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Advanced Flocculation Techniques for Sustainable Water Treatment: A Review on Types and Performance

Zainab Radhi Thamer, Saad Abu-Alhail Arab, and Dina Ali Yaseen*

Department of civil engineering, College of Engineering, University of Basrah, Basra, Iraq

*corresponding author: dina.yaseen@uobasrah.edu.iq
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Abstract

This review presented the stages of the treatment process and comprehensively focused on various flocculator types, including hydraulic, mechanical, and helical coiled tube (HCTF) flocculators, to assess their efficiency in water treatment. Each type was explained in detail, with its advantages and disadvantages, and when it is preferable to use it. This was done by reviewing many previous articles from 1986 to the current year 2024. These studies included research into the components of each type or studied one of the types to calculate operational efficiency or other advantages or disadvantages, and some of them included comparisons between different types of flocculators. Recent advancements in flocculation technology, including innovations like automated control systems, optimized coagulant formulations, and energy-efficient helical coiled tube flocculators (HCTFs), have significantly improved performance. These technologies offer precise control over flocculation dynamics, reducing chemical usage, energy consumption, and maintenance costs, while also providing more reliable and sustainable water treatment solutions. This study confirms what scientists have previously observed and underscores the advantages of helically flocculators as a viable and efficient alternative, aligning with the growing demand for cost-effective and space-efficient water treatment technologies.

Keywords: Flocculation; Helical coiled tube; Sustainable; Turbid water; Water treatment

1. Introduction

Water treatment is an essential process that ensures the availability of clean and safe drinking water (Yaseen *et al.,* 2019; Alfaiz *et al.,* 2023). The primary objective of water treatment is to remove contaminants and impurities from raw water to make it suitable for human consumption and use. This process includes several stages, at first screening, then coagulation, after that flocculation, and sedimentation at the end filtration (Rana *et al.,* 2023; Yaseen *et al.,* 2020).

The first step in water treatment processes is screening, which requires the removal of large particles and debris from the raw water (Naseer *et al.,* 2011; Mohammed *et al.,* 2013). This is done by coagulation, where coagulants such as alum or ferric chloride are used to destabilize colloidal particles in water. As noted by (Patel *et al.,* 2018), fast mixing in this step ensures an even distribution of coagulants, resulting in the formation of larger particles, or flocs. After that, the flocculation process promotes the slow mixing needed to form larger and denser flocs of unstable particles. According to Raida (2018) these larger flocs can be more easily removed in subsequent treatment stages.

After flocculation, water moves to sedimentation, which the flocs created in the previous stage settle by gravity, then the solid particles separate from the clearer water effectively (Patil *et al.,* 2018). After sedimentation, the filtration stage takes effect. During this stage, water is directed through a filter, usually sand, to remove any remaining particles. This process is necessary for ensuring the removal of microorganisms and fine particles as noticed by (Patil *et al.,* 2018).

The importance of coagulation and flocculation is based on their fundamental roles within water treatment systems. These processes are important for removing turbidity, microorganisms, bacteria, and various infectious agents from water. The overall effectiveness of the water treatment process is greatly affected by the efficiency of coagulation and flocculation by removing larger particles during the initial stages (Patil *et al.,* 2018; Raidah, 2018). This review made to evaluate the effectiveness of flocculators and select the suitable option according to the specific conditions and requirements.

2. Parameters Affecting Flocculation Efficiency

To ensure the effectiveness of the flocculation process, many parameters need to be considered. Key factors include mixing intensity, retention time, and the type and quantity of flocculants used. As SNI 6774:2008 standard outlines on planning procedures for water treatment, these elements are necessary to achieve an effective flocculation system (Raidah, 2018).

To summarize the process of water treatment involves multiple steps aimed at generating safe and clean drinking water. Coagulation and flocculation are essential steps that help remove impurities, make the next treatment stages more effective. Improving these processes is good for enhancing the efficiency of water treatment and delivering of high-quality drinking water.

Water treatment is important to ensuring the safety of water to use. The main goal of water treatment is to remove contaminants from water and making it suitable for several of applications, including drinking, industrial processes, and irrigation. This is achieved through a series of physical and chemical, beside biological processes that work together to remove turbidity.

According to the research presented by (Smith, 2020) flocculation plays an important role in water treatment, particularly in the removal of turbidity and suspended solids. The effectiveness of the flocculation process is influenced by some parameters like the speed gradient, detention time, and the design of the flocculation unit. The focus is on forming stable aggregates to facilitate easier removal of turbidity during the subsequent sedimentation and filtration stages.

3. Types of Flocculation

3.1 Hydraulic Flocculators

Hydraulic flocculators treat water by collecting small particles into larger flocs to remove them easily through sedimentation or filtration. These systems use the hydraulic energy of flowing water to create controlled turbulence. Improve efficient mixing without the need for mechanical energy input required in mechanical coagulation devices. Several designs of hydraulic flocculators, like horizontal baffled, vertical baffled, cyclone flow, perforated plate, and pulsator flocculators, each offer special advantages depending on the specific treatment requirements and water quality conditions. Research by García-Avila *et al* (2024) showed that the effectiveness of horizontal flow tubular hydraulic flocculators in developing communities, while Smith *et al.* (2023) confirmed the operational challenges of vertical baffled designs. The choice of flocculator is very important because it directly affects the efficiency of the flocculation process and the overall performance of water treatment. Understanding the principles and applications of hydraulic flocculators is necessary for improving water treatment systems to meet the growing need for clean and safe drinking water. Hydraulic flocculators include many designs, including horizontal baffled flocculators, vertical baffle flocculators, cyclone flocculators, porous plate flocculators, and impeller flocculators.

Horizontal baffled flocculator consisted of a basin with baffles arranged in a series of horizontal flow paths. Water enters to the flocculator and flows horizontally. This design motivates turbulence and improves particle mixing. Garcia-Ávila *et al.* (2024) evaluated the performance of baffled horizontal flocculators under different flow conditions.

