SATI tarryn@satgi.co.za Tel: 021 863-0366	CFPA inmaak@mweb.co.za Tel: 021 872-1501	HORTGRO anita@hortgro.co.za Tel: 021 870 2958	RAISINS SA ferdieb@raisinsa.co.za Tel: 054 495 0283	WINETECH andraga@sawine.co.za Tel: 021 276 0499
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FINAL REPORT 2024

SA WINE number : UWC BB 20-01

1. PROGRAMME & PROJECT LEADER INFORMATION

	Research Organisation leader	Project leader
Title, initials, surname	Prof JM Franz	Prof Ben Bladergroen
Present position	Deputy Vice-Chancellor: Research and Innovation	Director of the Energy Storage and Fluid Treatment Centre
Address	University of the Western Cape Science Faculty, Building 91 Bellville 7535	Robert Sobukwe Rd University of the Western Cape Science Faculty, Building 91 Bellville, 7535
Tel. / Cell no.	+27 21 959 4057	+27 79 509 1704
E-mail	jfrantz@uwc.ac.za	bbladergroen@uwc.ac.za

2. PROJECT INFORMATION

Project title	Shear enhanced flotation separation technology, optimized to treat wine industry wastewater
Short title	Enhanced flotation technology, optimized to treat wine industry wastewater

Fruit kind(s)	N/A		
Start date (mm/yyyy)	2020-01	**End date** (mm/yyyy)	2023-12

Key words	Chemical oxygen demand (COD), coagulation, organic impurities, shear separation flotation, suspended solids. sustainability, winery wastewater treatment

	CFPA	RAISIN SA	HORTGRO	SATI	SA WINE	ARC	OTHER
TOTALS All years	R 0	R 0	R 0	R 0	R 2900000	R 0	R 0

Total cost of entire project	R 2900000

3. EXECUTIVE SUMMARY

Objectives and Rationale

Wineries generate large volumes of wastewater throughout the year that cannot be disposed of in natural systems without pre-treatment. Shear enhanced flotation separation (SEFS) technology is envisaged to treat winery wastewater to a reusable standard and to generate a concentrated solid waste, which potentially could be used as fertilizer.

Methods

A SEFS system was designed, fabricated and commissioned to treat real winery wastewater. Winery wastewater has been collected from Winery X, located on the West Coast of South Africa during the harvest season. The results obtained at pilot scale have been compared to that obtained in the lab.

Key Results

Based on both laboratory and pilot plant optimized conditions, the SEFS technology has demonstrated greater effectiveness compared to the study conducted in previous years. This heightened efficacy can be primarily attributed to a significantly enhanced comprehension and mastery over the reactions occurring throughout the pilot plant treatment process.

Key Conclusion of Discussion

The results of this study concluded that the incorporation of a rotor stator high shear mixer enhances the treatment of winery wastewater. The SEFS treatment produces water that can be either used as grey water or can be further biologically treated to obtain better quality treated wastewater for crops.

Take Home message for Industry

Through our research we conducted a thorough evaluation of winery wastewater treatment constraints across the South African wine industry. This has provided insights into the challenges and opportunities within the sector using shear to enhance treatment efficiency.

4. PROBLEM IDENTIFICATION AND MOTIVATION

Problem Identification

The generation and disposal of wastewater by wineries have been a concern for decades. Conventional treatment methods such as sedimentation of winery wastewater are inefficient and newer methods are therefore being evaluated that are targeted to alleviate the cost implications as well as meet municipal discharge standards. Costs associated with both water consumption and winery wastewater treatment form an ever-increasing portion of the operational budget of many wineries, exacerbated by reduced rainfall and more stringent municipal regulations around effluent discharge. Re-use of winery wastewater for irrigation purposes without additional treatment is often not recommended as the Chemical Oxygen Demand (COD) and Total Dissolved Solids (TDS) levels cause the water to be an unfit source. The potential for water re-use in the wine industry is great but currently the cost of water treatment plants is too high, specifically for many small to medium scale wineries. This project will investigate a novel shear enhanced flotation separation (SEFS) technology to treat winery wastewater. SEFS technology used in this study was applied to treat winery wastewater to a potential reusable standard by reducing COD to appropriate levels.

