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Harnessing hydrodynamic cavitation, alkaline treatments and advanced oxidation processes for enhancement of sludge disintegration

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ABSTRACT

Anaerobic digestion (AD) is widely recognized as an effective technique for the safe and sustainable treatment of sewage sludge. However, the process is inherently slow, particularly during the hydrolysis phase, which is hindered by the presence of complex organic constituents such as extracellular polymeric substances (EPS), ultimately limiting overall digestion efficiency. To address this limitation, the present study evaluates the efficacy of various sludge pretreatment strategies – both individually and in combination – including hydrodynamic cavitation (HC), alkaline treatment, and advanced oxidation processes (AOPs) employing hydrogen peroxide (H_2O_2) and Fenton reagents. Experimental results demonstrated that HC alone, utilizing an orifice plate (β = 0.10) with 16 holes (2 mm diameter) under an inlet pressure of 5 bar for 30 minutes, achieved a disintegration degree (DD%) of 22.83%. Alkaline pretreatment at pH 12 (adjusted with NaOH for 30 minutes) resulted in a DD% of 18.35%. In contrast, H_2O_2 oxidation (40 mg H_2O_2/g TS for 30 minutes) and Fenton treatment (pH 3, 40 mg H_2O_2/g TS, 10 mg Fe^{2+}/g TS for 30 minutes) yielded significantly lower DD values of 2.06% and 1.93%, respectively. Moreover, the combination of HC with alkaline treatment produced the highest sludge disintegration performance among the tested hybrid approaches. This synergistic effect led to a substantial increase in soluble chemical oxygen demand (SCOD) from 1490 mg/L to 7578 mg/L and a maximum DD% of 38.32%, highlighting the enhanced effectiveness of this integrated pretreatment strategy.

Keywords: hydrodynamic cavitation, alkaline pretreatment, advanced oxidation, disintegration, sludge.

INTRODUCTION

The development in technologies and strategies of recent energy management became a significant issue in recent years, where the raised demand for energy poses increased concerns associated with global climate change and energy safety. Hence, the coming shift in production of sustainable energy through "Waste-to-Energy" (WTE) facilities participates in global energy demands with eliminating the dependence on fossil fuels (Mitraka et al., 2022). WTE has been a feasible waste management strategy in creating sustainable waste disposal approaches, it can give well-end products relative to other disposal procedures and provide a renewable energy in the shape of electricity, heat or fuels from small or negative value organic waste and reduce environmental pollution due to the reduction in organic waste volume heading to landfills and raise the reuse and recycling of disposed materials (Shen et al., 2016).

The massive amounts of sewage sludge and waste activated sludge (WAS) are being continuously generated as a leading by-product from wastewater treatment plants (WWTPs), in which the safe disposal and sludge processing might constitute 50–60% of total operational cost of these facilities. So, it must be treated because specific harmful substances such as heavy metals, pathogens, organic and inorganic contaminants can cause hygiene and public health concerns and pollute the environment (Maryam et al., 2021). Anaerobic digestion (AD) is considered an eco-friendly and cost-effective process, which can stabilize sludge, aid pathogen and odor elimination, and generate methane gas as renewable fuel. AD is a complex procedure including four key stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis, ultimately resulting in methane generation and lessening of WAS amount. Hydrolysis efficiency is normally hindered by the existence of high molecular weight organic matter such as recalcitrant cell walls and complex floc structure, that boost retention time and needed bioreactor size while decreasing the biogas production (Repinc et al., 2025). Sludge pretreatment methods are separated into physical, chemical, biological, and combined procedures (Abdelrahman et al., 2024) which are investigated to improve the complex organic and inorganic substances breakdown, releasing intracellular matter that obstruct methanogen activities (Machhirake et al., 2024). beside the distraction of the substrate's floc structure and EPS and promoting particle size reduction. This, in turn, improves the enzymatic activity and hydrolysis, fostering the organic particulate matter solubilization and improving sludge dewaterability (Mitraka et al., 2022).

Among mechanical pretreatment, cavitation is a phenomenon of nucleation, growth and collapse of vapor or gas-filled cavities in a small period (Askarniya et al., 2023; Wang et al., 2021). Besides, the high temperature and pressure through the cavitation process, the collapse of cavitation bubbles can carry different physicochemical impacts (Wang et al., 2021), where the physical effects of high shear wall stress up to 3.5 kPa (Askarniya et al., 2023) and 550 Mpa shock wave at a speed of 2000 m/s as well as a 450 MPa water hammer at 100 m/s by a micro jet occurred, resulting in particle disintegration and lysis of microorganisms, leading to biogas production improvement through biomass AD. In contrast, the thermal effect of cavitation enhances sludge dewaterability and reduces sludge's viscosity (Kim et al., 2019). While, for chemical effect, at extreme cavitation conditions and energy produced by bubble collapse, water molecules can be decomposed into various species with a high oxidation potential, containing hydroxyl radicals: (H°), (OH°), (OOH°) and H_2O, that react with organic compounds in the wastewater or treat sludge (Kim et al., 2019; Wang et al., 2021). Hydrodynamic cavitation (HC) is a promising technique because of its effective operation cost, high energy efficiency, and ability to induce chemical reactions (Zheng et al., 2022). Since HC can be created through alterations in pressure and flow caused by certain constructions (like orifice plate, venturi tube and nozzle), mechanical rotation of the rotating-type devices, and vortex-based devices (Wang et al., 2021). Islam and Ranade (2024) informed that HC improved the disintegration of substrate, leading to enhancement in SCOD by more than 34% after 80 passes while DD% raised by over 22%.

In chemical pretreatments, sludge is hydrolysed by adding chemical substances involving alkaline and acid hydrolysis or ozonation, and other oxidation methods like Fenton reaction (Neumann et al., 2016), where the chemical pretreatment techniques disintegrate sludge's floc structure with the help of strong chemicals (Mitraka et al., 2022). Alkaline pretreatment can cause noteworthy reduction in vital factors, such as total suspended solids, VFA and chemical oxygen demand, resulting in enhanced hydrolysis and WAS disintegration (Machhirake et al., 2024). Alkaline process efficiency is extremely reliant on the kind and concentration of alkaline matter, where sodium hydroxide showing higher performance compared to $Ca(OH)_2$, Mg $(OH)_2$ or KOH. Nevertheless, the chemical dose should be balanced, as exceeding ideal levels can lead to extreme acidity and nutrient leaching, ultimately decreasing biogas yield (Waseem et al., 2025). Where DD_{SCOD}% reached 11.3% at 0.8% NaOH solution (Maryam et al., 2021).