The study found that the design effectively motivated flocculation by generating local turbulence and increasing the particle collision rate. The study concluded that while these flocculators are effective at constant flow rates, their performance may degrade under conditions of large fluctuations in inflow, so careful design considerations are needed for inconstant conditions. Regarding the vertical baffle flocculator, this type has vertically oriented baffles to create a vertical flow path where water flows up and down through the baffles. This type is often called (over-under) design and assistance in mixing and flocculation. Smith *et al.* (2023) did a comparative analysis and found that while these flocculators achieve effective mixing, they are exposed to high pressure losses and vibrations that can effect efficiency. The study recommends improving baffle spacing and height to reduce these issues and improve performance. In terms of cyclone flocculator, this type uses the cyclonic effect to improve mixing. This design helps to achieve high mixing intensity. Johnson *et al.* (2022) studied the effectiveness of cyclone flocculators on treating turbid water. The study showed that the vortex motion increased the velocity gradient, increasing floc formation and settling rates. The authors found that cyclone flocculators are beneficial in applications where high turbidity water needs to be treated quickly although they may require careful design to control energy consumption. Regarding the porous plate flocculator, it consists of a plate with many holes through water for can flow. When the water flows through the holes, it experiences turbulence, which helps in mixing and flocculation. This design is effective in reaching uniform flow distribution. A study by Lee *et al.* (2021) evaluated the performance of porous plate flocculators in a water treatment pilot plant. The results showed that the design was effective in improving flocculation by supporting uniform flow and reducing dead zones. The study refers to the importance of holes' size and distribution in performance improvement and shows that careful design can improve flocculation efficiency. Finally, impeller flocculators, this type work by creating a vibrant flow, which improves mixing. This type of flocculator used a mechanism to change the flow rate and create turbulence that improved floc formation. The pulsating action can help break up flakes and improve flake growth. Thompson *et al.* (2020) studied the effectiveness of impeller flocculators in different water treatment types. The study found that pulsating flow increased flocculation and settling rates compared to old continuous flow systems. The researchers noticed that while impeller flocculators can be more complex to operate, their ability to adapt for changing impact conditions makes them a valuable option for dynamic water treatment environments (figure 1).

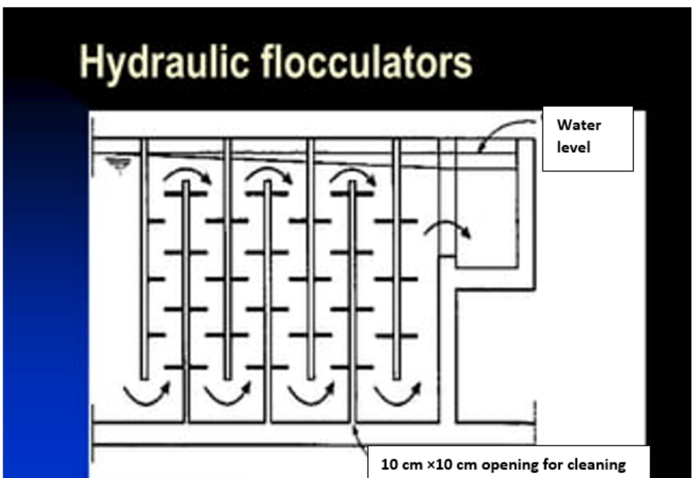


Figure 1. Hydraulic Flocculators (Van Leeuwen, 2011)

3.1.1 Advantages and Disadvantages of Hydraulic Flocculators

There are many advantages of hydraulic flocculators; they are energy efficient because they do not use electricity, so they do not use much power if compared to mechanical flocculators (García-Avila *et al.,* 2024). Besides, they require less maintenance because of the small number of parts (García-Avila *et al.,* 2024). Their simplicity makes them well suited for constant flows of water (García-Avila *et al.,* 2024). Furthermore, they are cheaper, making them more cost-effective when it comes to yearly operational costs than mechanical alternatives (García-Avila *et al.,* 2024).

However, hydraulic flocculators have some disadvantages. These often require larger areas of putting and can be a disadvantage in cases where space is small (García-Avila *et al.,* 2024). Additionally, the performance of hydraulic flocculators dependent on changes in flow rate may affect their mixing efficiency (García-Avila *et al.,* 2024). They may also have only limited capacity for mixing when compared to mechanical flocculators, especially with variable flow rates (García-Avila *et al.,* 2024). Finally, they are prone to big head losses, requiring additional pumping power (figure 2).

Each type of flocculator has special properties that make them suitable for specific applications in water treatment operations. According to research findings, horizontal and vertical baffled flocs are useful in maintaining a consistent flow, while cyclone flow and pulsator flocculators have proved advantageous because of their ability to mix intensively and adaptability. The perforated plate floc allows for even distribution of flow, improving the overall efficiency of flocculation. The choice of which type of flocculator should be employed is dependent on factors such as fluctuation in hydrology, effluent water quality standards, and operational limitations, among other things. Table 1 shows a comparison between previous studies that utilized hydraulic flocculators.

3.2 Mechanical Flocculators

Water treatment processes can use a mechanical flocculator. This system uses mechanical mixing to ensure turbulence and contact between the particles and the coagulant. Mechanical flocculators are firstly suitable for applications that require control of the density and duration of mixing. Different types of mechanical flocculators are available and utilized during the water treatment process. Each type has different properties and should be considered during the designing step to ensure improved flocculation. Firstly, a paddle flocculator, which uses rotating paddles to mix water, with design parameters such as paddle speed and geometry playing main roles in determining efficiency. Cleasby (1984) noticed in his research the importance of the velocity gradient (G) as a main design factor, while Hanson and Cleasby (1990)