Motivation

The purpose of this study is to deconvolute critical parameters related to shear enhanced flotation separation (SEFS) technology and apply a mobile unit at selected wineries to treat winery wastewater based. This study will guide wineries about the costs and benefits upon integrating SEFS at their wastewater treatment and re-use facility.

The SEFS technology potentially solves three main problems:

a) Significant reduction of water treatment cost so, water treatment becomes more cost effective than raw effluent discharge

b) It reduces the TSS, COD and TDS levels of effluents, reducing the burden on municipalities that do not meet the treatment standards, and making the treated effluent more compatible as a source for irrigation water

c) Water recovery and re-use from effluent can become more cost effective,

The technology incorporated in this study also reduces retention times, operating footprint and chemical consumption rates compared to traditional coagulation, flocculation and flotation treatment systems.

The outcomes of the project were aimed at evaluating and gaining insight into winery wastewater management practices within the South African wine industry. With the support of the DSI and South Africa Wine, we embarked on a journey to address the wastewater treatment constraints faced by wineries, with a specific focus on a more sustainable and competitive wine industry

5. ACCUMULATED PROGRESS TABLE

Objectives	Milestones (Significant event or stage in a project)	Date Achieved
Determine the financial viability of SEFS technology at winery X	O1M1: Complete design report for the SEFS technology O1M2: Commission the SEFS technology O1M3: Submit test report of SEFS technology at winery X O1M4: Submit costing report outlining the costs and savings at winery X	2022-12-31
Determine suitability of Capacitive Deionization (CDI) to remove sodium and potassium from winery effluent	O2M1: Study CDI technology using winery model effluent on lab scale O2M2: Study CDI technology using winery model effluent on stack level O2M3: Study CDI technology using real winery effluent on lab scale	2022-12-31
Build human capital around SEFS technology to treat winery wastewater	O3M2 Finalize a Master thesis on the application of CDI technology on winery effluent O3M3 Finalize a MComm study about the economic feasibility of SEFS technology for wineries O3M4 Finalize a PhD thesis on the application of SEFS technology to treat winery effluents	2023-12-17
Commissioning of a modified DAF system	Design, procure and build system	2023-08-31
Submit commissioning report		2024-08-19

6. WORKPLAN (MATERIALS AND METHODS)

Workplan 1: SA Wine will select one of their wineries which is deemed most suitable for this study. SA Wine will provide the winery data in terms of the quantity and quantity wastewater, municipal charges, irrigation needs, ongoing research studies. Such data will be used to modify one of the mobile treatment systems from Abrimix and sent to UWC for the duration of the project.

Following the commissioning of the mobile SEFS system, wastewater treatment trials took place on real effluent produced at the winery. The generated data was used to modify the system, optimize process conditions and find the most appropriate combination of additives. All experimental results will be compiled in a test report as part of a PhD study. In addition, a Master student from the Economic and Management faculty will perform an economic analysis on the SEFS process and include a sensitivity analysis as part of the student's MComm degree.

Workplan 2: Since 2015, UWC has developed electrodes for desalination technology known as capacitive deionisation (CDI). Earlier in 2019, UWC secured funding from the water research commission (WRC) to apply the know-how generated on CDI electrodes for the development of CDI stacks. So far, the research work has shown that CDI technology is particularly energy efficient for effluents with <2 g/l total dissolved solids. Workplan 2 aims to study how effective the CDI stack under development can be applied to remove potassium and sodium from winery effluent. It is expected that the funding from WRC (R2.2M over 4 years) will add significant value to this SA Wine study. A Masters student who was tasked to study the suitability of the CDI technology to remove potassium and sodium has been finalized his MSc thesis as part of the WRC project described under Workplan 2 at no cost to the SA Wine project.