Advanced oxidation processes (AOPs) have garnered a lot of interest as other techniques for sludge conditioning, where the high reactive species production like hydroxyl radicals can quickly disturb flocs of sludge and damage EPS, leading to enhanced sludge dewaterability and settleability (Zhen et al., 2014). A common oxidant in the advanced oxidation process is hydrogen peroxide (H_2O) which can produce potent oxidative hydroxyl radicals, it can release water by oxidizing EPS through sludge dewatering (Lin et al., 2022). The Fenton process is another well-established oxidation method containing reactions of hydrogen peroxide (H_2O) with catalyst iron ions (Fe^{+2}) to create highly active hydroxyl radicals (OH°) which have a high-level oxidation potential and are particularly efficient for EPS disintegration and the cell lysis of microorganisms in sludge, resulting in the release of intracellular materials.

Besides, it has been intensively applied for enhancing sludge dewatering (Zhen et al., 2017).

Although the pretreatment methods are generally applied in singular techniques as standalone processes, the sequential or simultaneous application of various methods has also been investigated (Mitraka et al., 2022). Whereas most pretreatment methods use much energy or have high installation and operation/maintenance costs, hence a combination of physical, chemical, and mechanical pretreatments is a good option to boost sludge solubilization, increase methane yield and reduce volatile solids besides the reduce in time and required chemical products, compared to single methods (Volschan Junior et al., 2021; Liu et al., 2020).

This study investigates the beneficial impacts of various sludge disintegration techniques – including HC using orifice plates, alkaline pretreatment, and advanced oxidation processes (AOPs) employing hydrogen peroxide (H_2O_2) and Fenton reagents – on the pretreatment of waste activated sludge. By optimizing key operational parameters for each method, both individually and in combination, the study demonstrates a substantial enhancement in sludge disintegration efficiency and a notable improvement in sludge characteristics. These advancements are critical for enhancing the overall performance of (AD), highlighting the transformative potential of integrated pretreatment strategies in modern wastewater management.

MATERIALS AND METHODS

Waste activated sludge

Waste activated sludge from the drying beds influent line was used in this investigation, which is produced from the sedimentation tank following biological treatment via the oxidation ditch process at Libo wastewater treatment plant in Diarb Negm, Sharqia, Egypt. The following Table 1. indicates the characteristics of studied waste activated sludge.

Table 1. The characteristics of investigated waste activated sludge

Parameter	Unit	Range
TS	g/L	9.19 – 38.69
TVS	g/L	6.27 – 26.63
TDS	g/L	0.77 – 1.86
TCOD	mg/L	9693 – 38750
SCOD	mg/L	139 – 2519
pH	-	7 – 7.4
Color	-	Dark brown

Experimental set-up

Experimental program consists of three pretreatment techniques that include physical pretreatment method (Hydrodynamic cavitation), chemical pretreatment methods (alkaline, H_2O oxidation and Fenton pretreatment) and combination between them for enhancement of sludge disintegration degree as explained in subsequent phases.

Physical pretreatment phase

Hydrodynamic cavitation (HC)

In the hydrodynamic cavitation pretreatment technique, waste activated sludge with a volume of 10 liters is pumped and passed through a multi-orifice with different geometry conditions in diameter and β coefficient, causing the cavitation phenomenon. The used pump (JSE 30HM model) has a power of 3 HP and pressure reaches about 9 bar, as well as the inner diameter of the pipe is 25 mm and control valves are used to adjust flow and pressure as shown in Figure 1.

Many parameters can influence cavitation performance besides geometry, such as pressure, time, temperature, frequency and power (Bhat and Gogate, 2021). Since the cavitation number is a dimensionless parameter used to predict the onset and severity of cavitation in fluid dynamics. It's calculated as the difference between the local pressure and the vapor pressure, divided by the kinetic energy per unit volume of the fluid.

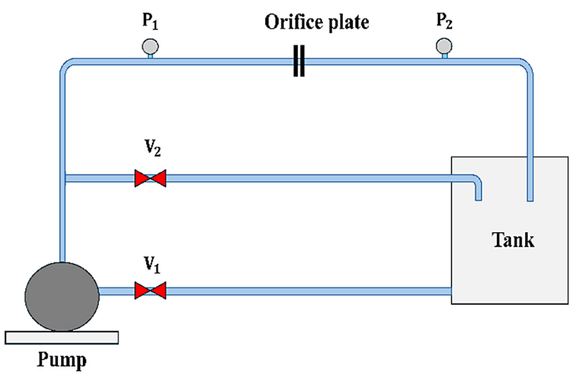

Figure 1. Hydrodynamic cavitation device

Hydrodynamic cavitation by orifice plates can be influenced in design by different key parameters such as the size, number, arrangement and shape of holes, while β and α are other important factors that are utilized to describe the orifice plates geometry that are defined by the following Equations 1 and 2 (Askarniya et al., 2023).

$$\beta = \frac{Total\ flow\ area\ of\ throat}{Cross\ sectional\ area\ of\ the\ pipe} \quad (1)$$

$$\alpha = \frac{Total\ perimeter\ of\ holes}{Total\ flow\ area\ of\ throat} \quad (2)$$

Consequently, the various investigated parameters are orifice geometry with β values of 0.05 to 0.25 and α values of 1.33 and 2, these values are consistent with other investigations (Askarniya et al., 2023; Yao et al., 2022), whereas 10 orifices with different geometry were investigated, as shown in Figure 2, also cavitation time was from 15 to 90 minutes in line with other research (Bhat and Gogate, 2021; Yao et al., 2022), while inlet pressure ranged from 2 to 7 bar, according to some studies (Askarniya et al., 2023; Wang et al., 2021) and the initial sludge concentration varied from 1 to 4%. Therefore, the HC model firstly operated at initial chosen conditions of 5 bar, 60 min, and TS of about 2%, then each parameter was later investigated.

Chemical pretreatment phase

Alkaline pretreatment

Alkaline pretreatment is performed by using NaOH with 2 M concentration as an alkaline reagent. NaOH is added to sludge samples to adjust alkalinity with a pH range of 8, 9, 10, 11 and 12, aligning with the conditions specified in various studies (Chang et al., 2011; Tian et al., 2015). Then, each sample with a volume of 500 ml was stirred for 1 min at 30 rpm and then for 30 min at 200 rpm at room temperature.

