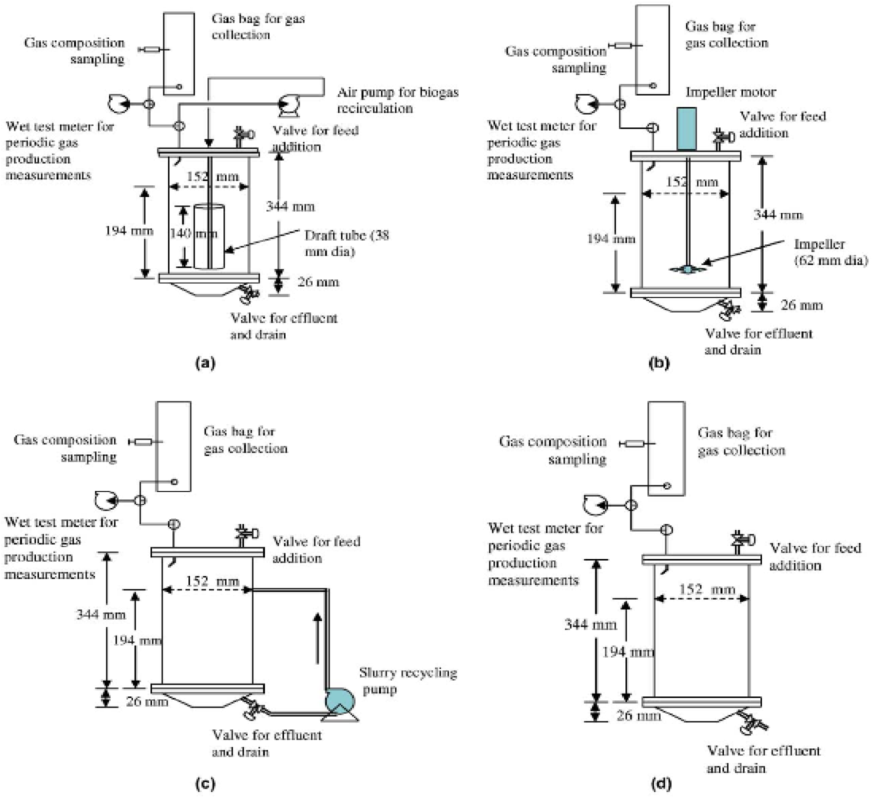


Figure 3 Schematic diagram of the experimental set-up (a) Digester 1, 2 and 8, (b) Digester 3, 6, and 9, (c) Digesters 4 and 10, (d) Digester 5 and 7 [71]

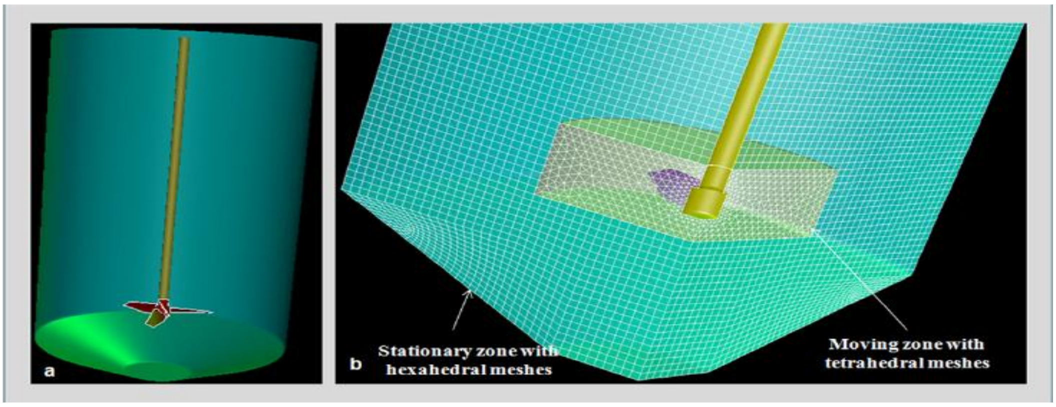


Figure 4 Geometry and grid for anaerobic digester with mechanical mixing: a) LES model; b) SGS model [147]