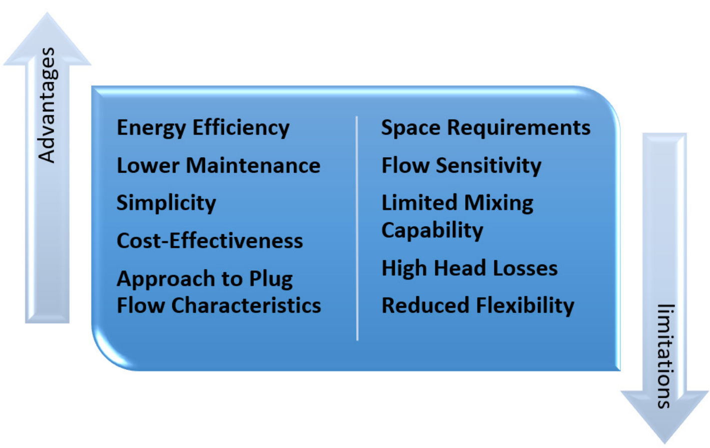


Figure 2. Advantages and Disadvantages of Hydraulic Flocculators

Table 1. Comparing between different hydraulic flocculators

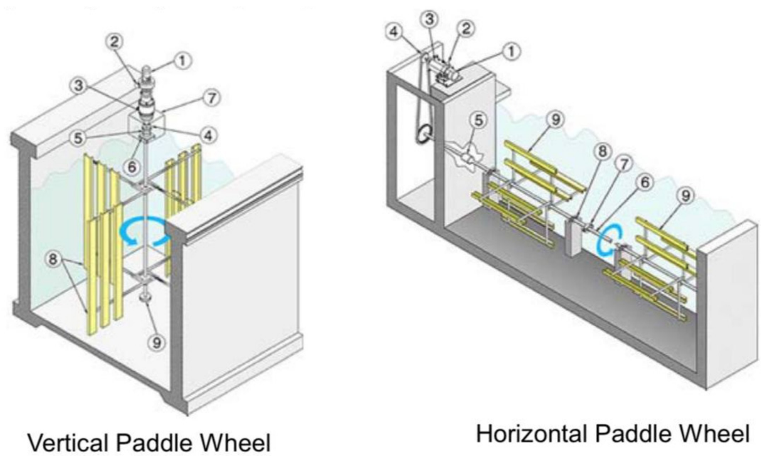
Researcher	Type of Water Used	Technique (Type of Flocculator)	Difference from Other Research	Results
García-Avila *et al.* 2024	Various flow conditions	Horizontal Baffled Flocculators	Evaluated performance in various flow conditions	Effective for consistent flow rates, performance degrades with fluctuations
Smith *et al.* 2023	Comparative analysis	Vertical Baffled Flocculators	Compared efficiency with horizontal designs	Higher head losses and vibrations, optimization recommended
Johnson *et al.* 2022	Turbid water	Cyclone Flow Flocculators	Explored effectiveness in treating turbid water	Improved floc formation and settling rates
Lee *et al.* 2021	Pilot-scale water treatment	Perforated Plate Flocculators	Evaluated performance in pilot-scale facility	Enhanced flocculation by promoting uniform flow
Thompson *et al.* 2020	Various water treatment scenarios	Pulsator Flocculators	Investigated effectiveness in various scenarios	Improved floc formation and settling rates, adaptable to varying conditions

showed how temperature and impeller geometry can affect performance. Another study by Vadasarukkai and Gagnon (2010) used computational fluid dynamics (CFD) and pilot plants to optimize paddle speed and enhance flocculation. Secondly, impeller flocculators; this type uses rotating blades within the flocculation tank. The design of these impellers affects system performance. Haisalkar *et al.* (1986) introduced a new electrical method for determining the power input to impeller mixers, which in turn helps calculate the G value for the design and operation of these systems. While Spicer *et al.* (1996) used image analysis to describe the influence of impeller type on floc formation, showing how different impeller designs affect the size and structure of the flocs. After that, in 1998, authors studied the effect of the G value on floc properties in a flocculator stirred by a Rushton impeller, pointing out the relationship between mixing intensity and floc properties. Then, Ducoste and Clark (1998) conducted an experimental study to evaluate the effects of impeller type and tank volume on floc size distribution using two impeller types and three tank volumes (5, 28, and 560 liters). This study provided valuable data on how different configurations affect flocculation efficiency. Yang *et al.* (2014) rated the effect of impeller speed on the efficiency of cylindrical flocculators using CFD, offering guidance on optimizing operational parameters for better performance. Grids or baffles in flocculation tanks boost mixing and turbulence. These structures have an impact on how the flow interacts with the flocs. Cho *et al.* (2010) used CFD to examine how partition shape affects the hydrodynamic behavior of flocculation tanks with horizontal paddles. Their study noticed how changes in tank design can improve flocculation efficiency. Sun *et al.* (2012) used CFD modeling to simulate the flow field in a cylindrical flocculation tank. They checked different baffle shapes around the tank's edge. Their study gave new ideas about how baffle design changes the flocculation process and flow dynamics.

Mechanical flocculators focus on the hydraulic conditions and flow patterns in the tank to improve flocculation. They often use advanced modeling techniques to improve performance. Bridgeman *et al.* (2009) presented a review of the application of CFD techniques in modeling mechanical flocculation processes, summarizing some studies, and presented the benefits and limitations of using CFD in this context. Other studies employed modeling methods and experimental techniques to clarify the understanding and optimization of mechanical flocculators. Ducoste and Clark (1999) validated the use of CFD techniques in modeling mechanical flocculators by comparing the simulation results with experimental results. Zhang *et al.* (2006) developed a 3D CFD model to study the effect of impeller geometry and speed on G value distribution in mechanical flocculators. Their work has advanced the understanding of how different design variables affect the mixing and flocculation processes. while He *et al.* (2018) studied both experimental and CFD studies on floc growth in square flocculation tanks provided with impeller mixers, giving extensive data about the effects of many design and operational parameters on floc formation and growth (figure 3).

3.2.1 Advantages and Disadvantages of Mechanical Flocculators

Mechanical flocculators have many advantages in water treatment processes. First, they give precise control over mixing intensity and duration, which is very important for improving flocculation efficiency. Cleasby (1984) confirmed the importance of the velocity gradient (G) as a main design parameter for paddle flocculators; this emphasizes the importance of control in achieving effective flocculation. In addition, mechanical flocculation is adaptable to a wide range of water types and flow rates. Hanson and Cleasby (1990) explained how impeller geometry and temperature-changing influence flocculation efficiency and display the flexibility of mechanical flocculators in different work conditions. Furthermore, studies by Ducoste and Clark (1998) and Spicer *et al.* (1996) discovered that different impeller types and configurations can clearly affect the size and quality of flocs; this highlights the high mixing efficiency that mechanical flocculators can achieve. Lastly, the use of computational fluid dynamics (CFD) has enabled detailed analysis and improvement of mechanical flocculators. Studies by Ducoste and Clark (1999) and Zhang *et al.* (2006) have shown that CFD can improve designs and operational strategies and improving the performance of mechanical flocculators.



1-stirring column; 2-shafarah; 3-stirring rods; 4- rotary motor; 5- paddle-wheel flocculator; 6-comprises a turbine; 7-speed regulator; 8-three blades, driven direct

Figure 3. Mechanical Flocculators (Muhammad Ahmad, 2018)

Mechanical flocculators have some disadvantages that affect their performance. One main disadvantage is increased complexity and cost connected with their precise control and adaptability. The need for designs like specific impeller types and formations and advanced techniques like CFD modeling can make these systems more expensive and hard to design and maintain (Cho *et al.,* 2010; Sun *et al.,* 2012). Additionally, mechanical flocculators may give inconsistent results under some conditions. McConnachie (1991) highlighted that different engine types can give different flocculation efficiencies, that means potential difficulties in achieving consistent performance in different systems and operational settings. The sensitivity of mechanical flocculators to design parameters is another disadvantage. Spicer *et al.* (1998) and He *et al.* (2018) proved that changes in impeller speed or tank volume, and baffle shapes can affect floc properties and overall efficiency that requires careful design. Vadasarukkai and Gagnon (2010) confirmed the importance of improving baffled flocculator designs to improve mixing without damaging large developed flocs, which can reduce flocculation efficiency. Lastly, the use of advanced methods like CFD modeling requires calibration and verification. Joodi (2012) showed that some studies do not have calibration or verification that can limit the reliability of the simulation results. Figure 2 shows a diagram of the advantages and disadvantages of mechanical flocculants (figure 4).

Overall, mechanical flocculators have important advantages in control, adaptability, and efficiency but also have disadvantages related to complexity, cost, and sensitivity to design and operational parameters. Table 2 shows a comparison between different mechanical flocculants.