Advanced oxidation pretreatment

For H_2O_2 oxidation pretreatment, H_2O_2 is added to sludge samples with dosages range of 20, 40, 60, 80 and 100 mg H_2O_2/g TS. While, in Fenton pretreatment, the pH of sludge samples was firstly adjusted to 3 using H_2SO_4 with 2 M concentration, then ferrous sulfates ($FeSO_4 \cdot 7H_2O$) is added as a source of Fe^{+2} ions,

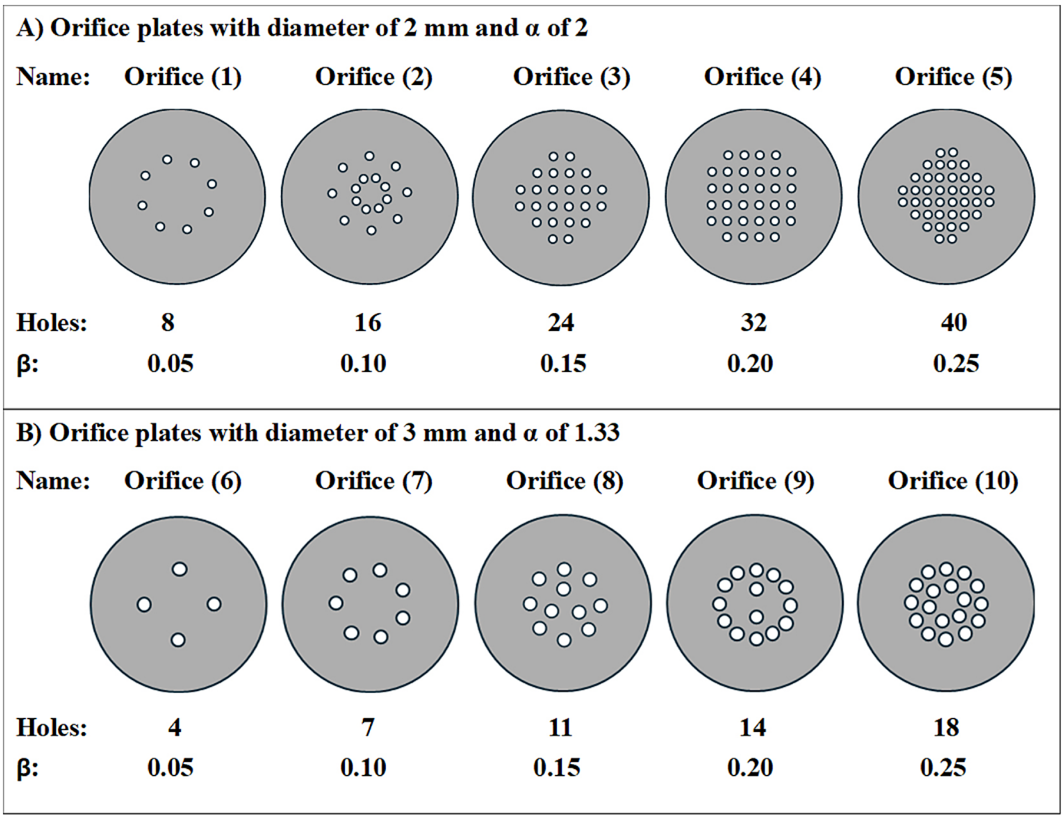

Figure 2. Orifice plates with different geometry in diameter and number of holes

where the dosages of Fe^{+2} ions were 2, 5, 10, 20 and 40 mg Fe^{+2}/g TS, then the Fenton reaction began at the moment of adding H_2O_2 with the optimum dose from H_2O_2 oxidation process, where these conditions and concentrations of both H_2O_2 or Fe^{+2} ions are consistent with some research (Yildiz and Cömert, 2020; Yildiz and Olabi, 2021). After chemical addition for both methods, each sample with a volume of 500 ml was stirred for 1 min at 30 rpm, then for 30 min at 200 rpm at room temperature.

Combination pretreatment phase

The combination between the physical phase (Hydrodynamic cavitation) and the chemical phase (alkaline, H_2O oxidation and Fenton pretreatment) was studied by applying the optimal parameters identified for each individual method. This approach aimed to assess the combined impact of these treatments on the enhancement of sludge disintegration.

ANALYSIS

The degree of disintegration (DD) is used to evaluate the sludge solubilization as calculated in the following Equation 3.

$$DD = \frac{SCOD_0 - SCOD_i}{TCOD_i - SCOD_i} \tag{3}$$

where: $SCOD_0$ and $SCOD_i$ are the pretreated and initial soluble chemical oxygen demand while $TCOD_i$ is the initial total chemical oxygen demand of sludge (Son et al., 2024).

TDS solubilization is another indicated parameter used to quantify sludge solubilization. It is determined by calculating the percentage of increase in total dissolved solids relative to the initial value, as expressed in Equation 4

$$\text{TDS solubiliztion} = \frac{\text{TDS}_0 - \text{TDS}_\text{i}}{\text{TDS}_\text{i}} \tag{4}$$

where: TDS_0 is the total dissolved solids of pretreated sludge, TDS_i is the initial total dissolved solids of sludge.

It is worth mentioning that all tests were performed in duplicate and the average value was recorded, the coloration between the results were more than 99% and any result below this value is rejected and retested.

RESULTS AND DISCUSSION

Physical pretreatment: Hydrodynamic cavitation

Effect of orifice geometry on sludge disintegration

Orifice geometry plays a significant role in sludge disintegration through the change in open diameter of 2 and 3 mm, and β coefficient of 0.05, 0.10, 0.15, 0.20 and 0.25, leading to more enhancement in disintegration degree. Where the results showed that DD% values ranged between 19.82% and 23.58%, while TDS solubilization% ranged between 200.00% and 242.47% when β varied from 0.05 to 0.25 for orifices with a diameter of 2 mm. Meanwhile, DD% ranged between 11.89% and 16.51%, while TDS solubilization% ranged between 150.00% and 164.67% when β varied from 0.05 to 0.25 for orifices with a diameter of 3 mm, where the optimum values were achieved at orifice (2) which have 16 holes with a diameter of 2 mm, β coefficient of 0.10 and openings area of 50.27 mm², whereas SCOD increased from 1662 to 6182 mg/L as well as DD% and TDS solubilization% reached 23.58% and 242.47%, respectively, as illustrated in Figure 3. These results are compatible with Askarniya et al. (2023) who have reported that the optimum β values are mainly in a range between 0.02 and 0.09 and the opening area is between 40 and 60 mm² for plates. Since the low values of β led to more sludge disintegration because at low values, the area is small and this results in increasing velocity and decreasing pressure according to the Bernoulli equation until the pressure reaches below vapor pressure, leading to more enhancement in cavitation efficiency and this is compatible with some other studies which have mentioned the positive impact of the decrease in this coefficient because the turbulence intensity is inversely related to β and the higher intensity of turbulence can lead to more violent collapse of bubbles and produce higher energy (Askarniya et al., 2023).