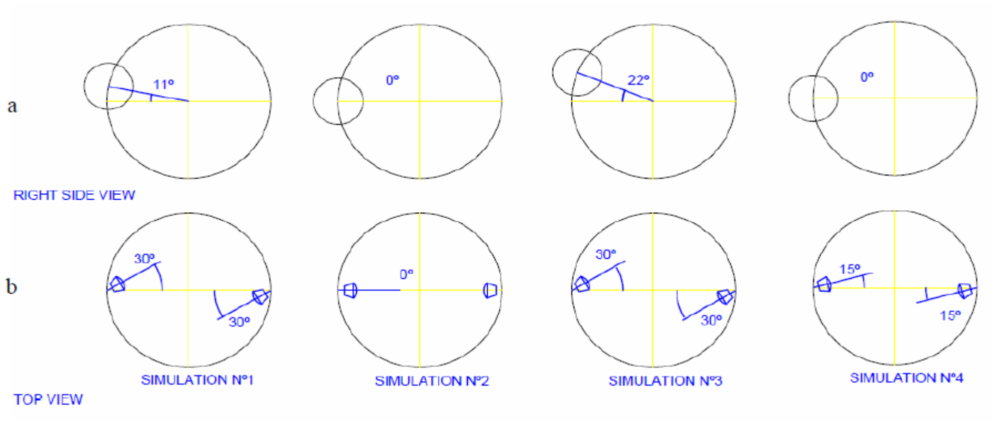


Figure 5 (a) Right side view of simulations; (b) top view of the simulations [148]

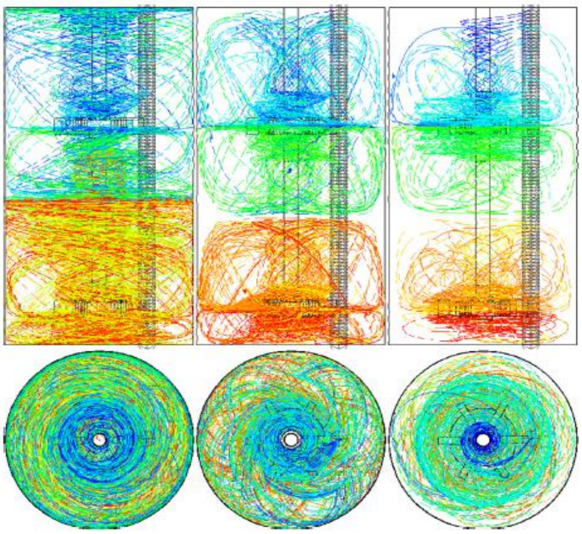


Figure 6 Trajectories of the particles within a digester for different solids content (water, 5.4%, 9.1% solids) with a rotation speed equal to 100 rpm [67]

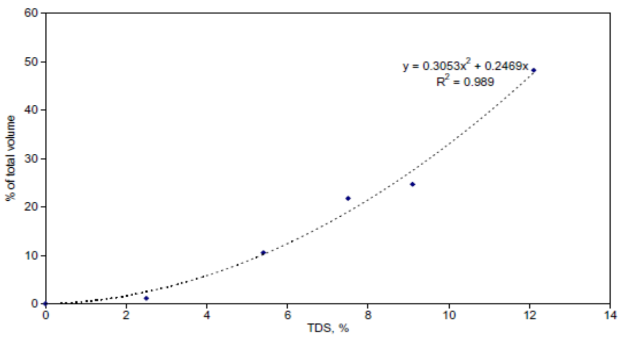


Figure 7 Influence of solids content on the dead volume in an anaerobic digester for a mixing speed of 100 rpm [67]

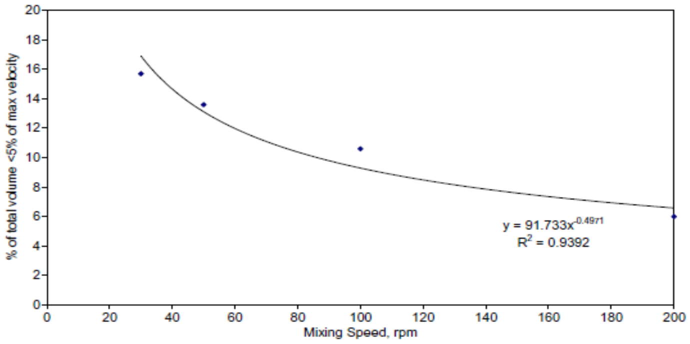


Figure 8 Influence of mixing velocity on the dead volume for an anaerobic digester with a sludge with a solids content equal to 5.4% w/w [67]