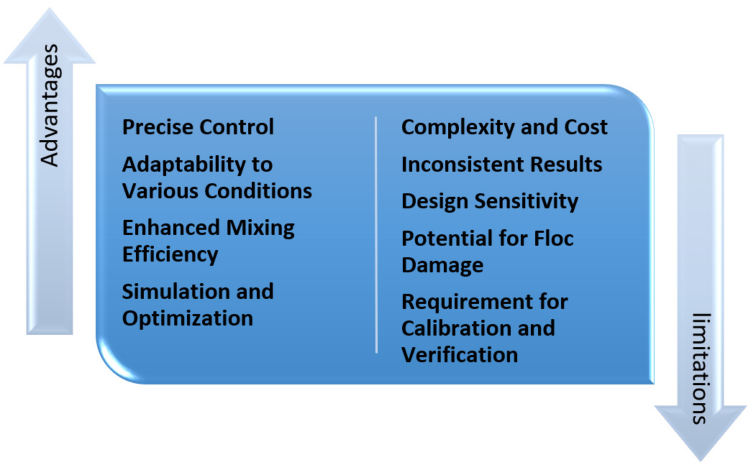


Figure 4. Advantages and Disadvantages of Mechanical Flocculators

Table 2. Comparing between different mechanical flocculators

Researcher(s)	Type of Water Used	Technique (Type of Flocculant)	Difference from Other Research	Results
Bhargava and Ojha1993	Not specified	Not specified	Developed a methodology using nomographs for baffled flocculators	Best agreement of experimental and theoretical head loss values at k=1.53; dimensions determined for specific flow rates.

Table 2. Comparing between different mechanical flocculators (Cont.)

Researcher(s)	Type of Water Used	Technique (Type of Flocculant)	Difference from Other Research	Results
McConnachie 1993	Synthetic river water	Coagulant types not specified	Experimental study with pilot unit; various baffle types	Best results at flow velocity of 0.10 m/sec; detention times range (20-25) min.
Swamee 1996	Not specified	Not specified	Formulated a geometric programming problem for optimum design	Optimum design satisfied velocity gradient condition (20-74 sec^{-1}; head loss coefficient (k) value of 2.
Haarhoff 1998	Not specified	Not specified	Developed a two-step design procedure	Increased flexibility by providing suitable floor slope and regulated water depth.
McConnachie and Liu 2000	Synthetic river water	Coagulated with alum	Assessed performance of various grid baffle arrangements	Best performance at t and Gt ranges (15-20 min and 25000-35000); head loss coefficient (k) varies with baffle type.
Haarhoof and Van der Walt 2001	Not specified	Not specified	Used CFD modeling to study performance of baffled flocculators	Optimum values for slot width, overlap distance, and water depth ratios determined for uniform G values.
Liu *et al*. 2004	Synthetic river water	Coagulated with kaolin	Developed "point-to-point method" for design using CFD and turbulent kinetic energy	Method results in excellent agreement with experimental results; efficiency increases with initial turbidity.

Table 2. Comparing between different mechanical flocculators (Cont.)

Researcher(s)	Type of Water Used	Technique (Type of Flocculant)	Difference from Other Research	Results
Zhang *et al.* 2006	Not specified	3D CFD Model (Impeller Geometry and Speed)	Developed a 3D CFD model to study the impact of design variables on G value distribution.	Advanced understanding of how impeller design variables influence mixing and flocculation processes.
Bridgeman *et al*. 2009	Not specified	Review Study (CFD Modeling)	Reviewed the application of CFD in modeling mechanical flocculation processes.	Provided a comprehensive review of CFD applications, highlighting its potential in flocculator design.
Cho *et al*. 2010	Not specified	CFD (Partition Shape Study)	Used CFD to study the effect of partition shape on flocculation tank hydrodynamics.	Showed that partition shape affects hydrodynamic behavior and flocculation efficiency.
Vadasarukkai and Gagnon 2010	Not specified	Pilot Plant and CFD (Paddle Flocculator)	Studied the effect of paddle speed on G values using CFD.	Demonstrated the need for optimization in paddle flocculators to enhance mixing without floc damage.
Sun *et al*. 2012	Not specified	CFD (Baffle Shape Study)	Simulated flow field in cylindrical flocculation tank with different baffle shapes using CFD.	Found that baffle shape influences flow field and flocculation efficiency.
He *et al.* 2018	Not specified	Experimental and CFD Studies (Floc Growth)	Conducted experimental and CFD studies on floc growth in square tanks with impeller mixers.	Provided detailed data on how design and operational parameters affect floc formation and growth.

3.3 Helically flocculators

Helically flocculators or helically coiled tube flocculators (HCTFs) are used in water treatment processes to improve the flocculation. Helically flocculators use a unique design where the flow of water is directed through a helically coiled tube, which gives some advantages in water treatment processes. The helical structure causes a spiral flow pattern that makes the mixing of water and coagulants better, and consequently helping particles collide and stick together to form stable flocs. This better mixing has an effect on the process, as shown in the study by Cahyana *et al.* (2021). They proved that the helical design reduces turbidity by creating the best flow conditions. Also, the curved shape of the helical tube lowers turbulence, which means the flocs don't break apart when they have formed. Hameed's (1995) research pointed out that gentle mixing is good to keep flocs intact.

In addition to improving flocculation efficiency, helically flocculators are designed to be compact and save space, which makes them suitable for use in facilities with small spaces. The coiled shape creates a longer flow path in less area than straight designs. Vigneswaran and Setiadi (1986) tested different HCTF setups in (Experimental Evaluation of Helically Coiled Tube Flocculators). This compact design allows flocculators to work in many places, from small community water plants to big factories, offering a flexible and effective way to clean water better. Coiled tube flocculators (HCTFs) have brought a big change in water treatment in coagulation and flocculation. These new devices have a helical design to mix particles and interaction that leads to better floc formation and clear water. The shape of HCTFs creates good flow patterns, which can decrease treatment times compared to old flocculation systems like baffled tanks. More and more researchers studied how HCTFs can offer effective and cheap ways to treat drinking water in developing areas where clean water is hard to make. Different types of helically coiled tube flocculators are studied by researchers. Firstly, horizontal coiled tube flocculators (HCTFs), this type works well in wide water treatment plants. They let water flow non-stop, which helps mix it and form flocs. Oliveira *et al.* (2017) studied the using of coiled tubes (HCTs) to clean water; they ran 84 tests to see how well HCTs could remove turbidity from water. They changed both the water flow and the shape of the tubes. HCTFs cleared out more than 80% of the turbidity, with the best result being 86.2%. This beat the old-school tanks with barriers. Plus, HCTFs did the job in under 2 minutes, which shows they could clean water fast. The study came up with something called the "swirl number" (SN). This number shows how the water's movement links to how well the HCTF clears out cloudiness. They found that when the SN increased the water got clearer. This means the system modification based on how the water flows and how the HCTF is built makes it work better. Secondly, vertical HCTFs; these types are installed in a vertical position that helps in small spaces. This makes flocs settle because of gravity while keeping the benefits of the spiral flow. Cahyana *et al.* (2021) studied the working efficiency of vertical helically coiled tube flocculators; they found these devices can reduce turbidity, which makes them a good choice for city water plants where space is tight. Their work aimed to set things right, like speed of flow, pipe size, coil size, flow rate, time in the system and how much coagulant to use. They wanted to find the best setup to clean the water. By running many tests they saw how different flow rates and pipe sizes changed how the flocs formed. The results showed that certain flow rates and volumes can enhance the quality of water cleaning. This makes spiral flocculators excellent for medium to high-level water cleaning.