On the other hand, α coefficient had a significant effect on hydrodynamic cavitation efficiency, whereas the orifices with a diameter of 2 mm that have α coefficient of 2 result in more

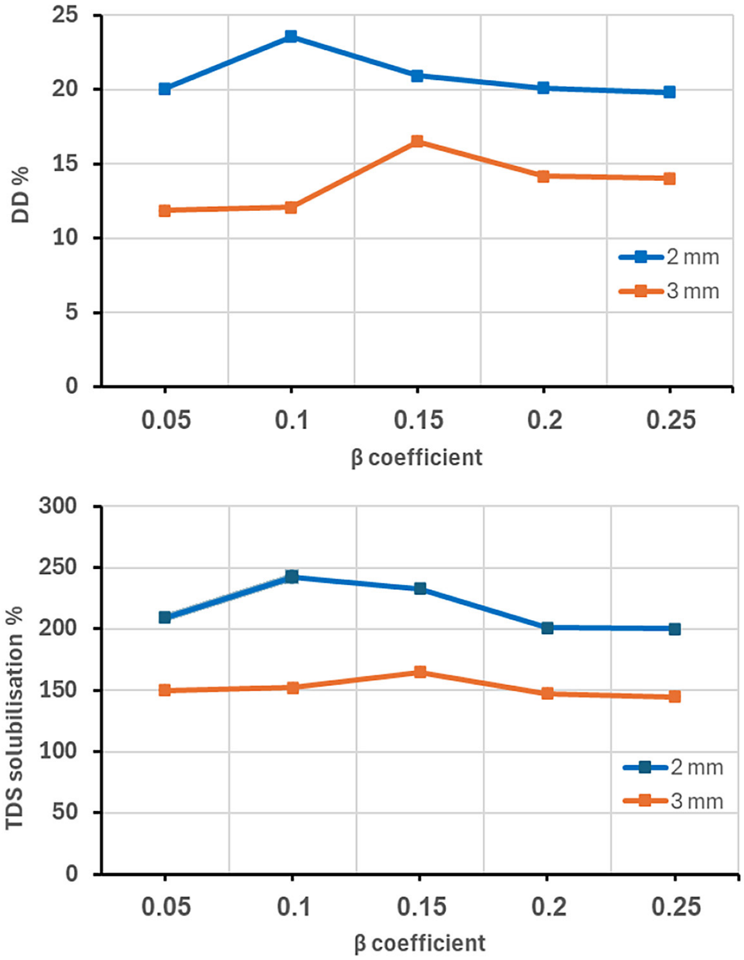

Figure 3. The effect of orifice geometry on sludge disintegration

disintegration and solubilization than orifices with diameter of 2 mm with α coefficient of 1.33 because at the same flow area, orifice with diameter of 2 mm has more surface area leading to extra shear force and friction and this enhanced the sludge disintegration as illustrated in the results in Figure 3. This observation copes with several studies that have recommended optimizing this value in different applications since there have been reports about α values of 2 besides, shear layer area and turbulence can be enhanced by an increase in α coefficient (Askarniya et al., 2023). At the same value of α (equals 2) in another research, DD of 22.98% was achieved by an orifice plate of 20 holes with 2 mm in diameter and inlet pressure of 3 bar at 240 min (Yao et al., 2022). While SCOD increased from 382 to 3068 mg/L after 120 min of hydrodynamic cavitation process using single orifice with 3 mm in diameter and the sludge viscosity reduced by 23–27% (Demir Karaçoban et al., 2024).

Effect of cavitation reaction time on sludge disintegration

As illustrated in Figure 4, the sludge disintegration efficiency was enhanced as the reaction time increased. Where DD% and TDS solubilisation% values varied from 7.08% to 23.77% and from 45.61% to 242.69%, respectively, when the time increased from 15 to 90 min. Hence, the time of 60 min is chosen as the optimum reaction time, showing an increase in SCOD by 4109 mg/L, and both DD% and TDS% reached 22% and 221.64%, respectively. While the reaction time more than 60 min led to a non-significant increase in sludge disintegration and consumed more energy unnecessarily. These results are consistant with another investigation by Wagdy et al. (2025) showing degradation degree of 25.24% after 60 min and 6 bar of hydrodynamic cavitation using an orifice with 16 holes and 2 mm diameter.

Many HC studies informed that the treatment time of 30−60 min has a significant increase in

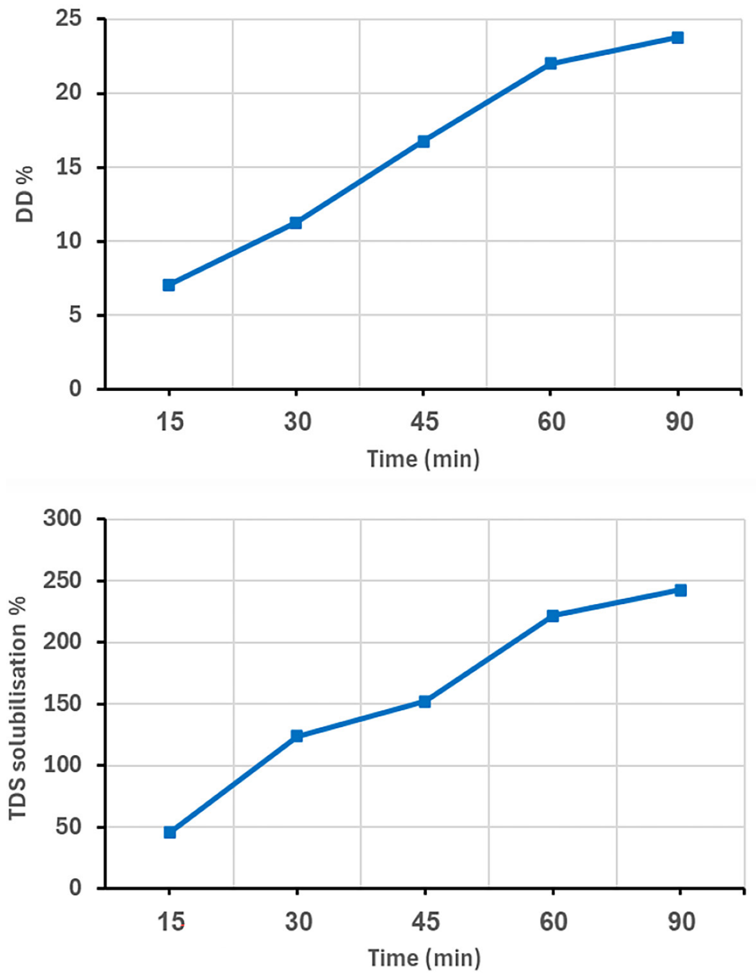

Figure 4. The effect of cavitation time on sludge disintegration

SCOD, and treatment time is very crucial where the excess treatment can degrade the sludge, thereby rendering the pretreatment useless, sludge disintegration through HC can be split into two parts, firstly SCOD is raised with cell lysis and organic substance dissolved. While excess cavitation-based disruption above a particular time resulted in a second stage since the total cells were damaged, leading to intracellular solubilization, and SCOD raised sharply, but microbial activity and biomethane potential went down. Besides, the extra and unnecessary energy consumption (Bhat and Gogate, 2021).

