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High suspended solids removal of Indian drain water with a down-scaled Dissolved Air Flotation (DAF) for water recovery. Assessing water-type dependence on process control variables

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ABSTRACT

The Barapullah drain crosses through New Delhi, India, and transports millions of cubic meters of stormwater, municipal sewage and industrial sewage to the Yamuna River. Seasonal variations and ambiguous annual discharges cause 20-fold fluctuations in hydraulic flows, pollutants type and concentration. Furthermore, New Delhi is among the most densely populated areas on the planet, with limited surface area and high water stress. Dissolved Air Flotation (DAF) units are known to be highly compact, robust, and an efficient suspended solids separation technology that enables further water recovery in a treatment train. Thus, a down-scaled column DAF was designed and used to determine the total suspended solids removal efficiencies, under different influent conditions. Three influents that resemble the Barapullah drain seasonal variations in composition, and a fourth that imitates the feed of DAF when located after an anaerobic bioreactor were tested. A total of 60 batch DAF experiments were completed and used to assess seven independent control variables for DAF operation, which are influent Total Suspended Solids (TSS), pH, temperature, DAF particles residence time, white water pressure, coagulants and flocculants concentration, and coagulation and flocculation time. Results showed that the down-scaled DAF could be steered from low to high removal efficiencies, comparable to full-scale systems. Maximum TSS removal varied between 92 and 96%. The effect and statistical relevance of the different performance variables on the measured separation efficiencies depended on the influent type. All variables, except temperature and pH, had a significant performance effect with a p-value below 0.1, for at least one influent. Pressure had a positive effect on separation efficiency, due to its importance in bubble formation. Moreover, the down-scaled DAF system had low removal efficiency for particles with spherical shapes, and diameters below 10 μm. Based on the high TSS removal for all tested influents, and the effect of the studied control variables, a full-scale DAF could efficiently remove the suspended solids of the Barapullah drain. The unit robustness for different flows and pollutant concentrations, and small footprint, show DAF suitability as part of a treatment train for water recovery, in densely populated areas.

1. Introduction

In recent years, New Delhi has consistently been labelled one of the most polluted and densely populated cities in the world (Balha et al., 2020; Mazhar et al., 2021). Annual per capita fresh-water availability is expected to decrease by 30% when compared to values of 2010, due to the increasing population and country development (Kaur et al., 2012). Sewage is discharged into clean water bodies contaminating them, which is exemplified by the water recovery challenges related to the Barapullah stormwater drain. This drain is currently heavily pol-

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Abbreviation: ADS, Anaerobic Digested Sludge; DW, Barapullah Drain Water; COD, Chemical Oxygen Demand; CFD, Computational Flow Diagram; DAF, Dissolved Air Flotation; DBT, Department of Biotechnology; DCW, Delft Canal Water; DO, Dissolved Oxygen; IITD, Indian Institute of Technology - Delhi; LOTUS^{HR}, Local Treatment of Urban Sewage for Healthy Reuse; MIX, Mix of Anaerobic Digested Sludge and Canal water; NWO, The Dutch Research Council; PBD, Plackett-Burman Design; PBR, Photo bioreactor; SBR, Sequencing Batch Reactor; SRT, Solids Retention Time; TERI, Energy and Resources Institute; TS, Total Solids; TSS, Total Suspended Solids; VSS, Volatile Suspended Solids; UV, Ultra Violet.

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luted with municipal sewage and industrial effluent year-round. At the Barapullah drain mouth, the Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS) varied from 320 to 1500 mg.L^{-1} and 30 to 510 mg.L^{-1}, respectively throughout the year 2019 (Indian Institute of Technology Delhi 2019). Aside from temperature fluctuations, ranging from 11 to 35 °C over the year, the Barapullah drain volumetric flow rates increase 20 times during the monsoon season in contrast to the dry season (Sontakke et al., 2008). These fluctuations in both influent quality and quantity, pose serious concerns for conventional and highly advanced wastewater treatment technologies. Giokas, Vlessidis, Angelidis, Tsimarakis and Karayannis (Giokas et al., 2002) concluded that the performance of the wastewater treatment plant of Ioannina (Greece) was affected by shifts in wastewater quality and quantity. Efficiency decreased during high wastewater flows or a rise in feed flow pollutants concentration. Furthermore, a lack of stability in a bioreactor operation when insufficient shower water was produced was observed in a system developed for water reuse for manned life support in Space (Lindeboom et al., 2020). A Dissolved Air Flotation (DAF) is proposed as pre-treatment for a multi stage treatment train, focused on healthy reuse of the Barapullah water. A DAF unit has a small footprint, high separation efficiency, robustness under a wide range of hydraulic loading rate, possibility of removing particles from 10 to 2000 μm (Kiuru, 1990).

DAF units have been widely used since the beginning of the 1960s for separating particulate matter from the liquid by flotation (Kiuri, 2001). Currently, these systems have been particularly useful in the pre-treatment of anaerobic digestion, to remove suspended solids. Cagnetta, Saerens, Meerburg, Decru, Broeders, Menkveld, Vandekerckhove, De Vrieze, Vlaeminck and Verliefde (Cagnetta et al., 2019) found the removal of up to 78% of TSS when a high-rate activated sludge process was followed by a DAF. Penetra, Reali and Campos (Penetra et al., 2003) reported a TSS removal of 96.7% when a DAF was located after an expanded bed anaerobic reactor. Some studies reported an increased overall performance by placing a DAF before the anaerobic digestion of municipal slaughterhouse wastewater (Harris et al., 2017; McCabe et al., 2014; Manjunath et al., 2000). Few articles have demonstrated the successful implementation of DAF units in wastewater reuse schemes. For example, DAF followed by Ultra Violet (UV) disinfection allowed the reuse of fruit and vegetable processing wastewater (Mundi and Zytner, 2015). One study even reported drinking water quality standards could be achieved when treating poultry slaughterhouse wastewater with a laboratory-scale Sequencing Batch Reactor (SBR), followed by a batch DAF (2.0 L cylinder and 10 cm diameter) and UV disinfection (De Nardi et al., 2011). Although the literature shows DAF systems have the potential to enable water reuse, particularly in combination with anaerobic digestion, the most typical applications still only consider DAF for conventional solid-liquid separation.

DAF performance has been measured by the efficiency at which particles and liquid are separated. Particle removal in a DAF depends on particle buoyancy and the possibility of forming bubble-particle aggregates (Wang et al., 2005). Therefore, liquid flow, hydraulic retention time, influent particle concentration, and bubble concentration and size are key control variables that can be used to increase particle separation. According to Van Nieuwenhuijzen (Van Nieuwenhuijzen, 2002), sludge particles from domestic wastewater have a negatively charged surface. Similarly, air bubbles have a negative zeta potential and surface charge through a wide variation of pH (Han and Dockko, 1998). Coagulants are needed to neutralize particle surface charge and promote particle-bubble collision, while flocculants are needed to agglomerate neutralized particles. Depending on incoming water quality, particle removal can thus, be enhanced by adding coagulants and flocculants (Bratby, 1980). While extensive knowledge in full-scale DAF systems removal was gained during the 1990s, the development of mathematical models and computers algorithms, for solving the equations governing the flow and particle-liquid-bubble interactions, are key to develop more efficient DAF units (Bondelind et al., 2010).