Variable diameter HCTFs have diameters that can be variable along the helical coil, which allows them to create tailored velocity gradients. This flexibility helps to improve floc formation by controlling the shear forces on the particles. Oliveira *et al.* (2017) in their research, showed how important this design is to achieve the best turbidity removal. Hameed *et al.* (1995) looked into how coiled flocculators increase flocculation efficiency through their unique flow dynamics and shapes. The study wanted to understand floc formation and analyze how different diameters of helical coils affect water treatment processes. The researchers studied different coil shapes to see how velocity gradients and flow patterns influence flocculation. The results revealed that coiled flocculators can greatly improve flocculation efficiency because of their distinct flow characteristics. The study showed that changing the diameter of the helical coils allows operators to improve flocculation performance. This makes these flocculators adaptable to specific water treatment requirements. This research shows how important the shape design is in making flocculation systems work better. The study proves that coiled flocculators can offer better flocculation efficiency due to their unique flow dynamics.

Also, modified HCTFs designed to improve performance, like changes in the helical pitch or extra mixing parts. Cahyana *et al.* (2021) studied many modifications to the standard HCTF design and saw that these changes may give better sedimentation and HCTFs can adapt to different water treatment needs. The study found that HCTFs decrease turbidity levels that good for small-scale water treatment. The small size of HCTFs has emerged as a big plus that makes them easy to set up and keep running in places that don't have a lot of infrastructure. The study concluded that HCTFs could play a main role in making water cleaner in areas that do not receive enough assistance. Vigneswaran and Setiadi (1986) studied how well coiled tubes (HCTs) worked like a coagulation-flocculation reactor in a clarification system. They compared HCTs to baffled tank setups. The research focused on how they removed turbidity and how long it took them to treatment. They checked coiled tube flocculators (HCTFs) against standard baffled flocculators and focused on turbidity removal and flocculation performance. They examined the efficiency of 48 different HCTF setups for treating water; results showed that the HCT system can remove up to 86.2% of turbidity, while old baffled tank systems manage around 60%. The study also showed that HCTs need less time to do the job, and the best flocculation times were about 15 minutes. The researchers tried changing some conditions, like flow rates and chemical amounts, to see how they affected flocculation. They found that HCTs could be a great option for water treatment in developing areas because they can make water cleaner while taking less time and being simpler to use. The tests showed that HCTFs made flocs and removed turbidity better than old baffled methods. At the end, the study said that HCTFs are a more effective choice for treating water. They do a better job of reducing turbidity and making flocs faster.

Oliveira and Teixeira (2017) tested coiled tubes (HCTs) like coagulation-flocculation reactors for water treatment. They wanted to see how well this system could clear water because that is very important for water quality. They set up an experiment using a coiled tube flocculator connected to a regular sedimentation tank. They ran tests to see how well it cleared the water and how long it took under different conditions. They also looked at two mathematical models to predict how well the flocculation would work. The results were good, and the HCT flocculator cleared up more than 80% of the turbidity, with the best result being 86.2%. This worked much better than the usual baffled tank systems, which are often used to treat water in poorer countries. Plus, it worked faster, taking less than 2 minutes compared to the longer times baffled tanks need. The study found that HCTs working with lower average velocity gradients produced the best results. This suggests that more shear stress hurts how well flocculation works. Also, the math models we have now didn't predict how flocculation behaved. This shows we need new models to better guess how well HCT systems can remove cloudiness from water. In the end, this research shows that coiled tubes could be a good and efficient way to clean water in places with limited resources.

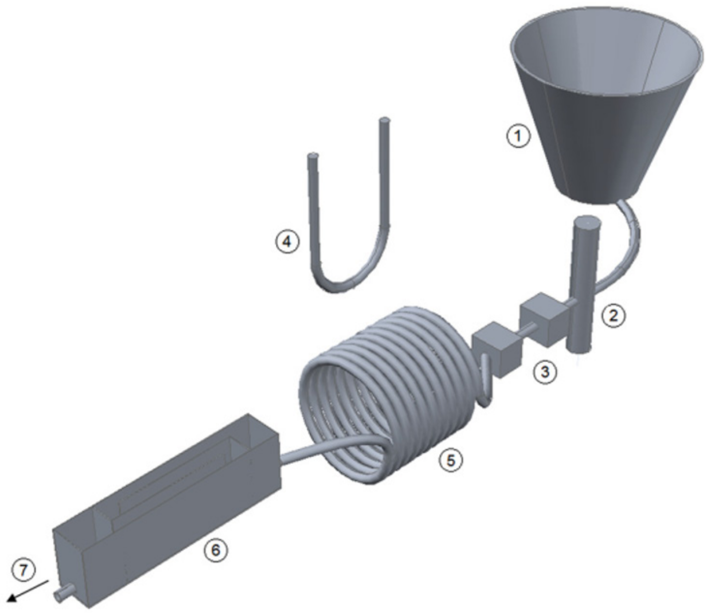
Additionally, Oliveira and Teixeira (2018) present original results of theoretical, experimental, and computational fluid dynamics (CFD) modeling studies of helically coiled tube flocculators, using a parameter capable of representing hydrodynamic characteristics in these reactors. The absence of parameters that satisfactorily depict the relationship between axial velocity and secondary flow in helically coiled tubes necessitates the creation of new parameters and/or the determination of the adequacy of existing parameters. The theoretical adequacy in the formulation of the swirl number (SN) that is applicable to helical units is proposed in this paper; the aim is to represent their hydrodynamic characteristics, which are not possible with the current formulation. This parameter is obtained using three-dimensional CFD modeling in 48 units with various hydraulic and geometric characteristics. Acting as flocculators, these 48 units are evaluated by experimental modeling, assessing an important parameter of the flocculation process turbidity removal efficiency (TRE). The results demonstrate, for the first time, the relationship between TRE and the SN, making possible an improvement in projects of helical units and optimizing hydraulic and geometric characteristics to achieve high operational performance units. The study evaluated 48 helically coiled tube flocculators with different hydraulic and geometric properties; key findings include:

- Turbidity Removal Efficiency (TRE): The research proved an important relationship between the swirl number (SN) and (TRE), indicating that higher SN values are related to improved turbidity removal.

- Hydraulic and Geometric Optimization: The results indicate that improving the hydraulic and geometric properties of the helical units can lead to improved operational performance in flocculation processes.