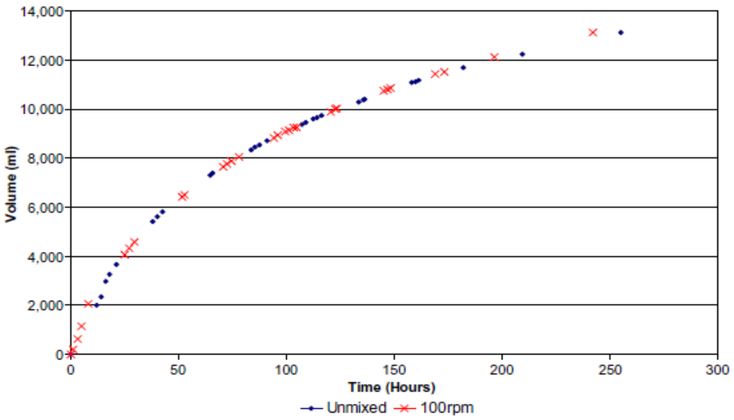


Figure 9 Cumulative gas production for a mixed and unmixed digester [67]

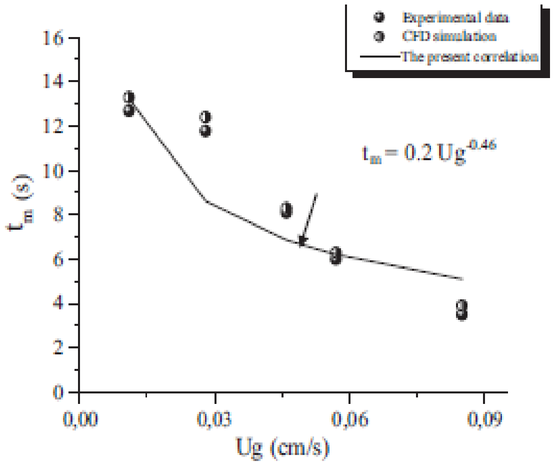


Figure 10 Mixing time versus superficial gas velocity in milli torus reactor [165]