Most recent literature on DAF is linked to the utilization of computation flow diagram (CFD) for further understanding the separation and contact zones (Yang et al., 2021). Lundh et al. (2001) used CFD and found that two flow structures are present in a DAF, a stratified flow and a downwards-vertical transport. A 3D CFD model was developed to analyse the optimization of the DAF in the wastewater treatment plant of Kluizen, Belgium by Satpathy, Rehman, Cools, Verdickt, Peleman and Nopens (Satpathy et al., 2020). While the results of this model showed alignment with what was found before in relation to the stratification of the water flow, it lacked to fully address particle-bubble agglomerates. Rodrigues and Béttega (2018) formulated a two-phase (bubble-liquid) 2D CFD model to assess the flow behaviour on a 1.50 m^3 pilot-scale DAF treating 10 m^3.h^{-1} of influent. Results showed that the Eulerian approach and κ-ϵ turbulence model where an adequate representation of the real flow behaviour inside the DAF. Lakghomi et al. (2015) developed an analytical and computational fluid dynamic model to assess the multiphase of particle-bubble-liquid. Their research was based on simulations for a fix bubble size. Nevertheless, both particles and bubbles vary in diameters, and therefore, findings are limited. Furthermore, a comparison to a full or down-scaled DAF unit is recommended to compare mathematical and real results. While mathematical models are being developed to understand fluxes inside DAF units, the multi-phase interactions between bubbles, liquid and particles remain complex and limited (Wang et al., 2018). An assessment on full and down-scaled DAF units, treating different influents and particles, should be carried out to complement and contrast the information gathered from mathematical models.

Some authors have used laboratory-scale DAF units to empirically assess flow conditions, and bubble formation, and bubble size (Han and Dockko, 1998; De Rijk and den Blanken, 1994; Mudde and Simonin, 1999; Han et al., 2002; Samstag et al., 2016). However, to the author's knowledge, no scientific studies are available that systematically assess the influence of all process control variables mentioned above, on particle removal for different types of particles, representing different 'real' wastewater. Potentially, this is because, on a down-scaled DAF, it is difficult to simulate the exact physical/hydraulic phenomena remaining representative for full-scale applications, since microbubbles are impossible to down-scale. Reported DAF units need large influent flows (between 5 and 100 m^3 per test) and are therefore not suited for experiments with real drainage and wastewaters in a laboratory setting (Edzwald and Haarhoff, 2011).

The application of experimental design has been used to evaluate the effects of many different variables at the same time for a wide range of environmental technologies, such as gasifiers, and solar reactors, among others (Raheem et al., 2015; Fermoso et al., 2010; Al-Muraisy et al., 2022; Inayat et al., 2020). The experimental design enables the gathering of maximum information from a dataset using a limited number of experiments (Fisher and Bennett, 1990). It does so by assuming that the influence of one variable stays the same despite the change in others. In addition, this tool provides information about variations generated by the system itself and also regarding uncertainties or errors present in experimental data (Mäkelä, 2017). The use of experimental design in down-scaled DAF systems is therefore proposed to predict particle removal efficiency for a set of control variables under different operational conditions. These conditions can resemble a wide variety of complex urban water reuse schemes, like the Barapullah drain wastewater.

This study analyses the performance of a down-scaled DAF, treating four different influent. Two influents imitate the varying conditions of the Barapullah drain, one influent is taken from the drain itself and tested in-situ, and the last influent is from a bioreactor that also mimics locating the DAF closer a household (upstream and concentrated). A novelty of this study is the assessment of seven DAF control variables (Annex A) on suspended solids removal, using the Plackett-Burman design, which resulted in a total of 60 batch DAF experiments. Based on the results, it will be evaluated to what extent the different control variables are key to enhancing suspended solids removal for different characteristic wastewaters. Additionally, down-scaled DAF solids removal performance will be compared to full-scale system performance, and the

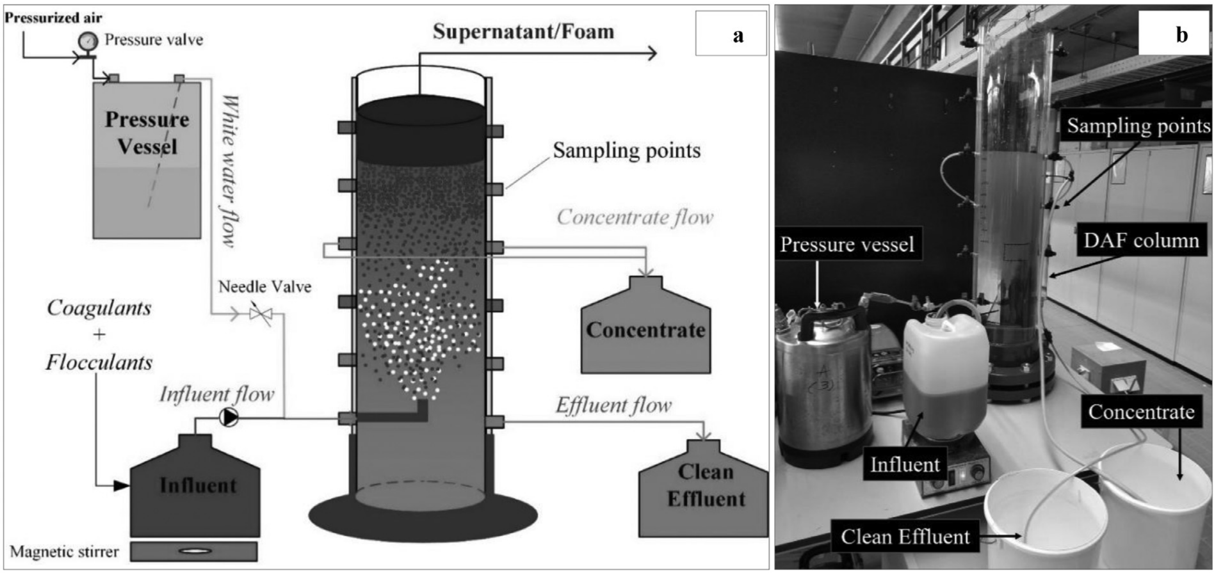

Fig. 1. Dissolved Air Flotation down-scaled experimental set-up. **Fig. 1.a** is a schematic image of the down-scaled DAF system. **Fig. 1.b** shows the system located in the Water Lab facilities (TU-Delft, The Netherlands). More pictures of the down-scaled DAF system can be seen in Annex F.

outcomes will be extrapolated for the treatment of the raw Barapullah drain water and/or bioreactor effluent. This culminates in the assessment of the possibility of using a DAF as part of a treatment train for water recovery in high population density megacities, like New Delhi, where available surface area and fluctuating hydraulic loads are considered serious barriers to water recovery, as a scarce resource.

2. Methods

2.1. Experimental set-up

Two identical down-scaled column DAF reactors were designed and then operated at TU-Delft WaterLab (Delft, The Netherlands), and the LOTUS^{HR} test site at the Barapullah drain (New Delhi, India), shown in Fig. 1. The columns were made of polymethyl methacrylate because of its optical characteristics. The DAF column dimensions were 0.20 m in diameter with a height of 1.00 m and the width was chosen to avoid the reactor wall causing changes in the hydrodynamic behaviour of the reactor medium, as described by Edzwald (1995). Sample and injection points were located every 0.15 m (the first at 0.20 m from the column bottom), in two diametrical opposite lines. Pressurized water was injected into the system from the lowest injection point and the flow rate was controlled through a one-way needle valve (Festo 193969, Esslingen, Germany). Tap water was stored in a stainless steel 10 L Thielman vessel, where the pressure was controlled and maintained by a pressure gauge (Festo pressure gauge, LR/LRS midi) at the desired value (3.0, 4.0, and 5.0 × 10^5 Pa). This influent is called white water. The DAF column located at TU Delft Water-lab was connected to the pressurized air (7.0 × 10^5 Pa) line from the facility, whereas the one placed at the Barapullah site was connected to an air compressor (Hitachi EC68, 1.5 HP and a capacity of 24 L.min^{-1}).