- CFD Modeling Validation: The CFD modeling results were validated with experimental data to be sure the reliability of the proposed swirl number as an important parameter in helically coiled tube flocculators.

Coiled tube flocculators provide a promising option to replace old flocculation systems. The studies by Oliveira *et al.* and Cahyana *et al.* highlighted the success of HCTFs in removing turbidity and reducing treatment times. As more people need effective ways to treat water, we will need to explore and improve HCTF designs more to address water quality issues around the world (figure 5).



(1) a reservoir of synthetic water; (2) a flow meter (flow controllers); (3) dosing pumps of chemical reagents; (4) pressure gauge connected at flocculator's input and output sections; (5) flocculator; (6) decanter system (settling tank); and (7) drain to the final disposal of the fluid

Figure 5. Schematic illustration of the hydraulic circuit (de Oliveira & Costa Teixeira, 2017).

3.3.1 Advantages and Disadvantages of Helically Coiled Tube Flocculators

Coiled tube flocculators have many advantages for water treatment. Their spiral shape creates a twisting flow that mixes water and coagulants better, which helps stable flocs to form. Cahyana *et al.* (2021) showed this improved mixing enhances turbidity reduction by creating good flow conditions. The smooth movement of the helical tube also controls flow dynamics. This design reduces turbulence that keeps flocs from breaking when they have formed. Hameed *et al.* (1995) noticed that this gentle mixing helps to keep flocs and make effective flocculation. These flocculators also save space because of the coiled shape that allows for a longer flow path in a smaller area compared to straight designs. This small size makes it good to use in many places, like small community setups and large industrial sites. Danieli Soares de Oliveira and Edmilson Costa Teixeira (2017). These flocculators are also more efficient by mixing well and forming flocs better; they remove more turbidity than old flocculation methods. Oliveira (2017) found that helically coiled flocculators could remove over 80% of turbidity, which is much better than old tanks with baffles. Lastly, helically coiled tube flocculators use less power. Their efficient flow path cuts down on energy needs, so they don't need as much mechanical stirring. Vigneswaran and Setiadi (1986) noted that this design leads to shorter processing times and lower energy use compared to older systems.

Helically coiled tube flocculators work well, but they have some disadvantages. One big issue is how hard they are to design (water flows and the system work). Oliveira and Teixeira (2018) mentioned that a helically coiled tube required specific models to nail the water flow and shape details. Another problem is that stuff can build up in them over time, making them less good at their job and needing more looking after. Cahyana *et al.* (2021) pointed out that this type required special design and materials to build and might be expensive. Oliveira (2017) noted that once this flocculator is operated, it's tough to tweak the system in case the water quality or quantity are changed. Hameed *et al.* (1995) mentioned that adjusting the design after operation to fit specific needs can be costly or not effective. Figure 6 shows the advantages and disadvantages of helically coiled tube flocculators.

All in all, each article sheds light on how coiled tube flocculators can make water treatment better. Studies explained different types of coiled tube flocculators to show how these systems can adapt and work well. Together, these articles recommended that more studies are required to add more knowledge about how these systems work for better water treatment. Table 3 compares previous studies based on several points.

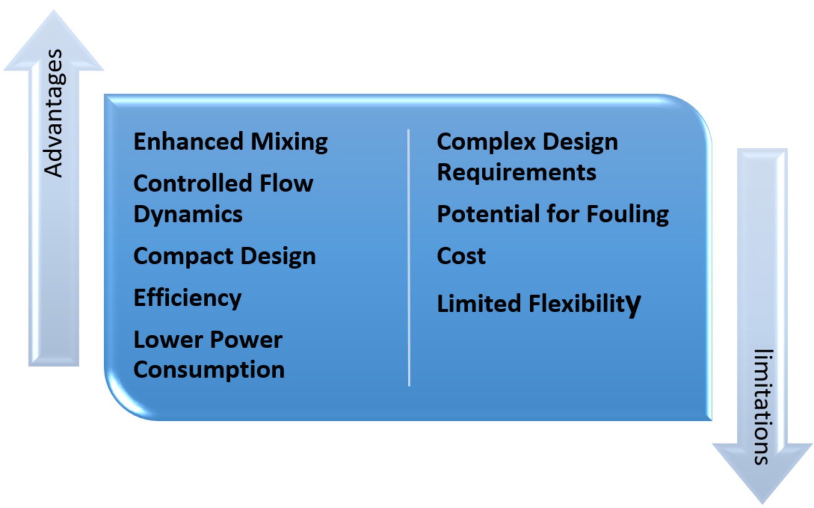


Figure 6. Advantages and Disadvantages of Helically Coiled Tube Flocculators

Table 3. Comparison between different helically coiled flocculators

Researcher(s)	Type of Water Used	Technique (Type of Flocculant)	Differences from Other Research	Results
Vigneswaran and Setiadi 1986	Not Specified	Spiral Flocculators	One of the earlier studies exploring spiral flocculators	Highlighted the efficiency of spiral designs in enhancing flocculation
Hameed et al. 1995	Various Water Samples	Helically Coiled Flocculator	Focuses on the impact of helical geometries on flocculation efficiency	Found enhanced flocculation efficiency due to high velocity gradient and efficient flow dynamics
Oliveira, D. S., & Costa Teixeira, E 2017	Drinking Water	Helically Coiled Tube Flocculator	Compares HCTFs to traditional baffled flocculators and evaluates multiple configurations	HCTFs showed rapid flocculation and higher turbidity removal compared to traditional methods
Oliveira 2017	Water Treatment Systems	Computational Fluid Dynamics (CFD)	Utilizes CFD modeling to understand hydrodynamic characteristics and optimize helical designs	Established relationship between swirl number and turbidity removal efficiency, improving design optimization
S. Oliveira and E. C. Teixeira 2018	Drinking Water	Helically Coiled Tube Flocculator	Studies theoretical, experimental, and CFD models of HCTFs	Achieved over 80% turbidity removal; demonstrated reduced processing times and efficient flocculation dynamics
Cahyana et al. 2021	Drinking Water	Helical/Coiled Flocculator	Evaluates novel helical flocculator design parameters like velocity gradient and coagulant dose	Demonstrated significant turbidity reduction efficiency; optimal configurations enhanced performance

4. Evaluation and Suggestion

After reviewing the previous articles about all types of flocculators, it can be noted that there is a difference between these three types, and the evaluation was based on several criteria as shown in table 4.

Flocculation is a critical process in water treatment, and the choice of flocculator significantly impacts treatment efficiency. Hydraulic, mechanical, and helical coiled tube (HCTF) flocculators each offer distinct advantages and disadvantages. Hydraulic flocculators don’t need much energy and are easy to use, but mechanical flocculators provide better mixing conditions. HCTFs are great at removing cloudiness and cutting down processing time because of their spiral shape. In the future, researchers should try to improve HCTF designs so they can be used in more places, fix problems with changing flow rates, and come up with standard ways to measure how well flocculators work compared to each other. When water treatment plants think about what they need, picking the right kind of flocculator can help make water cleaner and the whole plant work better.