Workplan 3: Objective 3 (Build human capital around SEFS technology to treat winery wastewater) will be reached in parallel to Objective 1 and 2.

7. RESULTS AND DISCUSSIONS

Section 1: Shear Separation and Flotation (SEFS) Technology

Pre-amble

This chapter describes how shear enhanced flotation separation (SEFS) technology can improve the effectiveness of winery wastewater treatment systems. After an introduction to the SEFS technology, a description of the common pollutants found in winery wastewater, their associated environmental impacts as well as discharge options is provided in the form of a brief literature review. In the experimental section, both the lab scale experimental findings and the pilot scale performance is presented. Even though the case study has evolved around the wastewater treatment facility at winery X, the learnings can be applied to any other winery.

7.1 Introduction to SEFS

Shear enhanced flotation separation (SEFS) is an emerging water treatment technology and may be classified as an advanced flotation technology. Flotation technology originates from the mineral processing industry and applies coagulation/flocculation in which the resulting floc is attached to air bubbles. The buoyancy of the lighter flocs is used to drive the separation of particulate material from the processed water. The SEFS technology adds hydrodynamic shear as an important aspect of the flotation technology and is claimed to boost the efficiency of the separation process. Since winery wastewater is loaded with colloidal matter, this project focuses on the development of an SEFS process optimized to treat winery wastewater.

7.2 Literature survey focusing on winery wastewater

The agricultural sector is one which requires and consumes enormous amounts of fresh water globally. Commercial wine production in particular uses large volumes of fresh water and through various processes, generates significant quantities of wastewater. The wastewater produced by wineries typically exhibit high levels of chemical oxygen demand (COD), total suspended solids (TSS), an acidic pH ranging from 2 to 5, with varying salinity and nutrient contents. The overall characteristics of winery wastewaters indicate that they are a potential environmental hazard if not processed and disposed of appropriately.

Wine waste consists of a matrix of solid and liquid components. The solid components in wine wastes are generated during processes such as destemming, pressing filtration and settling. The solid waste is composed of skins, stems, excess grape pulp, seeds, stalks and yeast cells that are generated during the process of fermentation.[1] In relation to percentage composition, it consists of 7.5% grape stems, up to 45% grape pomace and approximately 6% grape seeds.[2] The liquid component i.e., winery wastewater, on the other hand, is generated during the cleaning of barrels and tanks, washing of transfer lines and floors, wine extraction, as well as numerous other operations in filtration units and water drains.[3]

For every tonne of grapes processed, wineries typically produce 3 to 5 cubic meters of wastewater.[4] To contextualize this, the South African wine sector processed 1.2 million tonnes of grapes in total during the 2022 harvest season.[5] As a result, the total volume of wastewater generated in this specific vintage season is estimated between 3.6 to 6 million cubic meters.[6] Comparatively, the Australian wine grape crush for the 2022 harvest season was 1.7 million metric tonnes, implying that 5 to 10 million liters of wastewater was generated.[7] An estimated 10.5 to 17.5 million cubic meters of wastewater was produced during the vintage season in 2022 as a result of the joint processing of 3.6 million tonnes of grapes by the California wine production business in the United States.[8]

The generation of these extensive quantities of wastewater is a cause for concern considering the world's ongoing population growth and scarce water resources, which contributes to the challenge of limited access to clean fresh water.[9,10] This is made worse by the variable consistency and quality of wastewater from wineries, which fluctuates seasonally and typically contain chemical compounds that are harmful to the environment. As such, ensuring that appropriate treatment and disposal is consistently carried out becomes an essential objective for wineries.[11]

Winery wastewaters are notorious for their acidic pH, which is linked to the presence of various organic acids.[12,13] The electrical conductivity (EC) of winery wastewater may reach values up to 6.15 mS/cm.[14] Nutrients in winery wastewater have caused high reported levels of total nitrogen (TN) and total phosphorous (TP) at 640 mg/L and 657 mg/L, respectively.[15,16] Chemical oxygen demand (COD) values routinely seen in winery wastewater generally fall within the range of 300 mg/L to the possibility of reaching values of up to 300,000 mg/L.[17–19]

There are serious and diverse environmental consequences linked to the unsafe discharge of wastewater from wineries into the environment.[13] These include the release of foul odors mainly due to the high organic content of the wastewater, the degradation of soil quality, damage to vegetation as a result of wastewater disposal techniques and overall pollution of water bodies.[20] Based on these adverse environmental effects, wineries are requested to treat their wastewater to regulated standards before discharge into the environment.