Both systems were equipped with an influent pump (Watson Marlow 520) set to provide an equal influent flow compared to the pressure-driven white water flow. All influents were introduced into the DAF column through the white water line and injection point. The injection point involved a connector placed in a vertical position parallel to the column wall to promote an upstream flow and enhance particle removal. Clean effluent was removed from the sample point located diametrically opposite to the injection, in the lowest section of the column. Additionally, the concentrate/effluent was removed from a height of 0.65 m above the column bottom at the fourth collection point, from both sides of the column.

Before the start of each trial, the DAF column was filled with 20 L of tap water, corresponding to a height of 0.65 m. The pressure vessel was filled with tap water and pressurized following the experimental run requirements. Influent and white water flows were set to be equal (at 1.62 L.h^{-1}) and entered the down-scaled DAF column together. No additional nozzles were provided for the laboratory set-up, and white water flow was controlled via a one-way flow needle valve (GR-QS 6 FESTO, New York, United States).

2.2. Tested influents

Four different influents were selected based on possible DAF locations for wastewater treatment: as part of the primary treatment receiving raw drain water from the Barapullah drain or as the sludge and water separation mechanism after an anaerobic digester, which also mimics locating the DAF at household levels (closer to the pollution source).

2.2.1. The Barapullah drain water - BDW (New Delhi, India)

Water from the Barapullah drain was collected close to the drainage mouth with the Yamuna River by a pump, and stored in 100 L containers at the LOTUS^{HR} site. Drain water characteristics were measured immediately after collection.

2.2.2. Delft canal water - DCW (Delft, The Netherlands)

Drain water from a canal located next to TU-Delft Water Laboratory (Van der Burghweg, Delft, The Netherlands) was gathered using buckets. Canal water was collected in May. This water was chosen to be representative of the Barapullah drain pollutants concentration throughout the monsoon season (June to September).

2.2.3. Anaerobic Digested Sludge - ADS (Harnaschpolder wastewater treatment plant, The Netherlands)

Anaerobic digested sludge was taken from a domestic wastewater treatment plant (RWZI–Harnaschpolder, Den Hoorn, The Netherlands). The digester treats both primary and secondary sludge and operates under 22 days of Solids Retention Time (SRT) at 35°C. ADS influent was chosen to mimic the feed conditions of a DAF system when located after a bioreactor, or at a household level (close to the pollution source). Due to the down-scaled DAF reactor requirements, the collected sludge was sieved with a 0.71 mm filter before use.

2.2.4. Mix of anaerobic digested sludge and Delft canal water - MIX

Harnaschpolder anaerobic digested sludge and canal water were mixed at TU Delft Lab facilities. This mix influent was considered to mimic conditions of the Barapullah drain throughout the dry season. The sludge was sieved again with a 0.71 mm filter. The two components were mixed in a given ratio following the desired TSS content for each experiment.

2.2.5. Influents preparation

Calcium hydroxide $Ca(OH)_2$ was selected as coagulant and cellulose as flocculant due to their local commercial availability in India, and digestibility under anaerobic conditions. The same concentration of cellulose and $Ca(OH)_2$ was incorporated (ratio 1:1), where a rapid mixing at 100 rpm for one minute followed by slow mixing at 40 rpm was performed. Furthermore, pH was corrected after the addition of the coagulant and flocculant. Two of the key independent control variables assessed were concentration of coagulants and flocculants, and coagulation time. Thus, these values vary between 5.0 and 500.0 $mg.L^{-1}$ and, 10 to 30 min, respectively. The exact values are explained below.

Canal water from Delft was heated up to a temperature around 30 °C using a water bath. Additionally, the pH of canal water and Harnaschpolder sludge was increased to 8.5 when needed to mimic the Barapullah drain conditions. This was done by adding sodium hydroxide (NaOH). Since TSS concentration of influent was a variable to be tested, the Barapullah drain and canal water were either concentrated or diluted (with tap water) to reach TSS values between 30 and 510 $mg.L^{-1}$, while sludge was diluted to have a solids concentration between 500 and 5000 $mg.L^{-1}$.

2.3. Removal efficiencies calculation

To calculate the suspended solids removal for each experiment, an influent TSS dilution factor had to be determined. This dilution factor accounted for the 20 L of tap water inside the column, and the white water introduced into the system. The volume of white water incorporated per experiment was calculated based on the reactor mass balance, where the known inputs and outputs to the system were the volumes of influent, effluent, concentrate, and foam. The total volume of water inside the down-scaled DAF was kept at 20 L. Then, the diluted influent TSS concentration was calculated following the equation below (1). TSS removal efficiencies were determined considering the diluted influent and effluent TSS concentrations.

$$Diluted\ inf.\ TSS = (Original\ inf.\ TSS \times Influent\ Volume) / (Influent\ volume + \ White\ water\ volume + 20) \quad (1)$$

2.4. Key performance control variables and Plackett-Burman Design

Seven key control variables were selected to assess down-scaled DAF suspended solids removal efficiency. These variables were TSS, temperature, pH, residence time, pressure, coagulant and flocculants concentration, and coagulation time, as already delineated in the introduction. All independent control variables were studied at two levels (1, -1) and one centre point (0), based on the Plackett-Burman Design (PBD) (Plackett and Burman, 1946). The levels and centre point corresponded to the maximum, minimum, and mean values of each set of variables. TSS, pH, and temperature are influent control variables, while pressure, residence time, and coagulant concentration are defined as DAF operational control variables. To define the former three influent variables, the Barapullah drain water conditions and variations during the year were considered. Maximum and minimum values of TSS and temperature for canal and drain water influents were set to 30 and 500 $mg.L^{-1}$, and 29 and 35°C, respectively (Indian Institute of Technology Delhi 2019). Suspended solids concentrations between 500 and 5000 $mg.L^{-1}$ were selected for the sludge and mix influents. Maximum, minimum, and central values of residence time, pressure, coagulants and flocculants concentration, and retention time are shown in **Table 1**.

Plackett-Burman Design (PBD) was conducted taking between five and seven control variables, depending on the experiment. Screening design was selected as the methodology to identify the effect of the chosen variables and selection of the most important ones (statistical p-value below 10%). Furthermore, PBD was applied to formulate the experimental matrix, resulting in 12 different experiments and triplicates of the central point, summing up to 15 experiments per influent type (see Annex B with PBD matrix). The central point experiments were then used to calculate the standard deviation that later was applied in the analysis.

The analysis of the experimental data was performed using the Statistica 7.0 software and Protimiza software. The linear model to predict the main effects is described in equation below (2).

$$x_i = a + \sum b_i * X_i \quad (2)$$

Where x_i is the value of the independent variable in terms of TSS removal (%), a is the model intercept, X_i represents different levels of independent variables, and b_i is the coefficients as predicted by the equation.

2.5. Analytical methods

Total and volatile solids were measured according to Standard Methods (American Public Health Association 2013), and triplicate samples were taken and analysed. Temperature, pH, and dissolved oxygen (DO) measurements were conducted with a multi720 pH meter (WTW, Weilheim, Germany). COD measurements were done using HACH test kits LCK 314, 514, and 014 (HACH, Tiel, The Netherlands). Particle density was measured following the methods described by Blake and Hartge (1986) using a 100 mL pycnometer (Blaubrand, Wertheim, Germany). Finally, particle zeta potential was measured based on the electrophoretic light scattering technique with a Zetasizer nano (Malvern Panalytical, Almelo, The Netherlands).