Table 4. Difference between types of flocculators

Feature	Hydraulic Flocculators	Mechanical Flocculators	Helically Flocculators
Design	Use the energy of flowing water to create turbulence, with designs like horizontal/vertical baffled, cyclone flow, perforated plate, and pulsator.	Utilize mechanical mixing devices (e.g., paddles, impellers) to control turbulence and mixing intensity.	Helical or spiral flow path that creates a swirling motion for effective mixing and flocculation.
Energy Source	Also relies on hydraulic energy, eliminating the need for mechanical input.	Requires external mechanical energy to power mixing devices.	Utilizes hydraulic energy from the water flow, requiring no external power.
Advantages	Energy-efficient, low maintenance, cost-effective, simple operation for consistent flow rates.	Precise control over mixing intensity, adaptable to various water qualities and flow rates, enhanced mixing efficiency.	Compact design, consistent velocity gradient, efficient mixing, suitable for limited spaces.
Disadvantages	Requires larger space, performance can vary with flow changes, limited mixing capability, potential high head losses.	More complex and costly, sensitive to design parameters, potential floc damage with high mixing intensities.	Sensitive to flow rate changes, complex construction, potential design challenges for specific conditions.
Applications	Ideal for systems with consistent flow conditions, often used in developing communities and cost-sensitive applications.	Preferred in systems requiring precise control, used for treating variable water qualities and in complex treatment processes.	Suitable for installations with space constraints, effective for drinking water treatment.

Table 4. Difference between types of flocculators (Cont.)

Feature	Hydraulic Flocculators	Mechanical Flocculators	Helically Flocculators
Typical Performance	Effective in particle aggregation and flocculation, with variations depending on design type.	High flocculation efficiency and control over floc characteristics, optimized through design and CFD techniques.	Efficient in turbidity reduction and rapid flocculation; high velocity gradient enhances efficiency.
Operational Complexity	Low to moderate, dependent on the design and flow conditions.	High, due to the need for mechanical components and control systems.	Moderate, requiring careful design to maintain optimal flow conditions.

• **Helically Flocculators:** Best suited for installations with limited space and where energy efficiency is critical. They offer small design and effective mixing, but it requires careful design to manage flow sensitivity.

• **Hydraulic Flocculators:** Perfect for applications with consistent flow conditions where simplicity and cost effectiveness are a priority. Less effective in highly variable conditions and require more space.

• **Mechanical Flocculators:** Preferred when control over the flocculation process is required. They are more complex and expensive, but they provide high efficiency and control over floc properties.

The choice between these types depends on factors like available space, energy consumption, desired control level, water quality and operational constraints, but based on the previous explanation, it preferred to choose helically flocculators for the following reasons:

1) Compact Design and Space Efficiency:

Helically coiled tube flocculators (HCTFs) are famous because of their compact design, which makes them perfect for installations where space is limited. Their coiled structure allows for a longer flow path within a smaller space compared to old linear designs, as discussed by Oliveira and Teixeira (2017).

2) Energy Efficiency:

HCTFs use the hydraulic energy of the water flow that reduces the need for mechanical energy. This design needs lower operational costs and improves the sustainability of the water treatment process, as noted by Vigneswaran and Setiadi (1986). The efficient flow path reduces energy consumption, which makes these flocculators more energy efficient compared to old systems.

3) Consistent Mixing and Flocculation:

HCTFs create a constant speed gradient and swirling motion because of their helical design, which improves mixing efficiency and promotes flocculation. This improved turbidity reduction and gave better water quality, Cahyana *et al.* (2021) and Hameed (1995) showed the advantages of the helical structure in achieving stable and effective floc formation.

4) Low Maintenance Requirements:

HCTFs usually require less maintenance because of fewer moving parts compared to mechanical systems. So that lower maintenance costs and reduced maintenance time improve overall operational efficiency. Cahyana *et al.* (2021) confirmed the importance of maintenance to sustain performance but noted that the overall maintenance requirements are low.

5) Suitable for Variable Flow Rates:

Because HCTFs are sensitive to flow changes, the helical design can handle moderate differences in flow. This feature makes them suitable for a different of operating scenarios as discussed by Oliveira and Teixeira (2017). They found helical structures give effective mixing and flocculation across a range of flow conditions.

6) Improved Turbidity Reduction:

Compared to older systems, research found that HCTF units often achieve higher turbidity removal rates than old baffled systems. Studies by Oliveira *et al.* (2017) and Vigneswaran and Setiadi (1986) have shown that HCTF units can achieve turbidity removal efficiencies of up to 80%.

7) Adaptability to Various Applications:

HCTFs can be used in many types of water treatment, including drinking water, wastewater and industrial purposes. Their adaptable design and efficient performance make them suitable for different water treatment situations, as noted by Cahyana *et al.* (2021) and Oliveira and Teixeira (2017).

8) Cost-Effective Over Time:

While setting up HCTFs requires specialized knowledge, the long-term savings from using less energy and needing less maintenance can make them less expensive than other flocculation systems. The studies by Oliveira *et al.* (2017) and Vigneswaran and Setiadi (1986) showed that HCTFs can save money in the long run because of their efficiency and durability.

5. Conclusion

This study looked at different types of flocculators used in water treatment, with a focus on hydraulic, mechanical and helically flocculators.

Based on previous research, it can be concluded that hydraulic flocculators are simple and energy-efficient, where they use controlled water turbulence to mix. However, they don't work well with changing flow rates and need a lot of space. Mechanical flocculators offer more control over how long and how intensively the water is mixed which improves the process, but they are more complex and come with higher operating and maintenance costs.

On the other hand, helically flocculators are distinguished by their design, energy efficiency, and ability to reduce water turbidity. They provide consistent mixing and require less maintenance, which makes them perfect for modern water treatment plants that aim to save space, reduce costs, and improve water quality. The helical tube design allows for fast mixing using natural water flow, which lowers the need for extra energy. This not only reduces costs but also requires less maintenance compared to mechanical systems, making them a sustainable and effective choice for water treatment needs nowadays. Additionally, helically flocculators can handle moderate changes in water flow while still delivering excellent results.

References

Alfaiz SK , Yaseen DA , Alawadi WA. Water De Chlorination by Non-Modified and Modified Biochar Derived from Date Palm. Journal of Ecological Engineering 2023, 24(12), 377–387.

Bridgeman J, Jefferson B, Parsons SA. Computational Fluid Dynamics Modelling of Flocculation in Water Treatment: A Review. Eng Appl Comput Fluid Mech. 2009; 3(2): 220-41.

Cahyana EN, Utomo YJ, Astuti Y, Rahardjo W. Novel helical or coiled flocculator for turbidity reduction in drinking water treatment. Int J Environ Sci Technol. 2021; 18(2):439-50. https://doi.org/10.1007/s13762-020-02743-y

Cho Y, Yoo S, Yoo P, Kim C. Evaluation of the Effect of Baffle Shape in Flocculation Basin on Hydrodynamic Behavior Using Computational Fluid Dynamics. Korean J Chem Eng 2010; 27: 874-80.