Effect of inlet pressure on sludge disintegration

The major importance of inlet pressure on sludge disintegration is shown in Figure 5, whereas the increase in the inlet pressure from 2 to 7 bar led to enhancement in DD% and TDS solubilization% which raised from 11.96 % to 27.03% and from 134.75% to 305.93%, respectively. The pressure of 5 bar is chosen as the optimum pressure value for cost and energy saving reasons, where SCOD increased by 4176 mg/L while DD% and TDS solubilization% reached 22.91% and 255.08%, respectively. These results showed the effective enhancement in sludge disintegration as the inlet pressure increased since this enhancement could happen as a result of the creation of more bubbles and an increase in the cavitation zone in addition to the intensity of bubbles collapse due to the growth in inlet pressure (Askarniya et al., 2023).

Although the good impact of the increase in the inlet pressure, the high values may cause a negative effect on sludge pretreatment. Whereas the super cavitation or chocked cavitation caused by inlet pressure values exceed the ideal values, resulting in a filled cavitation zone and cavity clouds creation. Thus, in the orifice plates case, the optimal value falls within the range of 2–7 bar, as noted in numerous studies (Askarniya et

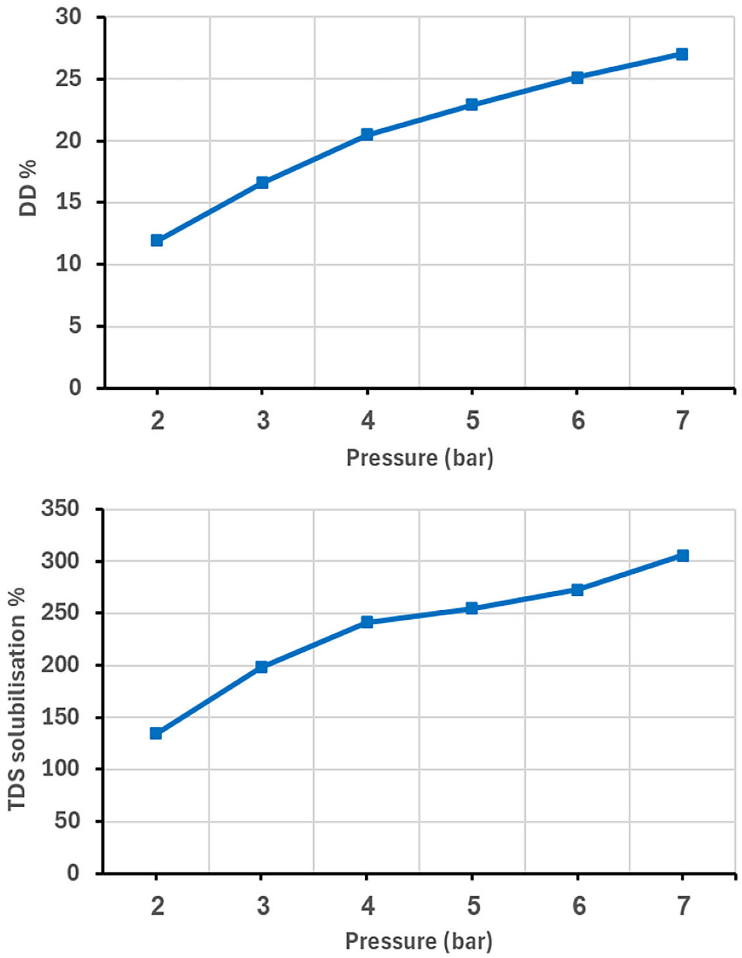

Figure 5. The effect of inlet pressure on sludge disintegration

al., 2023). While, Cai et al. (2018) studied the inlet pressures in range between 3.1 to 5.5 bar for HC with 12 holes of 1.5 mm diameter orifice plate. Most research using only HC pretreatment for bio-sludge has revealed that the ideal pressure ranges are from 2 to 4 bars, where the very high cavitating impacts can harm intracellular materials, resulting in reducing the produced biogas amount (Bhat and Gogate, 2021). In the same context, it was also reported that the optimum input pressure could be in the range of 0.2–0.8 MPa for orifice plates and 0.3–0.5 MPa for venturi, whereas the ideal pressure range of orifices is much greater, probably due to different hole number or the various holes form and size (Wang et al., 2021).

Effect of initial concentration on sludge disintegration

Studying the initial sludge concentration effect demonstrated an inverse relationship between initial total solids (TS) concentration and sludge disintegration degree as indicated in Figure 6, where at initial sludge concentration of TS about 1% to 4%, the disintegration degree was in a range between 10.78% and 23.33%, in addition to TDS solubilization% ranged between 116.88% and 320.83% as indicated in Figure 6. Although SCOD increased when TS increased but the disintegration degree was enhanced when TS changed from 1% to 1.5%, then above this value, the enhancement in DD% decreased as TS increased. This reduction in DD% is consistent with the results reported by Li et al. (2013), where TS of sludge plays a significant role in sludge disintegration since the results indicated that sludge disintegration was negatively impacted by an increase in TS under all conditions examined, showing a decrease in DD%, where for TS of 9.58 g/L DD% values were always the maximum at the same homogenization pressure with the same homogenization cycle number, but it was always the lowest for TS of 24.60 g/L.