Particle characteristics and morphology was assessed using a digital microscope and FIJI-ImageJ processing software Schindelin et al., 2012). For ADS, DCW, and MIX, high definition images were taken with a digital microscope (VHX-5000 Series by KEYENCE). The Barapullah drain water images were captured with a digital microscope (NIKON ECLIPSE E600, illustrated 3.5b). These images were then processed using FIJI-ImageJ and morphological data, i.e. particle size and circularity were analysed in MS Excel. Circularity is defined based on particle perimeter and area by FIJI-ImageJ, following the equation shown below ((3).A value of 1.0 indicates a perfect circle, while one closer to 0.0 shows an elongated shape. DCW had the lowest amount of particles with a circularity above 0.7, being 67% of the total amount of solids.

$$circularity = 4\pi \times \left(area/perimeter^2\right) \quad (3)$$

Nine images from each stream were stacked together to have a more representative sample condition. For each influent and effluent, particle frequency was calculated by dividing the number of observed particles in a diameter range, by the total number of counted particles in the stacked image.

3. Results

3.1. Influent characteristics

The characteristics of the used influents DCW, BDW, and ADS are presented in **Table 2**. The BDW was collected during the dry season (June 2019). To mimic BDW during the dry season, DCW (of an average temperature of 9.4 ± 0.1 °C) mixed with ADS was used.

Table 1
Plackett-Burman design (PBD) for screening of independent control variables.

Control Variables	Values	Units	Delft canal water -DCW	Barapullah drain water – BDW	Anaerobic digested sludge - ADS	Mix influent - MIX
Total Suspended Solids	30	mg.L^{-1}	+	+		
	270	mg.L^{-1}	+	+		
	510	mg.L^{-1}	+	+		
	500	mg.L^{-1}			+	+
	2750	mg.L^{-1}			+	+
	5000	mg.L^{-1}			+	+
Temperature	29	°C	+			
	32	°C	+			
	35	°C	+			
Residence time	780	s	+	+	+	+
	990	s	+	+	+	+
	1200	s	+	+	+	+
pH	6.7		+			
	7.2		+			
	7.6		+			
	7.0				+	
	7.8				+	
	8.5				+	
Pressure	3.0	10^5 Pa	+	+	+	+
	4.0	10^5 Pa	+	+	+	+
	5.0	10^5 Pa	+	+	+	+
Coagulant and floc-culants concentration	5.0	mg.L^{-1}	+	+	+	+
	252.5	mg.L^{-1}	+	+	+	+
	500.0	mg.L^{-1}	+	+	+	+
Coagulation time	600	s	+	+	+	+
	1200	s	+	+	+	+
	1800	s	+	+	+	+

Table 2
Summary of tested influents characteristics. BDW stands for the Barapullah Drain Water, DCW for Delft Canal Water, and ADS for Anaerobic Digested Sludge.

Parameter	*Influents*			
	Units	**BDW**	**DCW**	**ADS**
Temperature	°C	32.3 ± 1.8	9.4 ± 0.1	35.0 ± 1.0
pH		7.2 ± 0.2	7.8 ± 0.1	6.9 ± 0.1
Dissolved Oxygen	mg.L^{-1}	0.5 ± 0.3	10.5 ± 0.2	0.09 ± 0.01
Chemical Oxygen Demand	mgCOD.L^{-1}	328.4 ± 65.1	77.3 ± 7.5	39,500 ± 3,200
Total Solids	mgTS.L^{-1}	782 ± 240	840 ± 48	37,300 ± 100
Total Suspended Solids	mgTSS.L^{-1}	97 ± 64	32 ± 7	36,800 ± 1,500

Table 3
Summary of TSS removal efficiencies performed in the down-scaled column DAF units, with the following four different types of influents: Delft canal water (Delft, The Netherlands), the Barapullah drain water (New Delhi, India), anaerobic digested sludge (Harnaschpolder, Den Hoorn, The Netherlands), and mix of anaerobic digested sludge and Delft canal water.

	Delft canal water	The Barapullah drain water	Anaerobic digested sludge (ADS)	Mixed water (MIX)
	(DCW)	(BDW)		
Maximum removal	96%	94%	92%	95%
Minimum removal	45%	69%	66%	29%
Standard deviation	4%	3%	4%	2%
Runs with removal efficiency below 80 %	9	3	4	6
Runs with removal efficiency above 90 %	1	3	2	4

3.2. Delft canal water (DCW)

Raw DCW with a minimum and maximum TSS of 30 mg.L^{-1} and 500 mg.L^{-1}, respectively was treated by DAF according to the PBD. TSS removal efficiencies were between 45 and 96% (Table D.1 Annex D), with a standard deviation of 4% (obtained from the central point runs), and is summarized for all tested influents in Table 3. The highest suspended solids removal efficiency achieved was 96 ± 4%, when the influent had a TSS concentration of 30 mg.L^{-1}, temperature of 29 °C, residence time of 1200 s, pH of 7.6, pressure of 5.0×10^5 Pa, coagulant concentration of 5.0 mg.L^{-1} and coagulation time of 1800 s. Suspended solids removal efficiency below 80% were considered a low DAF efficiency, which was observed in nine out of fifteen runs in DCW.

Influent particle size and shape were assessed and compared to their respective effluents. DCW influent contained 67 ± 8 % of particles with a diameter below 10 μm, which was the lowest fraction of small particles compared to the other influents. In contrast, a total of 97 ± 1% of effluent particles were observed to be below 10 μm, representing the highest percentage for all effluents.

Statistical analysis of the selected performance variables was conducted on each of the four different types of influents. A summary of

Table 4
Heat map of ANOVA statistical results showing the effect of influent TSS concentration, temperature, down-scaled column DAF residence time, pH, pressure, coagulant and flocculants concentration, and, coagulation time, for TSS removal efficiencies from all types of influents. Acronym DCW corresponds to Delft canal water, BDW to the Barapullah drain water, ADS to anaerobic digested sludge, and MIX for the mixed influent of Delft canal water and anaerobic digested sludge. Red cells correspond with negative effects and green ones with a positive one. Additionally, in bold are those effects that corresponded to statistical p-values below 0.1.

	Effect				
Independent Variables	*DCW*	*BDW*	*ADS*	*MIX*	
Total Suspended Solids concentration	**12.16**	**-0.09**	-4.03	**15.30**	High positive effect
Temperature	-0.50		-4.22		
Residence time	**15.50**	-0.01	4.06	5.80	
pH	2.16		-0.42		Neutral effect
Pressure	5.50	0.02	**10.50**	**15.10**	
Coagulant and flocculants concentration	1.16	0.04	1.33	**14.80**	
Coagulation time	**22.16**	-3.80	-0.05	7.70	High negative effect

the effect and p-value of each variable is shown in Table 4. Statistical significance was considered when p-values were below 10% (0.10). A negative effect means that an increase in the variable leads to a decrease in the total suspended solids removal. Furthermore, for a given influent, a high absolute effect of a variable entitles a more preponderant outcome. DCW had three control variables with a statistically important effect on TSS removal. These variables were TSS concentration, residence time, and coagulation time, with p-values of 0.03, 0.02, and 0.01, respectively. All control variables had a positive (dimensionless) effect, the highest being coagulation time.

3.3. *The Barapullah Drain Water (BDW)*

TSS removal efficiencies were between 69 and 94 ± 3% for BDW (Table D2, Annex D). Under the same conditions of DCW mentioned above, TSS removal of the BDW only reached 83 ± 3%. Different results were obtained under the same experimental conditions. While the central point parameters were the same for DCW and BDW, removal efficiency for the latter was 1.7 times higher than the one obtained for DCW, 88 ± 3% and 51 ± 4%, respectively. Furthermore, in six out of seven runs that had the same conditions for both influents, solids removal of BDW was between 1.2 and 1.9 times higher.