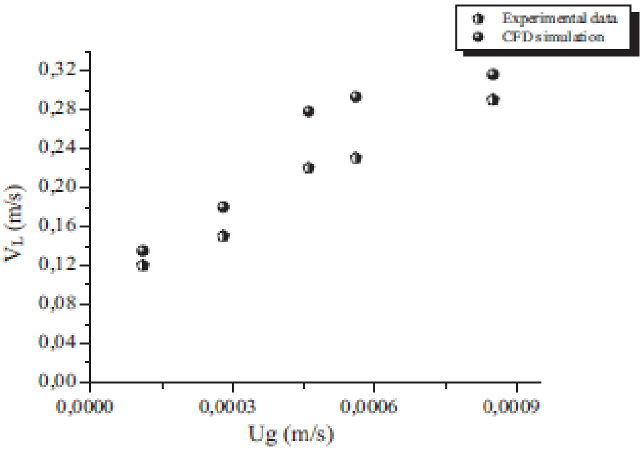
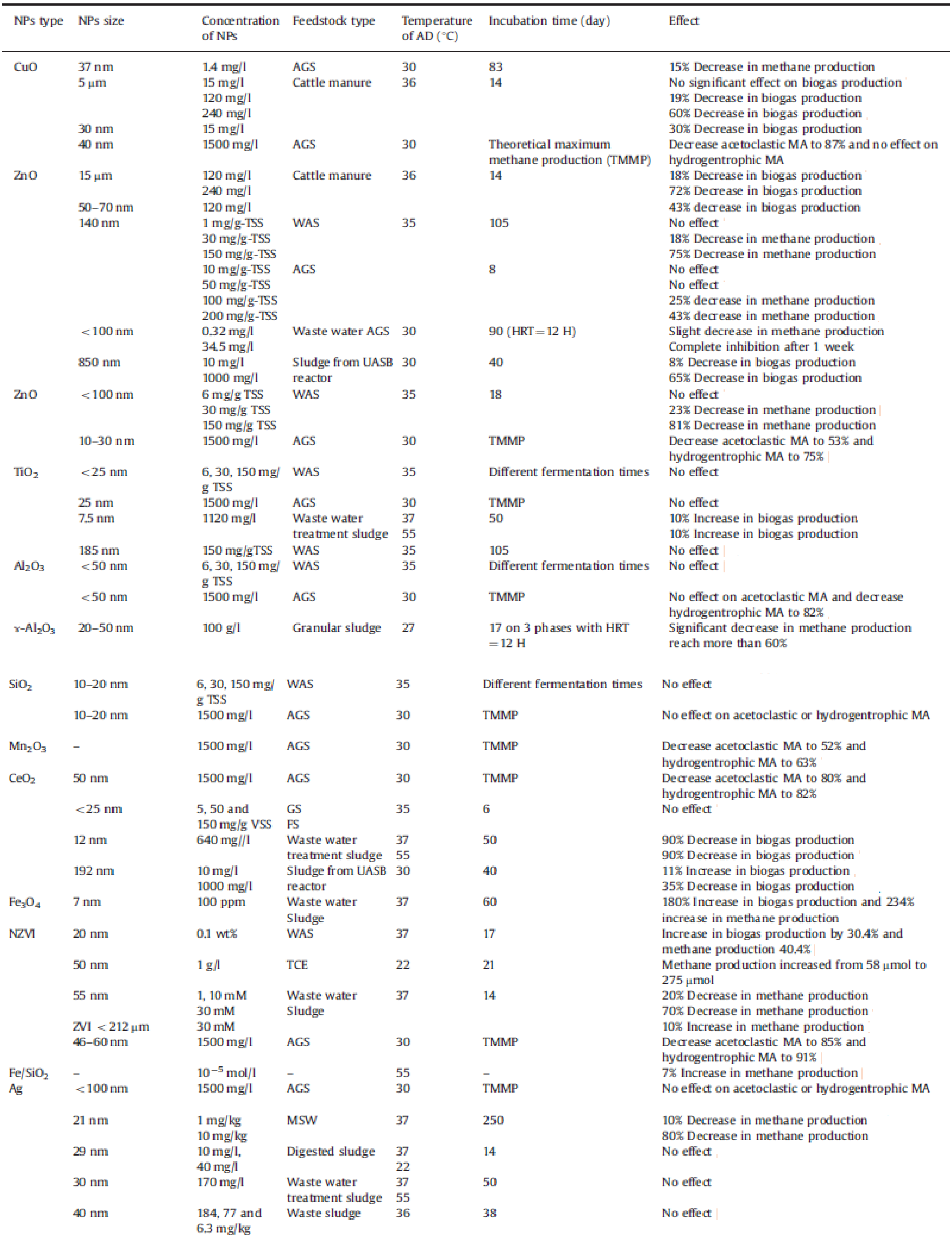


Figure 11 Liquid circulation velocity versus superficial gas velocity in milli torus reactor [165]

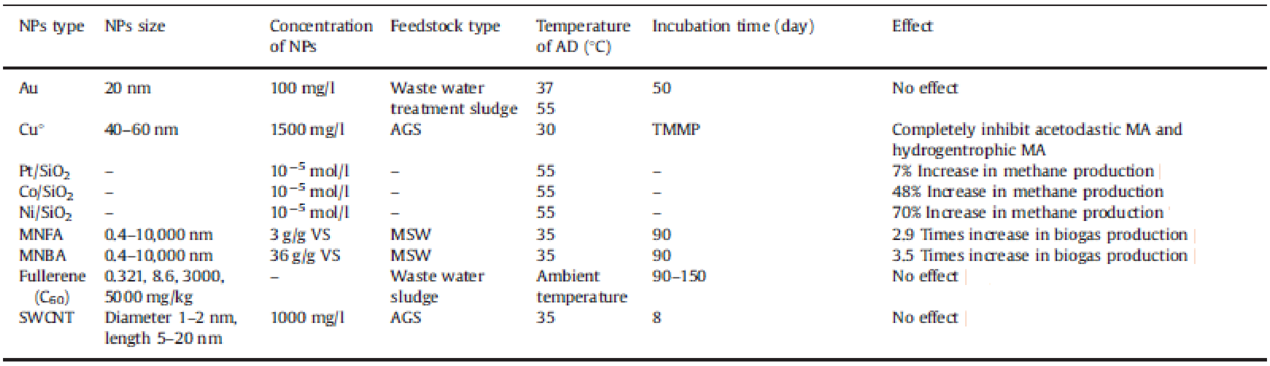
Table 1 AD feedstock and Biogas yield ([a]: tFF: tons fresh feed) [235]