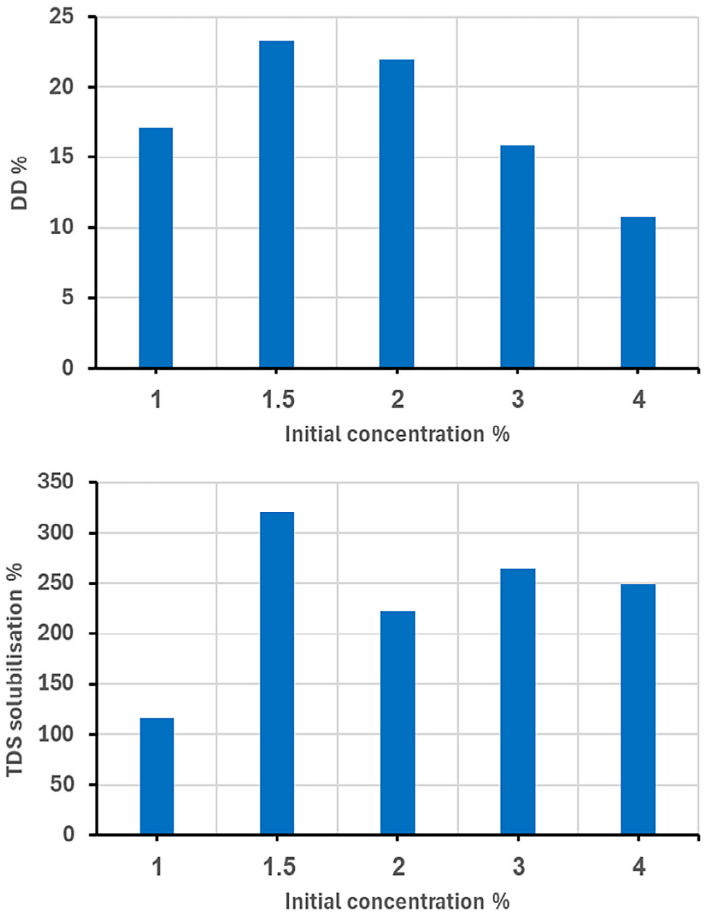

Figure 6. The effect of initial concentration on sludge disintegration

Chemical pretreatment

Alkaline pretreatment

Alkaline pretreatment using NaOH plays a very crucial role in the improvement of sludge disintegration degree through the increase in pH value as demonstrated in the experimental results, where the dissolved matters such as SCOD ranged between 2434 mg/L and 5668 mg/L, in addition to DD% varied from 1.52% to 18.35%, also TDS solubilization% value increased in a range of 22.29% to 357.96% when pH changed from 8 to 12 for 30 min of pretreatment as showed in Figure 7. These enhancements are caused by the disintegration mechanism of alkaline pretreatment that is built on the damage of cell walls and membranes through hydroxyl anions, distraction of sludge flocs, and transport of the solid phase of intracellular and extracellular polymeric substances into liquid phase (Sąhinkaya et al., 2012)**,** besides the probable increase in soluble macromolecules such as proteins and carbohydrates (Nguyen et al., 2021). Also, a study presented similar results with COD solubilization of 0.27% (control), 0.9%, 5%, 11%, 18% and 19% when sludge pretreated at pH of 9, 10, 11, 12 and 13 for 30 min respectively, however at higher NaOH dosages, no appreciable incremental increases in COD solubilization were seen (Chang et al., 2011). While the alkaline dosages for pretreatment ranged from 0.04 to 0.12 g NaOH/gTS with maximum COD solubilization of 10.6% (Machhirake et al., 2024).

The level of solubilization depends on chemical dosage, which usually reaches higher solubilization at large values. Nevertheless, very high dosages decrease AD activity (Nguyen et al., 2021), in addition to the high alkaline dosage can lead to the accumulation of Na^+ and K^+, inhibiting methane generation yield (Machhirake et al., 2024). Consequently, the pH must be adjusted to the range of methanogenesis, which will inevitably raise the cost of pretreatment. However, a small quantity of remaining alkali may help to stabilize pH during the acidogenesis process, enhancing the ability of the system to serve as a buffer (Mitraka et al., 2022).

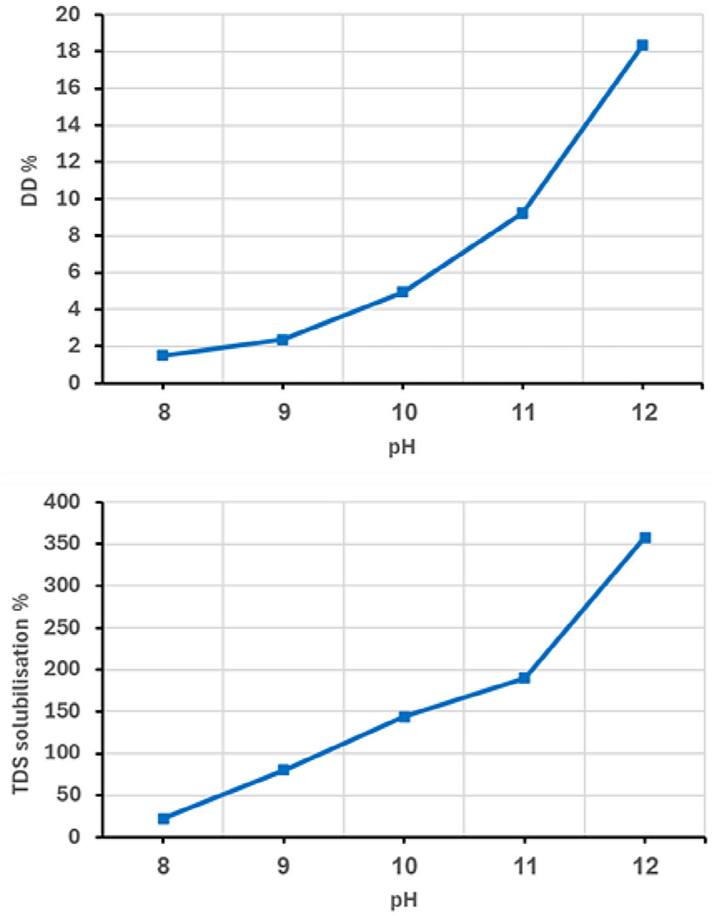

Figure 7. Alkaline pretreatment effect on sludge disintegration

H_2O_2 oxidation

Sludge disintegration and TDS solubilization enhanced when H_2O_2 amount increased until a specific dose but above this value, the disintegration degree decreased where the excess amount of H_2O_2 may decompose sludge, whether in particulate or soluble state. So, after 30 min of H_2O_2 oxidation with dosages of 20, 40, 60, 80 and 100 mg H_2O_2/g TS, SCOD increased from 1821 (untreated) to 1966, 2132, 2108, 2082 and 1955 mg/L, respectively with maximum DD% of 2.06% at H_2O_2 dose equals 40 mg H_2O_2/g TS, as illustrated in Figure 8.

H_2O_2 pretreatment showed a small increase in sludge disintegration as indicated in the experimental results, this observation was also informed by Feki et al. (2015) where the solubilization of COD enhanced by the rise of H_2O_2 dose and time reaction, however extreme H_2O_2 amounts may decline the total degradation efficiency and reduce the solubilization rates, they found that solubilization increased from 10.7% at raw sludge to the highest solubilization of 16% at 1.8 g/L of H_2O_2 and the increase above this amount does not enhance organic matter solubilization. Similarly, the disintegration degree (compared to $SCOD_{NaOH}$) was 5.23% when waste sludge disintegrated by hydrogen peroxide oxidation (Sari Erkan, 2022). While at H_2O_2 concentration of 0.5 mmol/L, SCOD raised by 385 mg/L comparing with no adding H_2O_2 (Yuan et al., 2021).