BDW influent had the highest fraction of particles smaller than 10 μm when compared to other influents, corresponding to 94 ± 2% of the total particles. Furthermore, particle circularity of all influents was similar. The majority of particles have a circularity above 0.7 and can be considered as spheres, 84 ± 4% on BDW, while the percentage of elongated particles with a circularity value below 0.3 was around 1 % for this influent. Only one control variable had a significant effect on TSS removal from BDW. Influent total suspended solids had a negative effect (p-value of 0.06). While an increase in TSS resulted in a decrease in removal efficiency for this influent, the effect was contrary for DCW and the MIX influent.

3.4. *Anaerobic Digested Sludge (ADS)*

Suspended solids removal efficiencies were between 66 and 92 ± 4% for ADS (Table D3, Annex D). Nine out of the 15 experiments performed had a TSS removal between 80 and 90%. The maximum removal was obtained when TSS was 500 mg.L^{-1}, residence time was 1200 s, pressure was 5.0 × 10^{5} Pa, coagulant concentration was 5.0 mg.L^{-1}, coagulation time of 1800 s, temperature was at 35°C, and pH was set at 8.5.

ADS influent had the highest fraction of particles between 10 and 40 μm when compared to the other influents (16 ± 7%), and 6 ± 2% were larger than 40 μm. The effluent had the lowest fraction of small particles (diameters below 10 μm), and the highest fraction of large particles (diameters above 40 μm), 77 ± 6% and 5 ± 1%, respectively. All effluents had a high fraction of circular particles, showing values between 78 and 93% of the total number of particles. On the other hand, elongated particles with circularities below 0.3 represented less than 2 % of the particle fraction in all effluents.

Pressure, residence time, and, coagulants and flocculants concentration had a positive effect on ADS, but only the pressure was significant (p-value of 0.04). When pressure, residence time, or concentration of coagulants and flocculants were increased, higher suspended solids removal was observed from the down-scaled column DAF system. A rise in temperature resulted in a negative effect on both the removal of suspended solids in ADS and DCW but was not significant (*p*-value>0.1). Besides temperature, pH variations had no statistical effect on any of the tested influents, nor consistency in its positive or negative impact of the effect.

3.5. *Anaerobic digested sludge and Delft canal water mix (MIX)*

This influent presented the largest number of experiments with high removal efficiencies above 90%, i.e. four out of 15, but the sufficient removal efficiencies (between 80 and 90%) were not extraordinary with 9 out of 15 runs. The TSS removal efficiency varied between 29 and 95 ± 2% for the mixed influent (Table D4, Annex D). Under equal experimental conditions, TSS removal was 1.1 to 1.3 times higher for the MIX than ADS in four out of seven runs. The latter had a better removal only in one run (87 ± 4% in comparison to 29 ± 2% of the MIX influent). The lowest removal efficiency of 29 ±2% was obtained under an influent TSS of 500 mg.L^{-1}, residence time of 1200 s, pressure of 3.0 × 10^{5} Pa, coagulant concentration of 5.0 mg.L^{-1}, and 1800 s coagulation time.

All effluents but the MIX had a smaller frequency of particles above 40 μm when compared to particles in the corresponding influents. Frequencies of particle sizes for the four different influents and their respective DAF effluents can be seen in Fig. 2. Even though elongated particles were predominant in all four influents and their respective effluents, the MIX effluent had the lowest proportion of particles with a circularity above 0.7 (78 ± 9%) and the highest one with circularity between 0.3 and 0.7 (19 ± 5%). Fig. 3 shows particle images of all influents and effluents, and particle circularity frequency can be found in Annex E.

For the MIX runs, three independent control variables positively affected the solids removal, i.e. influent total suspended solids (*p*-value of 0.06), pressure (*p*-value of 0.06), and coagulant and flocculants concentration (*p*-value of 0.07). The highest effect was found for TSS concentration (12.16), which means that small changes on influent TSS had the highest impact on suspended solids particle removal of the down-scaled DAF.

4. Discussion

A total of 55 out of 60 experiments showed that removal efficiencies were in the ranges of 50 to 96%, while only 5 experiments had removal efficiencies below 50%. Moreover, 32 out of the 54 experiments had TSS removal efficiency above 80%, which was considered