Substrates	Biogas yield (m^3/tFF[a])	Methane percent
Liquid pig manure	28	65
Liquid cattle manure	25	60
Distillers grains with soluble	40	61
Pig manure	60	60
Cattle manure	45	60
Chicken manure	80	60
Organic waste	100	61
Beet	88	53
Sweet sorghum	108	54
Grass silage	172	54
Corn silage	202	52
Forage beet	111	51



NPs type	NPs size	Concentration of NPs	Feedstock type	Temperature of AD (°C)	Incubation time (day)	Effect
CuO	37 nm	1.4 mg/l	AGS	30	83	15% Decrease in methane production
	5 μm	15 mg/l	Cattle manure	36	14	No significant effect on biogas production
		120 mg/l				19% Decrease in biogas production
		240 mg/l				60% Decrease in biogas production
	30 nm	15 mg/l				30% Decrease in biogas production
	40 nm	1500 mg/l	AGS	30	Theoretical maximum methane production (TMMP)	Decrease acetoclastic MA to 87% and no effect on hydrogentrophic MA
ZnO	15 μm	120 mg/l	Cattle manure	36	14	18% Decrease in biogas production
		240 mg/l				72% Decrease in biogas production
	50–70 nm	120 mg/l				43% decrease in biogas production
	140 nm	1 mg/g-TSS	WAS	35	105	No effect
		30 mg/g-TSS				18% Decrease in methane production
		150 mg/g-TSS				75% Decrease in methane production
		10 mg/g-TSS	AGS		8	No effect
		50 mg/g-TSS				No effect
		100 mg/g-TSS				25% decrease in methane production
		200 mg/g-TSS				43% decrease in methane production
	< 100 nm	0.32 mg/l	Waste water AGS	30	90 (HRT = 12 H)	Slight decrease in methane production
		34.5 mg/l				Complete inhibition after 1 week
	850 nm	10 mg/l	Sludge from UASB reactor	30	40	8% Decrease in biogas production
		1000 mg/l				65% Decrease in biogas production
ZnO	< 100 nm	6 mg/g TSS	WAS	35	18	No effect
		30 mg/g TSS				23% Decrease in methane production
		150 mg/g TSS				81% Decrease in methane production
	10–30 nm	1500 mg/l	AGS	30	TMMP	Decrease acetoclastic MA to 53% and hydrogentrophic MA to 75%
TiO_2	< 25 nm	6, 30, 150 mg/g TSS	WAS	35	Different fermentation times	No effect
	25 nm	1500 mg/l	AGS	30	TMMP	No effect
	7.5 nm	1120 mg/l	Waste water treatment sludge	37	50	10% Increase in biogas production
				55		10% Increase in biogas production
	185 nm	150 mg/gTSS	WAS	35	105	No effect
Al_2O_3	< 50 nm	6, 30, 150 mg/g TSS	WAS	35	Different fermentation times	No effect
	< 50 nm	1500 mg/l	AGS	30	TMMP	No effect on acetoclastic MA and decrease hydrogentrophic MA to 82%
γ-Al_2O_3	20–50 nm	100 g/l	Granular sludge	27	17 on 3 phases with HRT = 12 H	Significant decrease in methane production reach more than 60%
SiO_2	10–20 nm	6, 30, 150 mg/g TSS	WAS	35	Different fermentation times	No effect
	10–20 nm	1500 mg/l	AGS	30	TMMP	No effect on acetoclastic or hydrogentrophic MA
Mn_2O_3	–	1500 mg/l	AGS	30	TMMP	Decrease acetoclastic MA to 52% and hydrogentrophic MA to 63%
CeO_2	50 nm	1500 mg/l	AGS	30	TMMP	Decrease acetoclastic MA to 80% and hydrogentrophic MA to 82%
	< 25 nm	5, 50 and 150 mg/g VSS	GS FS	35	6	No effect
	12 nm	640 mg//l	Waste water treatment sludge	37	50	90% Decrease in biogas production
				55		90% Decrease in biogas production
	192 nm	10 mg/l	Sludge from UASB reactor	30	40	11% Increase in biogas production
		1000 mg/l				35% Decrease in biogas production
Fe_3O_4	7 nm	100 ppm	Waste water Sludge	37	60	180% Increase in biogas production and 234% increase in methane production
NZVI	20 nm	0.1 wt%	WAS	37	17	Increase in biogas production by 30.4% and methane production 40.4%
	50 nm	1 g/l	TCE	22	21	Methane production increased from 58 μmol to 275 μmol
	55 nm	1, 10 mM	Waste water Sludge	37	14	20% Decrease in methane production
		30 mM				70% Decrease in methane production
	ZVI < 212 μm	30 mM				10% Increase in methane production
	46–60 nm	1500 mg/l	AGS	30	TMMP	Decrease acetoclastic MA to 85% and hydrogentrophic MA to 91%
Fe/SiO_2	–	10^{-5} mol/l	–	55	–	7% Increase in methane production
Ag	< 100 nm	1500 mg/l	AGS	30	TMMP	No effect on acetoclastic or hydrogentrophic MA
	21 nm	1 mg/kg	MSW	37	250	10% Decrease in methane production
		10 mg/kg				80% Decrease in methane production
	29 nm	10 mg/l,	Digested sludge	37	14	No effect
		40 mg/l		22		
	30 nm	170 mg/l	Waste water treatment sludge	37	50	No effect
				55		
	40 nm	184, 77 and 6.3 mg/kg	Waste sludge	36	38	No effect