Most wineries have some form of effluent treatment system in place for processing their wastewater, however, alternative methods are continuously being researched and proposed which are aimed at (i) maximizing both efficiency and flexibility of the treatment process to handle fluctuations in impurity concentrations (organic and inorganic species) and effluent volumes, (ii) capital cost moderation, (iii) ease of operation and maintenance, (iv) a smaller footprint and finally (v) meeting specified discharge requirements for winery effluents.

Coagulation and flocculation have to date been the staple processes during water and wastewater treatment.[21–23] Generally, colloidal particles present in wastewater are negatively charged. The presence of these negative charges produces repulsion forces within the medium, hence decreasing the tendency of particles to aggregate, form floccules (flocs) and enhance sedimentation and flotation techniques. There have been extensive reports and literature studies related to conventional and emerging winery wastewater treatment options.[18,24–27]

However, many of these technologies are more applicable to treat wastewater from medium to large scale wineries rather than those from the many small wineries. A relatively new and emerging treatment option involves the use of hydrodynamic shear mixing with flotation.[28]

Hydrodynamic shear mixing has been previously used during emulsion processing as well as for the possessing of tight stable emulsions in petroleum wastewater treatment.[29,30] The basic principle of this technology involves the intentional destabilization of colloidal suspensions. This destabilization is achieved by subjecting the suspension to shear flow through mechanical agitation. The primary objective of this process is to facilitate the aggregation of micron sized solid particles, resulting in the formation of larger flocs, which are more effectively separated from the liquid phase.[31]

The aggregation of colloidal particles is facilitated by shear flow through two primary mechanisms. In the case of kinetically stabilized colloidal suspensions exhibiting a sufficiently high energy barrier that prevents aggregation, it is possible for the convective energy (process of thermal energy exchange in fluids via the motion of matter within them) transmitted by the fluid to facilitate the particles to overcome the repulsive barrier and undergo aggregation. In the second situation, when dealing with totally destabilized suspensions, the rate of collisions is solely determined by the strength of the flow field. This leads to a significant acceleration of the aggregation kinetics in comparison to a purely diffusive mechanism.[32]

High shear mixers (HSMs) are considered to be an innovative and appealing form of process intensification equipment.33 These mixers show great potential with regard to enhancing the liquid-liquid extraction process inside solid-liquid-liquid systems. However, there is a scarcity of literature reporting on this particular aspect.

High shear mixers, much like flotation devices have been mostly used in emulsion and mineral processing.[34–37] However, their potential to serve as an alternative treatment method for winery wastewater is yet to be proven. The potential of this technology to alter particle size as well as surface charges of colloidal particles needs to be explored in further detail, specifically in a practical sense.

This study focused on the key parameters of turbidity, total suspended solids (TSS), and particulate chemical oxygen demand (COD) in relation to the efficiency of winery wastewater treatment utilizing a hybrid shear enhanced flotation separation (SEFS) pilot plant. Due to the complexity of the treatment system (a non-symmetrical system), which consists of a multi-phase medium, the shear rate/speed in the rotor stator mixer configuration, is an intricate parameter to quantify. As such the terms shear rate/speed used throughout this paper has been simplified and quantified using revolutions per minute (rpm).