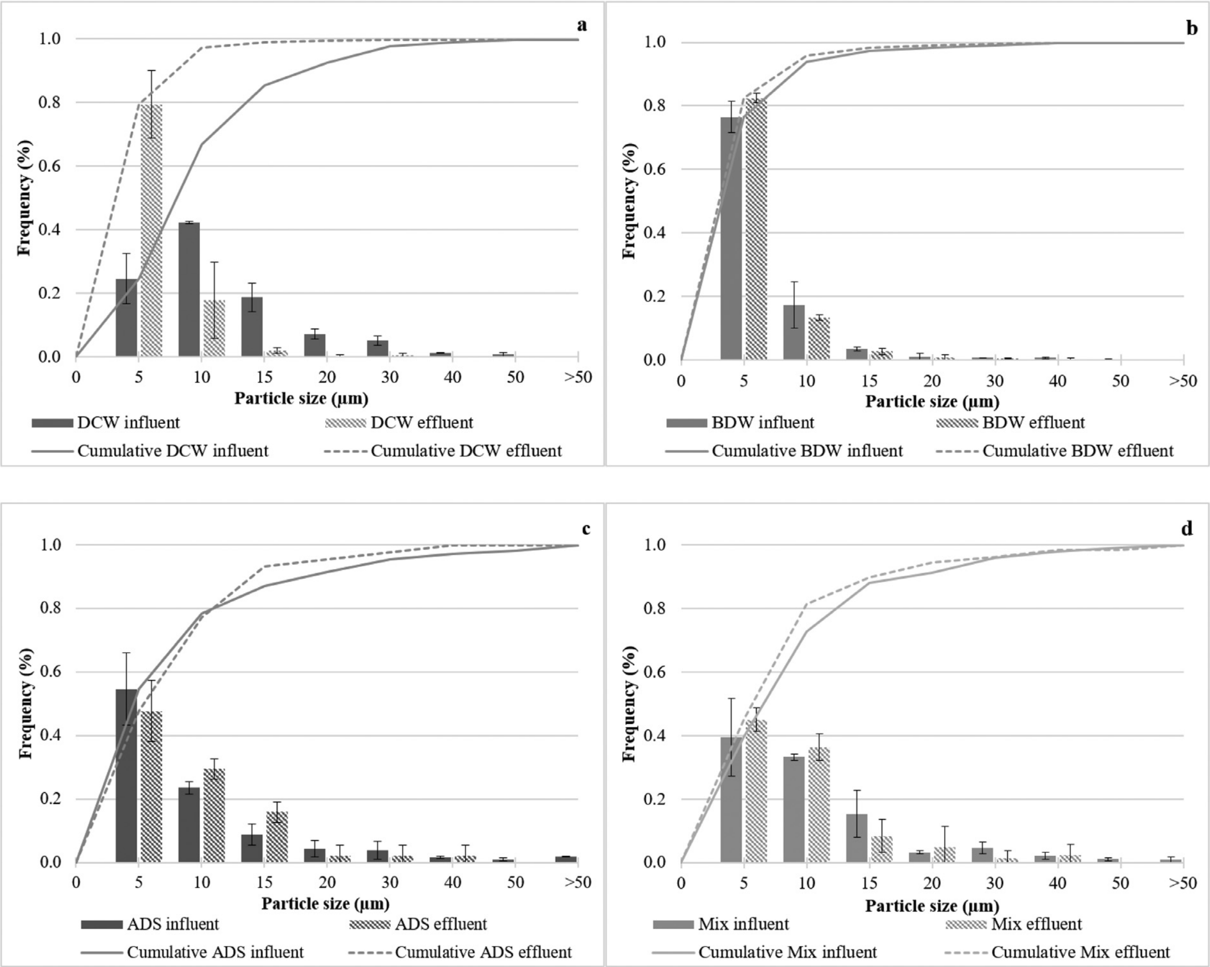

Fig. 2. Particle size distribution and frequency for all influents and their respective effluents were performed at the central point condition of Plackett-Burman Design. Results are based on particle image analysis performed using FIJI-ImageJ. Fig. 2.a and .b show the results for Delft canal water and the Barapullah drain, respectively. Both runs were conducted under the following conditions: 270 mg.L^{-1}, residence time of 990 s, pressure of 4.0 × 10^5 Pa, coagulant concentration of 252.5 mg.L^{-1}, and coagulation time of 1200 s. Additionally, Delft canal water had a pH of 7.15 and a temperature of 32°C. Fig. 2.c and .d show the results for anaerobic digested sludge and mix influent respectively. Both runs were conducted under the following conditions: 2750 mg.L^{-1}, residence time of 990 s, pressure of 4.0 × 10^5 Pa, coagulant concentration of 252.5 mg.L^{-1}, coagulation time of 1200 s. Additionally, anaerobic digested sludge had a pH of 7.8 and a temperature of 30°C.

as sufficient removal for DAF application. In the study conducted by Penetra et al. (2003), a pilot-scale DAF treating 100 m^3.h^{-1}of the effluent of an anaerobic expanded bed system fed with domestic wastewater, had a suspended solids removal efficiency between 49.4 and 96.4%. Similarly, investigated the removal of organics and suspended solids on a pilot-scale DAF treating an effluent flow of 2 m^3.h^{-1} from a high-rate activated sludge process of domestic wastewater. The DAF influent had a TSS concentration of 1.0 g.L^{-1} and total removal of 78%. Finally, TSS removal reached up to 98.5% on a full-scale DAF treating 188 m^3.h^{-1} of wastepaper-recycling wastewater, with influent TSS of around 7.0 g.L^{-1} (Ansari et al., 2018). Thus, the tested down-scaled column DAF system has a representative removal when compared to pilot and full-scale systems, enabling suspended solids removal studies under down-scaled systems. The results obtained in the down-scaled DAF presented in this work are, therefore, comparable to literature and conventional pilot and full-scale DAF systems. Furthermore, the down-scaled column can be used to predict DAF suitability and definition of the operational conditions. Finally, the down-scaled DAF is of particular use for mathematical models developed to understand the flows and particle removal from different types of wastewaters. This system could be used to contrast the suspended solids removal efficiency obtained from the models.

Aside from achieving a comparable suspended solids removal efficiency to full-scale systems conventionally used in water reuse applications, the down-scaled column DAF proved to be able to efficiently remove suspended solids when located either at the end of the Barapullah drain or after a biological digester (closer to the pollution source). Maximum solids removal for BDW and ADS were 94 and 92%, respectively. The down-scaled DAF had a footprint below 0.3 m^2 and was able to handle almost 400 L of influent per day. According to the Central Pollution Control Board of India, daily per capita wastewater production reaches around 220 L in New Delhi, and around 100 L in class I cities (Central Pollution Control Board 2009). Consequently, the designed column DAF could be used for treating the wastewater produced on a household level, where the surface area is scarce. The focus of the investigation was on DAF suspended solids removal, as a pre-treatment step. Post-treatment for removal of dissolved organic matter and nutrients (phosphorus and nitrogen) is recommended for further water utilization. Most biological systems for nutrient removal require the presence of organic matter. Conventionally a 100:5:1 COD:N:P ratio is recommended for aerobic systems (Metcalf et al., 2014). Thus, to enable post-treatment and nutrient recovery, the DAF unit should not remove all organic matter, but mostly the particulate one. Furthermore, sys-

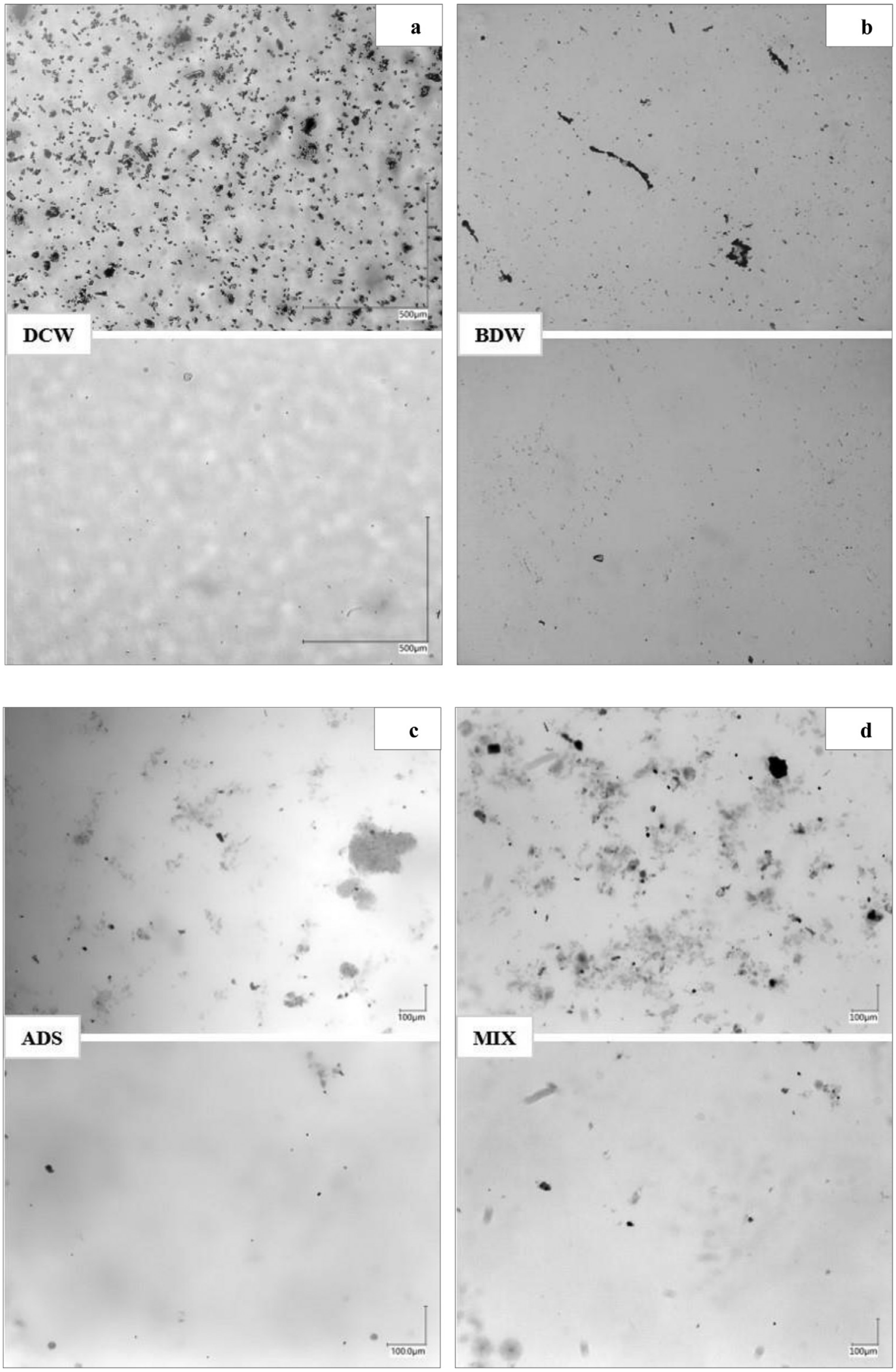

Fig. 3. Particle images of the four different influents and their respective effluents. For each stream, the top panel is the influent to the DAF, and the bottom panel is the corresponding effluent. All pictures were taken for the runs of the central points (runs seven, eight, and nine), following the Plackett-Burman Design shown in Annex B. Fig. 3.a shows the particles of the Delft canal water (DCW). Fig. 3.b shows the particles of the Barapullah drain water (BDW), in New Delhi, India. Fig. 3.c displays particles of the anaerobic digested sludge (ADS) taken from Harnaschpolder (Den Hoorn, Delft). Finally, Fig. 3.d shows the particles of the MIX influent, which entitles a combination of ADS and DCW. All these images were used to analyse particle size and circularity (among other characteristics) with the software FIJI-ImageJ.