Table 2 A summary of the reported nanoadditives and their effect on biogas production rate [235]



NPs type	NPs size	Concentration of NPs	Feedstock type	Temperature of AD (°C)	Incubation time (day)	Effect
Au	20 nm	100 mg/l	Waste water treatment sludge	37 55	50	No effect
Cu°	40–60 nm	1500 mg/l	AGS	30	TMMP	Completely inhibit acetoclastic MA and hydrogentrophic MA
Pt/SiO_2	–	10^{-5} mol/l	–	55	–	7% Increase in methane production
Co/SiO_2	–	10^{-5} mol/l	–	55	–	48% Increase in methane production
Ni/SiO_2	–	10^{-5} mol/l	–	55	–	70% Increase in methane production
MNFA	0.4–10,000 nm	3 g/g VS	MSW	35	90	2.9 Times increase in biogas production
MNBA	0.4–10,000 nm	36 g/g VS	MSW	35	90	3.5 Times increase in biogas production
Fullerene (C_{60})	0.321, 8.6, 3000, 5000 mg/kg	–	Waste water sludge	Ambient temperature	90–150	No effect
SWCNT	Diameter 1–2 nm, length 5–20 nm	1000 mg/l	AGS	35	8	No effect

Table 2 (continued) A summary of the reported nanoadditives and their effect on biogas production rate [235]

Table 3 Application of Computational Fluid Dynamics in anaerobic digester with perfect mixing (MRF=multiple reference frame, SM= sliding mesh, RANS=Reynolds-averaged Navier–Stokes, LES=large eddy simulation, SKE=standard k–ω, RKE=realizable k–ε)