Fenton pretreatment

The Fenton process is considered an advanced well method for the pretreatment of sludge, where Fe^{+2} ions play an active role as catalytic reagents for H_2O_2 to release more OH° radicals, which aid in pre-treating the sludge. While after 30 minutes of Fenton pretreatment with H_2O_2 dose of 40 mg H_2O_2/g TS as optimum dose from H_2O_2 oxidation phase and pH of 3 with Fe^{+2} ions dosages of 2, 5, 10, 20, and 40 mg Fe^{+2} /g TS the experimental results found that the maximum disintegration of 1.93% was at 10 mg Fe^{+2} /g TS with an increase in SCOD

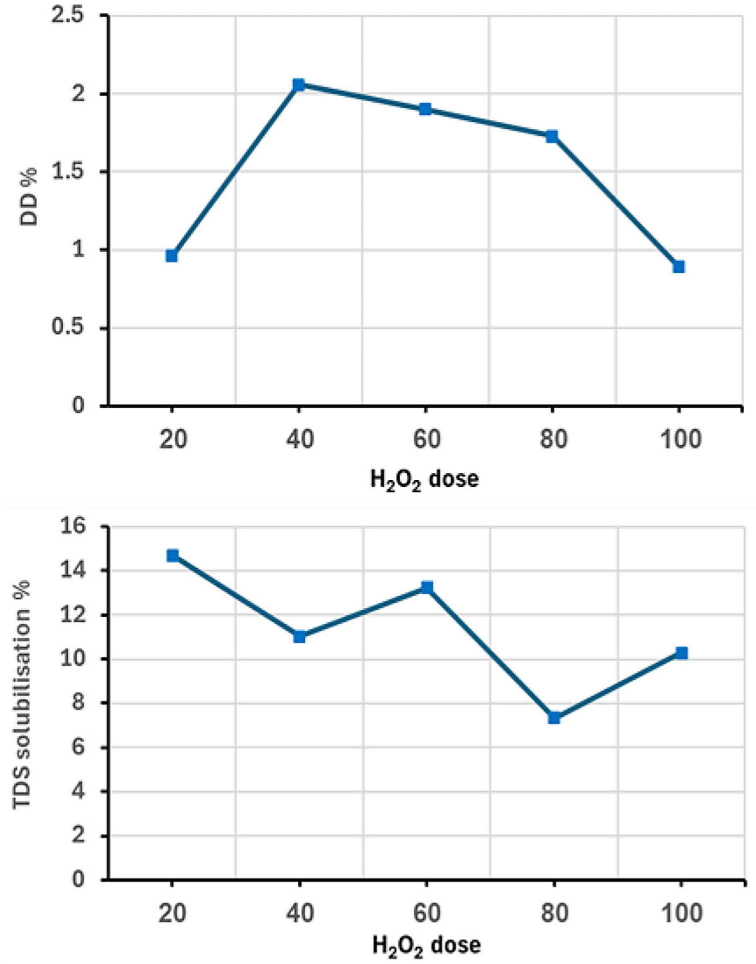

Figure 8. H_2O_2 oxidation effect on sludge disintegration

by 350 mg/L, as illustrated in Figure 9, but a reduction in DD and SCOD happens at doses of iron and H_2O_2 above specific values due to the high oxidation potential of OH° radicals, which can mineralize organic matter to carbon dioxide and water as well as sludge disintegration inhibition (Yildiz and Cömert, 2020). So, the enhancement of sludge disintegration is smaller and not high like results of physical method (HC), this may be the addition of iron catalyst that can motivate the mineralization action rather than solubilization, leading to a small disintegration degree. Therefore, iron dose optimization is a very important element to decrease the chemical Fenton sludge that restricts the treated sludge use in final disposal as well as the high cost of the extra amount of iron (Şahinkaya et al., 2015).

Yildiz and Olabi (2021) also indicated that the maximum DD reached at dose of 10 mg Fe^{+2}/g TS, but the dose of 6 mg Fe^{+2}/g TS was defined as the optimum dose for economic conditions, while extra ferrous iron reacted with OH° radicals, leading to a radical scavenging impact, consequently decreasing SCOD and DD. Similarly, COD release augmented substantially from 292.7 to 510.2 mg/L (0.74-fold) during 0 to 20 min of Fenton pretreatment (Gong et al., 2015).

Combination pretreatment

The hybrid pretreatment methods have a significant impact on sludge disintegration than individual pretreatment due to the synergic effect of these hybrid techniques. This fact was found when studying the combination between hydrodynamic cavitation at optimum conditions (orifice plate with β coefficient of 0.10 and diameter of 2 mm, 60 min and inlet pressure of 5 bar) with alkaline pretreatment (pH of 12), H_2O_2 oxidation (40 mg H_2O_2 /g T) Sand Fenton pretreatment (pH 3, 40 mg H_2O_2/g TS and 10 mg Fe^{+2}/g TS), as indicated in Figure 10, whereas