Cleasby JL. Is Velocity Gradient a Valid Turbulent Flocculation Parameter? J Environ Eng. 1984; 110(5): 875-97.

de Oliveira DS, Costa Teixeira E. Experimental evaluation of helically coiled tube flocculators for turbidity removal in drinking water treatment units. Water SA. 2017; 43(3): 378-86.

Ducoste JJ, Clark MM. The Influence of Tank Size and Impeller Geometry on Turbulent Flocculation: I. Experimental. Environ Eng Sci. 1998; 15(3): 215-24.

Ducoste JJ, Clark MM. Turbulence in Flocculators: Comparison of Measurements and CFD Simulations. AIChE J. 1999; 45(2): 432-36.

García-Avila F, Gnecco I, Albuja J, Guerrero R. Evaluation of horizontal flow tubular hydraulic flocculators in developing communities. Water Treat J. 2024; 28(3): 123-34.

Haisalkar VA, Paramasivam R, Bhole AG. An Innovative Technique for Determining Velocity Gradient in Coagulation-Flocculation Process. Water Res. 1986; 20(10): 1307-11.

Hameed T. Characterization of floc formation in helically coiled flocculators. J Environ Eng. 1995;121(4):292-99. https://doi.org/10.1061/(ASCE)0733-9372(1995)121: 4(292)

Hanson AT, Cleasby JL. The Effects of Temperature on Turbulent Flocculation: Fluid Dynamics and Chemistry. J Am Water Works Assoc. 1990; 82(11): 56-73.

He W, Xue L, Gorczyca B, Nan J, Shi Z. Experimental and CFD Studies of Floc Growth Dependence on Baffle Width in Square Stirred-Tank Reactors for Flocculation. Sep Purif Technol. 2018; 190: 228-42.

Johnson P, Clark M, Lewis R. Effectiveness of cyclone flow flocculators in treating turbid water. Int J Environ Sci Technol. 2022; 18(5): 987-98.

Lee H, Kim S, Park J. Performance evaluation of perforated plate flocculators in a pilot-scale water treatment facility. Water Res. 2021; 134: 105-16.

McConnachie GL. Turbulence Intensity of Mixing in Relation to Flocculation. J Environ Eng. 1991; 117(6): 731-50.

Mohammed RN, Abualhail S, Lv X. Fluidization of fine particles and its optimal operation condition in multimedia water filter. Desalination and Water Treatment. 2013 Jun 1;51(22-24):4768-78.

Muhammad Ahmad, “Coagulation and Flocculation,” https://www.slideshare.net/muhammadahmad294/coagulation-and-flocculation-91035489#22.(2011)

Naseer R, Abualhail SA, Xi-Wu L. Fluidization and optimum backwashing conditions in multimedia filter. Research Journal of Applied Sciences, Engineering and Technology. 2011 Nov 25;3(11):1302-7..

Oliveira S, Teixeira EC. Baffled channel flocculators: Comparative study with helically coiled tube flocculators. J Water Process Eng. 2018;25:203-11. https://doi.org/10.1016/j.jwpe.2018.08.003

Oliveira S, Teixeira EC. Hydrodynamic study and optimization of helically coiled tube flocculators using computational fluid dynamics. Chem Eng J. 2017; 316:577-88. https://doi.org/10.1016/j.cej.2017.01.104

Patil G, Sambrekar B, Dukare G, Kansaga P, Hingmire A. Study of Water Treatment Plant Jalgaon. Int J Innov Res Sci Eng Technol. 2018; 7(4): 4038-44. DOI: 10.15680/IJIRSET.2018.0704128.

Raidah R. Flocculation Process. Int J Sci Technol Res. 2018; 9(1): 1470-74.

Rana AA, Dunya AHA, Dina AY. Optimization of Ceramic Filter for Greywater Treatment by using Horizontal Flow Constructed Wetland. IOP Conf. Ser.: Earth Environ. Sci. 2023; 1262 082010

Smith J. Solid State Technology 2020; 63(6).

Smith J, Doe A, Brown L. Comparative analysis of vertical and horizontal baffled flocculators. J Water Process Eng. 2023; 42(2): 56-67.

Spicer PT, Keller W, Pratsinis SE. The Effect of Impeller Type on Floc Size and Structure During Shear-Induced Flocculation. J Colloid Interface Sci. 1996; 184(1): 112-22.

Spicer PT, Pratsinis SE, Raper J, Amal R, Bushell G, Meesters G. Effect of Shear Schedule on Particle Size, Density, and Structure During Flocculation in Stirred Tanks. Powder Technol. 1998; 97(1): 26-34.

Sun J, Cui S, Sun Z, Kang Y. Numerical Simulation of Flow Fields in Different Baffled Flocculation Reactors. Adv Mater Res. 2012; 550: 3037-40.

Thompson G, Nguyen T, Patel S. Investigation of pulsator flocculators in dynamic water treatment environments. Environ Technol Innov. 2020; 19: 100958.

Vadasarukkai YS, Gagnon GA. Determination of Conventional Velocity Gradient (G) Using CFD Technique for a Pilot-Scale Flocculation System. J Water Supply Res Technol-Aqua 2010; 59(8): 459-70.

Vigneswaran S, Setiadi D. Experimental evaluation of helically coiled tube flocculators for water treatment. Water Res. 1986; 20(5):637-45. https://doi.org/10.1016/0043-1354 (86)90027-3.

Van Leeuwen, "Coagulation and Flocculation,". https://www.slideshare.net/slideshow/van-leeuwen-2011-coagulation-and-flocculation0ppt/252415974.(2011)

Yang Z, Wu Z, Zeng G, Huang J, Xu H, Feng J, et al. Assessing the Effect of Flow Fields on Flocculation of Kaolin Suspension Using Microbial Flocculant GA1. RSC Adv. 2014; 4(76): 40464-73.

Yaseen DA, Abu-Alhail S, Mohammed RN. An experimental sedimentation tank for enhancing the settling of solid particles. J. Water Land Dev. 2021; 49: 63–73

Yaseen DA, Abu-Alhail S, Khanfar HA. Assessment of water quality of Garmat Ali River for irrigation purposes. InE3S Web of Conferences 2019 (Vol. 118, p. 03054). EDP Sciences..

Zhang J, Anderson WB, Huck PM, Stubley GD, Tadwalkar A. Evaluation of a Computational Fluid Dynamics Modelling Approach for Prediction of Flocculation Mixing Performance at the City of Toronto's RL Clark Water Treatment Plant. Conf Ontario Water Works Assoc(AWWA)/Ontario Municipal Water Assoc (OMWA) Joint Annual Conf, Toronto, Ontario. 2006.