Authors	**Spatial dimensional**	**Fluid property**	**Mixing method**	**Phase method**	**Multiphase approch**	**Modeling turbulence**	**Modeling impeller**	**CFD software**
Vesvikar and Al-Dahhan [131]	3D	Newtonian	Gas mixing	Gas-liquid	Euler-Euler	Rans (SKE)		CFX®
Wong [132]	3D	Newtonian	Mechanical pumping	two-phase		Rans (SKE)		CFX®
Wu and Chen [133]	3D	Non-Newtonian	Mechanical pumping	single phase		Rans (SKE)		Fluent®
Meroney [134]	3D	Newtonian	Mechanical pumping	single phase		Rans (SKE)		Fluent®
Terashima et al. [6]	3D	Non-Newtonian	Mechanical pumping	single phase		Rans (SKE)		CFX®
Wu [142]	3D	Non-Newtonian	Mechanical stirring/pumping	single phase		Rans (RKE)	MRF	Fluent®
Wu [138]	3D	Non-Newtonian	Mechanical stirring/pumping	single phase		Rans (RKE)	MRF	Fluent®
Wu [143]	3D	Non-Newtonian	Mechanical pumping	single phase		Rans (RKE)	MRF	Fluent®
Wu [136]	3D	Non-Newtonian	Gas mixing	single phase		Rans (12 models)		Fluent®
Wu [144]	3D	Non-Newtonian	Mechanical pumping	gas phase	Euler-Euler	Rans (12 models)		Fluent®
Wu [145]	3D	Non-Newtonian	Jet mixing	single phase		RANS (12 models)		Fluent®
Mendozal et al. [148]	3D	Newtonian	Mechanical stirring	single phase		Rans (SKE)		STAR-CCM®
Wu [146]	3D	Non-Newtonian	Mechanical stirring	single phase		RANS (6 models)	MRF/SM	Fluent®
Wu [147]	3D	Non-Newtonian	Mechanical stirring	single phase		LES	SM	Fluent®
Bridgeman [67]	3D	Non-Newtonian	Mechanical stirring	single phase		Rans (5 models)	MRF/SM	Fluent®

Table 4 Application of Computational Fluid dynamics in fermenters for bio-hydrogen production

Authors	Spatial dimensional	Primary liquid property	Phase method	Multiphase approch	Modeling turbulence	Modeling impeller	CFD software
Ding et al. [105]	3D	Newtonian	Gas-liquid two phase	Euler-Euler	RANS (SKE)	MRF	CFX®
Wang et al. [150]	2-D	Newtonian	Gas-liquid two phase	Euler-Euler	RANS (SKE)		CFX®

Table 5 Application of Computational Fluid Dynamics in biofilm reactor

Authors	**Reactor type**	**Spatial dimensional**	**Primary liquid property**	**Phase model**	**Multiphase approch**	**Modeling turbulence**	**CFD software**
Ren et al. [230]	UASB	3-D	Newtonian	Gas-liquid-solid three phase	Euler-Euler	Rans (SKE)	Fluent®
Lima et al. [151]	UASB	2-D	Newtonian	Gas-liquid-solid three phase	Euler-Euler	Rans (SKE)	CFX®
Wang et al. [152]	EGSB	2-D	Newtonian	Gas-liquid-solid three phase	Euler-Euler	Rans (SKE)	CFX®
Wang et al. [153]	EGSB	2-D	Newtonian	Gas-liquid-solid three phase	Euler-Euler	Rans (SKE)	CFX®

Table 6 Application of Computational Fluid Dynamics in photo-bioreactor (DNS=direct numerical simulation, RSM=Reynolds stress model, SKO=standard k–x)

Authors	**Spatial dimensional**	**Primary liquid property**	**Phase model**	**Multiphase approch**	**Modeling turbulence**	**Modeling impeller**	**CFD software**
Luo and Al-Dahhan [168]	2D/3D	Newtonian	Gas-liquid two phase	Euler-Euler	RANS(SKE/RSM)		CFX®
Marshall and Sala [237]	3D	Newtonian	Single phase		DNS		
Perner-Nochta and Posten [238]	3D	Newtonian	Single phase		RANS(SKE)		Fluent®
Pruvost et al. [160]	3D	Newtonian	Single phase		RANS (5 model)		Fluent®
Pruvost et al. [159]	3D	Newtonian	Single phase		RANS (SKO)	MRF	Fluent®
Pruvost et al. [155]	3D	Newtonian	Single phase		RANS (SKO)	MRF	Fluent®
Sato et al. [157]	3D	Newtonian	Gas-liquid two phase	Euler-Lagrange			owen software
Sun et al [239]	2D	Newtonian	Liquid-solid two phase	Euler-Lagrange			Fluent®
Wu et al. [156]	3D	Newtonian	Single phase		RAND (SKE)		Fluent®