Due to significant variations in wastewater contaminant levels among wineries, the implementation of a universally applicable, environmentally friendly and sustainable waste management system seems practically unattainable. This study investigated the design, fabrication and modification of a shear enhanced flotation separation (SEFS) pilot plant to be used as a primary treatment stage during winery wastewater processing. This technology combines the synergistic advantages of hydrodynamic shear, coagulation, flocculation and dissolved air flotation. To date there have been only limited publications on the feasibility and application of hydrodynamic shear and its potential to assist with coagulation/flocculation and flotation efficiencies specifically for winery wastewater treatment. The results obtained indicate that the SEFS pilot plant may well be able to process winery wastewater to a quality where reuse of the water for irrigation of crops may be considered.

Most wastewater treatment involves at least one physical treatment stage primarily to remove large solid particulates present in the wastewater. This is a straightforward step which is simple, effective and also aids in the prevention of primary and secondary treatment equipment from becoming clogged with solids like seeds, stalks and leaves. This preliminary treatment phase involves the use of screens/grits to remove large matter (skins, pips, stems and lees) with particle sizes greater than 500 μm.

Primary physicochemical treatment has most commonly been used to as pre-treatment to reduce organic load and turbidity of winery wastewater prior to biological treatment.16 Some of the advantages of physicochemical treatment methods are a reduction of sludge build-up and wear on treatment pumps, the enhancement of treatment efficacy via the addition of chemicals as well as improvement of the suitability of the wastewater for disposal on land. Coagulation and flocculation are among the most used primary treatment methods of winery wastewater.

Primary treatment methods are important to remove suspended solids in winery wastewater prior to the semi-treated effluent being transferred to biological treatment processes. The next section of this report describes the experimental setup during lab scale studies and subsequently the obtained optimized process parameters which were transferred to the pilot plant (Section 2).

7.3 Experimental Methods

7.3.1 Winery X water treatment facility as case study

The wastewater treatment facility at Winery X, a winery located on the West Coast of South Africa was selected as the most appropriate location to study the SEFS treatment technology. The layout of the effluent treatment plant is shown in **Appendix A1**. Briefly, the inherent set up at the winery involves the effluent being gravitationally fed from the cellar through a grit where solid materials (grape pomace) consisting of skin, stem, residual pulp, seed, small pieces of stalks, and yeast cells from the wine fermentation process are removed. Since 2022, the effluent flows from the grit into a lime alkalisation pit (lime pit) where pre-mixed lime water is added to keep the pH above 9. The moment the pH in the lime pit drops below 9, the lime water dosing pump is activated. The effluent from the lime pit flows over into three interconnected settling dams (Dam A-C). Eventually the effluent is pumped to three biological treatment dams (Dam 1-3). Thereafter, the treated effluent is discharged to natural fields via irrigation.

7.3.2 Alkalization Study

Batch studies were conducted in 5 L beakers (sample volume = 4 L) at atmospheric pressure and temperature. A lime slurry solution was made by adding 100 g of hydrated lime ((CaOH)2), obtained from Cape Lime (Pty) Ltd to 900 mL of distilled water in a volumetric flask. pH adjustments from raw effluent (pH 4) to pH 7, 8, 9 and 10 were carried out using 725 mg/L, 788 mg/L and 825 mg/L and 900 mg/L lime slurry, respectively. Following pH adjustments in the 5 L beakers, 8 × 500 mL samples were used as a batch for each pH value.

7.3.3 Coagulation and flocculation

Based on the treatment efficiency in different types of wastewater, aluminium based polymeric coagulants and polyacrylamide flocculants were selected as treatment chemicals during this study.[38–41] The coagulant used in this study was AB121 which is a blend of aluminium chlorohydrol (ACH) with a specific gravity of 1.3 (available as a 1% vol. solution). The flocculant used was AB796, which is a blend of polyacrylamides (granules) and made up to a 1% (w/v) solution with ultrapure distilled-deionised water obtained from a Milli-Q (Millipore Co.) system. The coagulant and flocculant chemicals were supplied by Abrimix (Pty) Ltd, South Africa. The coagulant was used as received while a stock flocculant solution of 10 000 ppm was made using 1000 mL distilled water on a weekly basis. The effect of coagulant dosage was investigated using the optimum pH values obtained during alkalization studies. The optimal dosage of coagulant was evaluated using zeta potential analysis.