tems like wetlands and algae photo-bioreactors (PBR) benefit from the absence of particulate matter (Chen et al., 2018; Langergraber et al., 2003). The potential of DAF as an alternative pre-treatment for water reuse could be useful for policymakers, water authorities, environmental planners and technologists among others, to reduce the stress on land and drinking water availability, while reducing pollutants concentration in drain streams.

4.1. Delft canal water versus anaerobic digested sludge suspended solids removal

DCW and ADS are compared due to their differences in particles characteristics and concentration. While ADS intends to emulate the feed of a DAF system when located after an anaerobic bioreactor, DCW mimics the rainy season conditions of the Barapullah drain. DCW has between

50 and 500 mg.L^{-1} of suspended solids, whereas ADS TSS concentration tends to be 10 times higher. Moreover, around 75% of ADS solids are organics, while this was only 65% for DCW. Suspended solids characteristics, such as density, size, shape, and organic content have an impact on particle removal by flotation. Based on Navier-Stokes, lower particle densities correspond to lower settling velocities and therefore, higher rising velocities when bubbles collide with particles and form agglomerates (Constantin and Foias, 2020). DCW had an average particle density of 1.077 ± 0.022 g.cm^{-3}, while the ADS influent particle density was 1.044 ± 0.030 g.cm^{-3}. Benjamin and Lawler (2013) reported that activated sludge from municipal wastewater has a density between 1.01 and 1.10 g.cm^{-3}, while Forster-Carneiro et al. (2010) have stated that anaerobic digested sludge from a municipal wastewater treatment plan had a density of 1.054 g.cm^{-3}. Particles with lower densities had higher residence time in the column, enhancing the collision chances. Residence time had the highest positive impact on DCW among the other analysed parameters, as shown in **Table 4**. Thus, particle density has a high impact on their residence time inside the down-scaled DAF column and consequently on suspended solids removal efficiency. DCW had the highest particle density compared to all tested influents, which explains why this influent had nine out of 15 experimental runs with poor removal efficiency, considered below 80%.

Besides density, suspended solids are assessed based on particle size (diameter), shape, and organic content. Around 97 ± 1% of the suspended solids from DCW effluent had diameters below10 μm, whilst this frequency was 77 ± 6% for ADS. Both influents had a similar cumulative particle size frequency for particles above 10 μm, as shown in **Fig. 2**. The best particle removal is achieved when particles and bubbles have similar sizes (Edzwald, 1995). Bubble sizes in DAF (at pressures between 2.0 and 5.0 × 10^{5}Pa) can vary from 10 to 140 μm having an average bubble size of around 60 μm (De Rijk and den Blanken, 1994; Han et al., 2002; Edzwald, 1995). Further studies can be done to assess the effect of bubble size distribution on particle removal, in the down-scaled DAF column, and correlate the changes in bubble size distribution with white water pressure.

Ellipsoidal particles cover a greater horizontal area than circular ones, enabling greater collision possibilities with bubbles (Gjaltema et al., 1997). Thus, higher removal by flotation is expected when particles resemble an ellipse in contrast to when they are circular. When compared to the other influents, DCW had the highest amount of ellipsoidal particles with a circularity below 0.3, and the lowest amount of round ones (Table E2, Annex E). Furthermore, particles with the lowest circularities corresponded overall, to the ones with higher Ferret's number and hence, greater shape irregularity. This enhances the chances that after bubbles collide with particles, they form a more stable agglomerate. Therefore, due to the irregularity and elongation of the particles, an increase in particle concentration can also lead to higher removal efficiencies in flotation, as seen in DCW and the MIX influent.

Coagulant and flocculants concentration and coagulation time had a positive effect on DCW. The coagulant used was calcium hydroxide (lime), an inorganic compound classified as a strong base with low solubility (Farhad and Mohammadi, 2005). Lime addition showed to be an effective coagulant due to the increase in particle zeta potential when added to several Calcium Silica Hydrates synthesized from silica, and dehydrated and decarbonated calcium hydroxide (Viallis-Terrisse et al., 2001). Both DCW and ADS had negative zeta potential of -11.6 ± 1.1 and -18.2 ± 1.0 mV, respectively. Similarly, air bubbles have a negative zeta potential between 0 and -58 mV when formed in diverse conditions and mediums (McTaggart, 1922; Li and Somasundaran, 1991; Yang et al., 2001; Fan et al., 2004; Elmahdy et al., 2008). According to, collision efficiency between particles and bubbles increases when particle zeta potential is close to zero. Coagulants, such as lime, are usually added to reduce particle surface charge to zero, promoting particle-particle or particle-bubble collisions. Since ADS had a higher concentration of particles than DCW, and also higher absolute zeta potential, more coagulant is needed for ADS than for DCW to increase particle zeta potential. Thus, to achieve high TSS removal, an increase in coagulants and flocculants concentration can be expected for the Barapullah drain water during the dry season, compared to the rainy season.

Flocculation is used after coagulation to promote the formation of larger flocs. In contrast to inorganic flocculants, organic ones do not harm the biomass (sludge) with metal salts (Vandamme et al., 2015), which is advantageous for biological post-treatment of the separated suspended (bio)solids. Cellulose-based flocculants are promising due to their biodegradability, abundance, and low cost. Furthermore, cellulose has a neutral charge and for this type of polymeric substance, bridging has been considered the main flocculation method (Kitchener, 1972). The time and concentration needed to promote particle bridging vary substantially based on particle characteristics. Coagulation and flocculation time had the highest (and statistically important) positive impact on DCW, while it had a mostly neutral effect on ADS (**Table 4**). The maximum coagulation and flocculation time in these experiments was 30 min, in comparison to the 60 to 120 min reported in other works (Agarwal et al., 2001; Mishra et al., 2002). Thus, coagulation and flocculation time might not have been enough to promote the formation of bigger flocs. The impact of $Ca(OH)_2$ and cellulose on zeta potential and TSS removal of all influents at different concentrations and retention times should be assessed in further research.

4.2. The Barapullah drain water versus mix influent suspended solids removal

Nine out of the fifteen runs of BDW had a TSS removal between 80 and 90%, while for the MIX influent, this value was reduced to five (**Table 3**). The MIX influent was selected to represent the Barapullah drain over the dry season, where the concentration of pollutants and solids is high, while the BDW influent was tested during the monsoon season. Suspended solids content had an important impact on removal for three of the influents but not the same expected effect. For BDW, an increase in the solids content was linked with a decrease in the removal efficiency (negative effect). The opposite happened for the Mix influent, where characteristics of the ADS (charge, size, shape, and organic content) are expected to be dominant.