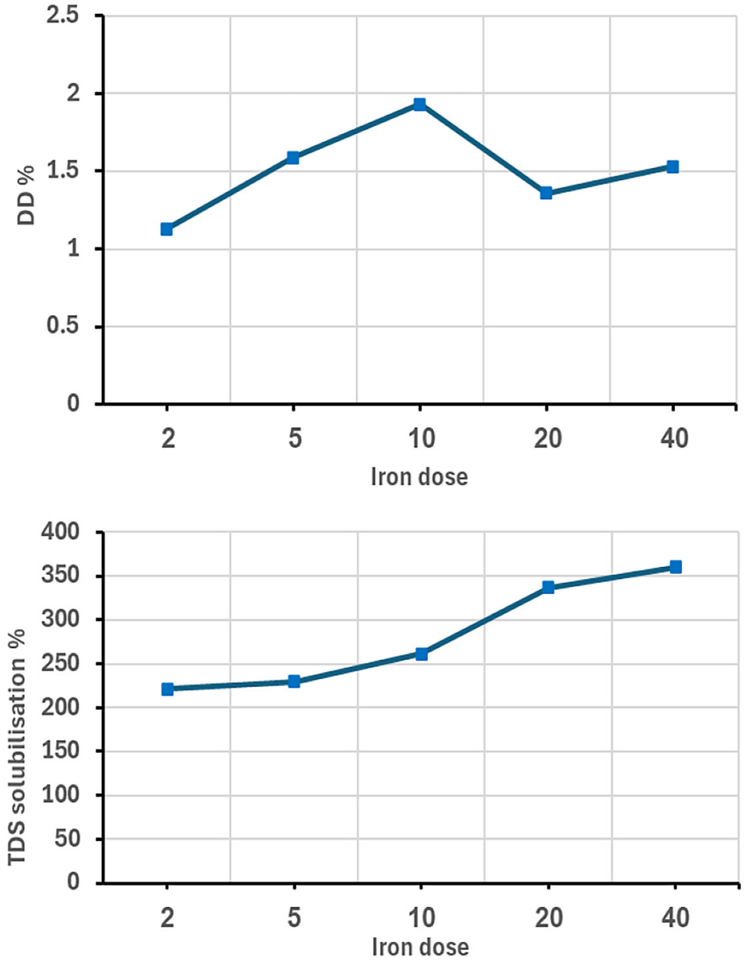

Figure 9. Fenton effect on sludge disintegration

SCOD increased from 1490 to 7578 mg/L with a DD% value of 38.32 % for combined HC with alkaline pretreatment technique which was more effective with a high sludge disintegration degree than the combination of HC with H_2O_2 or Fenton. Similarly, G. Lee et al. (2019) combined HC (orifice with 27 holes of 1 mm diameter, up and downstream pressure difference of around 4.5 bar) with alkaline treatment (pH of 11) for sludge treatment, which led to a maximum DD of 48.4% for combined HC with alkaline while reached 11.9% and 16.2% for HC and alkaline treatment respectively.

On the other hand, SCOD increased from 593 to 3484 mg/L and DD% reached 16.32% for combined HC with H_2O_2 oxidation. While for HC with Fenton pretreatment, SCOD increased from 1900 to 2200 mg/L and the DD% was 1.5%. Consequently, H_2O_2 or Fenton pretreatment combined with HC was not efficient in terms of sludge solubilization and had a small increase in SCOD because the chemical addition of H_2O_2 or Fenton reagents can be motived by HC technology to produce more hydroxyl radicals, leading to more sludge oxidation and decomposition mechanism of sludge to CO_2 and H_2O_2 in addition to the reduction in solid content than solubilization of sludge where the reduction in TCOD, TS, and TVS were 8.29%, 4.31% and 4.04%, respectively for combined HC with H_2O_2 pretreatment moreover the reduction in TCOD, TS, and VS were 35.97%, 17.94% and 27.96%, respectively, for combined HC with Fenton pretreatment. Similarly, there are some studies also achieved that the combination of cavitation between H_2O_2 or Fenton pretreatment has little solubilization and high sludge reduction. Among these similar research, Gong et al. (2015) illustrated a small disintegration in COD release that increased from 292.7 to 709.0 mg/L (1.4-fold) for cavitation by ultrasonic with Fenton, while COD removal reached 94.8% in the ultrasonic-Fenton process, while it reached 17.3 and 25.9% for

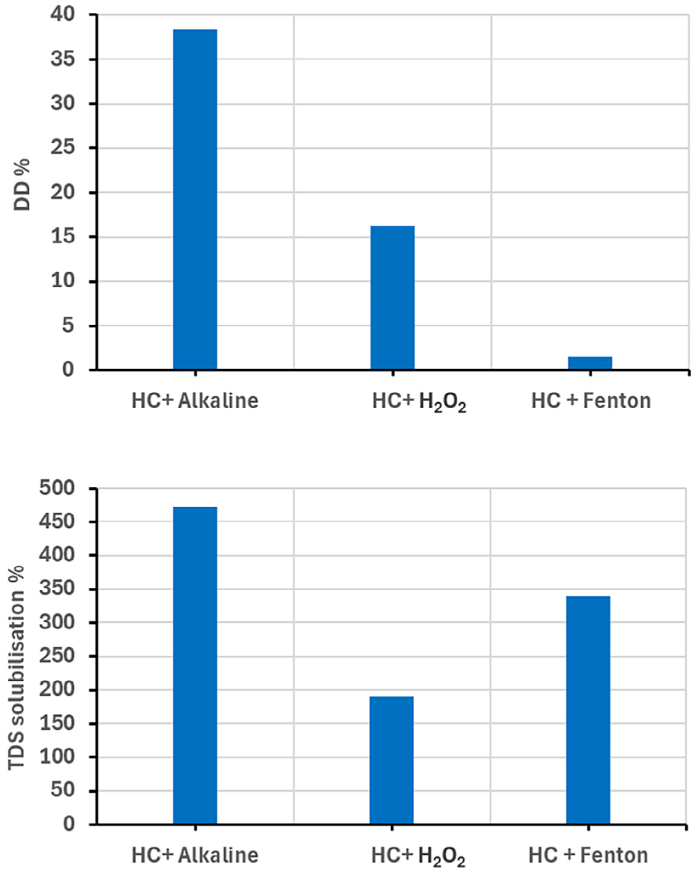

Figure 10. The effect of combination pretreatment methods on sludge disintegration

ultrasound and Fenton, respectively. Clearly, at the combination of US with Fenton, a higher OH° radical generation happened, leading to a kinetic rate increase of COD removal (Santos et al., 2022). Whereas OH° can non-selectively oxidize most organic pollutants to CO_2 and H_2O, as well as mineral salts during rapid chain reaction, due to the very high reactivity and brief lifetime (Gong et al., 2015). Furthermore, the COD removal rate of leachate treatment by iron-carbon micro-electrolysis (ICME) with Fenton was 46.03%, where the combination of Fenton after the ICME process enhances the removal rate of COD, since Fenton's reagent can supplementarily oxidize organic contaminants (Dong et al., 2023). Conversely, the Fenton process or combined with other methods like cavitation, showed a good effect for sludge dewatering than disintegration, whereas capillary suction time decreased initially from 50 to 28.9 and 19.8 s in 20 min after Fenton and HC/Fenton respectively. Moreover, the moisture content of sludge varied from 81.1% to 76.3% and 70.2% for Fenton and HC/Fenton treatments, respectively (Cai et al., 2018).

CONCLUSIONS

Overall, the investigated sludge pretreatment technologies demonstrated notable improvements in sludge characteristics and significantly enhanced disintegration efficiency prior to anaerobic digestion. HC using orifice plates, along with chemical pretreatments involving alkaline addition (NaOH), H_2O_2, and Fenton reagents, led to increases in soluble chemical oxygen demand and total dissolved solids. The disintegration degree achieved was 22.83% for HC, 18.35% for alkaline pretreatment, 2.06% for H_2O_2, and 1.93% for the Fenton process. The highest DD% (38.32%) was obtained when HC was combined with alkaline treatment, indicating a strong synergistic effect. These findings suggest that HC is more effective than individual chemical treatments and its efficiency is significantly enhanced when coupled with alkaline pretreatment. While these single and combined methods show promise for full-scale application in sludge management, future research should focus on optimizing energy consumption to improve their overall sustainability.

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