BDW was the influent with the highest fraction of particle diameters below 10 μm, 94 ±2% versus 73 ± 11% on the Mix influent (**Fig. 2**). This difference in particle size could explain the negative impact of influent TSS concentration on BDW removal efficiencies. From the effluent particle size distribution, the fraction with diameters below 10 μm is poorly removed in the down-scaled DAF set-up. While both influents have similar particle shape, the high fraction of small particles (below 10 μm) of BDW implies lower chances for collision between particles and bubbles. According to Edzwald (1995), particle collection efficiency depends on the transport of the particle to bubble surfaces and is governed by Brownian diffusion, interception, and sedimentation (when particles' and bubbles' diameters are less than 100 μm). Small particles are mainly governed by Brownian diffusion (random movement). Collision efficiency between different particle sizes and a bubble is shown in Annex C. To promote interception and flotation (or sedimentation) of particles, the interaction between particles and bubbles is key. Bigger particles of up to 100 μm have higher chances to collide with microbubbles (Edzwald, 1995). Thus, if an influent has a big share of small particles, an increase in the influent suspended solids can lead to a decrease in removal efficiency, due to the lack of available surface area needed to promote collision between particles and bubbles.

Flotation and sedimentation of particle-bubble agglomerates also depend on their density, since they determine the agglomerate density, and therefore, flotation velocity (Constantin and Foias, 2020). BDW had the lowest average particle density of 1.004 ± 0.005 g.cm^{-3} when compared to the other influents. The MIX influent solids are expected to have a similar density to ADS (1.044 ± 0.030 g.cm^{-3}). For the same particle size and shape (spheres), a solid with a density of 1.044 g.cm^{-3} settles down almost 10 times faster than a particle with a density of

1.004 g.cm^{-3} (0.90 cm.h^{-1} versus 0.12 cm.h^{-1}, respectively for 10 μm particles). Since the average diameters for bubbles and particles of all influents are around 60 and 10 μm, respectively, the moment a particle collides with a bubble, the floating velocity is mostly governed by the bubble diameter. A higher particle density implies higher settling velocities, which can be linked with shorter times in the DAF column. Hence, fewer chances of collision with bubbles. Thus, a greater collision between bubbles and particles can be expected for the influent with the lowest particle density (BDW). This is aligned with what was observed for the BDW, where the number of experiments with TSS removal efficiencies above 80% (sufficient) was the highest.

An increase in bubble concentration enhances the chances of collision (Edzwald, 2010). White water pressure is directly linked with bubble concentration and size. According to Henry's law; air concentration in the liquid depends on set pressure, temperature, and Henry's constant (Van't Hoff, 1884). The amount of microbubbles formed upon pressure release to atmospheric conditions directly relates to the dissolved air concentration under pressurized conditions. For example, the dissolved air concentration increases 1.6 times when pressure changes from 3 to 5×10^5 Pa. Next to more microbubbles formation at higher pressure, this phenomenon is enhanced due to a decreased in average bubble size at increased pressures up to 5.0×10^5 Pa (De Rijk and den Blanken, 1994, Han et al., 2002). De Rijk and den Blanken (1994) found that the average bubble diameter changed from 107 to 74 μm at 3.0 and 5.0×10^5 Pa, respectively. The rising velocity of the bubbles will decrease with microbubble size, according to the Navier-Stokes equation (Constantin and Foias, 2020), which will enhance the residence time in the column and thus the chance for collision. Considering the dissolved air concentration at each pressure, white water flow, the bubble diameters, and the air density at 20°C, the number of bubbles generated at 3.0×10^5 Pa and 5.0×10^5 Pa in the experiment were 9.4×10^7 and 4.7×10^8, respectively. Thus, an increase in pressure has the following cumulative effects on air bubbles: an increase in quantity due to increased gas solubility, a decrease in size, and thus a decrease in rising velocity. All three aspects are conducive to particle and bubble collision. The stability of floc and bubble agglomerates, however, mostly depends on particle and bubble charge and therefore, appropriate coagulation and flocculation, as described in Section 4.1.

The MIX influent has more than 99% of its particles coming from ADS, thus, coagulation and flocculation are expected to behave similarly to ADS. Organic content and particle zeta potential are key aspects to further assessing and understanding the effect of coagulants and flocculants concentration and time. However, these two characteristics were not possible to measure on BDW, due to the unavailability of technical equipment in-situ. BDW is expected to have a high concentration of inorganic solids (clay), and thus it is expected to have a negative zeta potential.

5. Conclusions

A Dissolved Air Flotation (DAF) has been studied in a down-scaled column system as part of an open sewage treatment train to recover water, for the Barapullah drain in New Delhi (India). Four different types of influents were tested. Three influents resemble the Barapullah drain seasonal variations in composition, BDW, DCW, and MIX influent (combination of DCW and ADS). The fourth tested influent (ADS) mimics the feed of DAF when located after an anaerobic bioreactor or closer to the pollution source (household level). Design of experiments was used as a tool to assess the effect of a set of control variables on the down-scaled DAF suspended solids removal, namely suspended solids, temperature, pH, residence time, pressure, coagulants and flocculants concentration, and coagulation time. Below are the conclusions from the study.

Suspended solids removal obtained from the down-scaled DAF are comparable to full-scale systems. The use of design of experiments proved to enable the analysis of a set of seven DAF performance control variables (influent TSS concentration, pH, temperature, residence time, pressure, coagulant and flocculant concentration and, coagulation time), obtaining suspended solids removal that fluctuate from 29 to 96%. DAF high suspended solids removal is accordance to requirements for a post-treatment focus on nutrient removal.

The Barapullah drain suspended solids were efficiently removed by a DAF system. The maximum TSS removal efficiency obtained was 96 ± 4% for DCW. Similarly, the maximum BDW TSS removal was 94 ± 3%, whilst for the MIX influent TSS removal reached 95 ± 2%. Furthermore, DAF proved to be efficient in the removal of TSS when located after an anaerobic bioreactor (ADS influent) or next to the pollution source, with maximum removal of 92 ± 4%.

Particles with a diameter below 10 μm and more rounded shapes are less prone to be removed by DAF. Small particles' collision with air bubbles is governed by Brownian diffusion. They have fewer chances of collision with bubbles and less available surface area to attach to bubbles, even when their small size allows them to have longer residence time inside the down-scaled column. All tested influents had effluents with a high frequency of round particles and diameters below 10 μm, above 78 and 77%, respectively.

The positive or negative effect of DAF control variables' on suspended solids removal depends on the influent characteristics. An increase in pressure had a positive effect on all influents TSS removal, and a significant impact on the most concentrated influents, ADS and MIX. Influent TSS concentration had a variable effect, due to the difference in density, size, shape, charge, and organic matter of particles, in the tested influents. Finally, the addition of $Ca(OH)_2$ and cellulose as a coagulant and organic flocculant respectively had a positive impact on the TSS removal of all influents.

The easy availability of materials to build the system, low cost of analytical methods, and usage of free software to measure particle size and shape, made the down-scaled DAF system a promising tool to test full-scale DAF performance, for inflows as low as 15 L.h^{-1}.

The robustness and compactness of DAF installations, in combination with the high hydraulic loading rate and low TSS concentration in the effluent, make DAF systems useful for the pre-treatment of open drain sewage. Due to the DAF small surface area and high suspended solids removal, it could be located either downstream or closer to the pollution source. The knowledge on DAF usage as an alternative pre-treatment for water reuse, could be beneficial for policymakers, water authorities, environmental planners and technologists, among others, to reduce the stress on land and drinking water availability, while minimizing pollutants concentration in drain streams.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2022.100567.

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