7.3.4 Coagulation and flocculation dosages

In a typical coagulation experiment, aliquots of coagulant with various concentrations (1, 2, 3, 4, 5, or 10 mg/L) were added directly to the 500 mL sample while stirring with the high shear mixer for 2 min at 250, 2 000, 4 000 and 6 000 rpm, respectively. At the point where the coagulant dosage reached a zeta potential value close to 0 mV (i.e., iso-electric point), the addition of flocculant commenced where the sample was stirred using low shear at 250 rpm for 10 minutes.

7.3.5 Shear Mixing

The hydrodynamic shearing of the effluent was conducted using a PUXIL JRJ300-1 High Speed Shearing Emulsifier. This unit consists of a gas inlet, rotor, stator, air flow meter, speed control and two pressurized air nozzles (**Figure 1**). This mixer has a processing capacity of 40 L, working head configuration of 70 mm, output power of 300 W and speed range 100–11000 rpm. The lab scale shearing mixing setup was equipped with two pressurized air nozzles which were set to deliver an air flow rate of 450 ln/h (normal litre per hour, defined as a unit of volume for gases equal to the volume of 1 litre at a pressure of 1 atmosphere and a standard temperature of 20°C).[42]

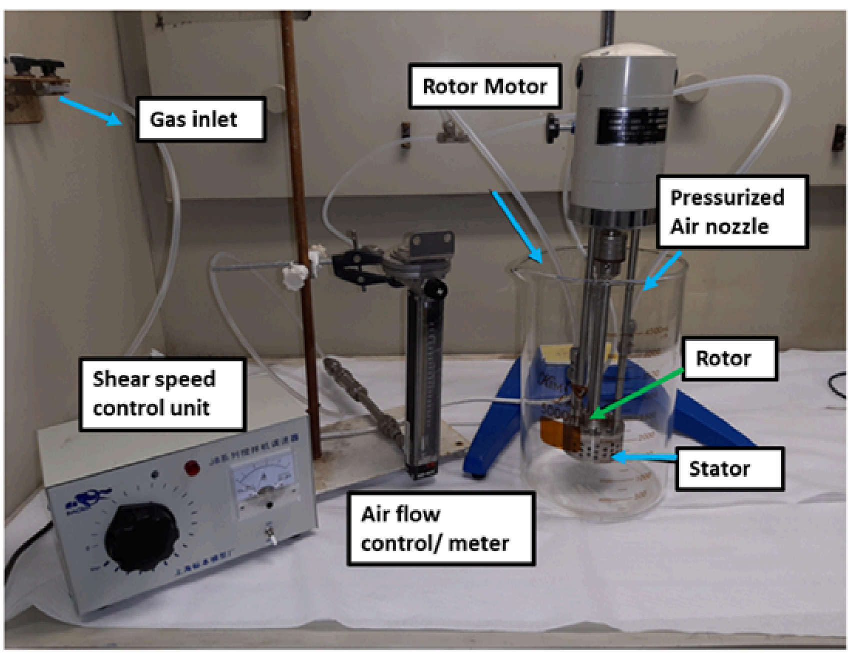

Figure 1. Shear enhanced flotation separation lab scale unit.

7.4 Analytical methods

Determination of pH and electrical conductivity were carried out using a portable multi-meter (Hach, HQ40d) with an equipped conductivity probe. The meter calculates an estimate of total dissolved solids (TDS) by multiplying the electrical conductivity (EC) reading with a conversion factor. The factor (from EC in mS/m at 25°C to TDS in mg/L) is reported to have an average value of 6.5.[43] The turbidity, measured in NTU (Nephelometric Turbidity Units) of the wastewater was measured using a spectrophotometer (Hach 2100Q). The chemical oxygen demand (COD) of the samples was obtained using a Thermo Fisher Scientific Orion Aquafast 3140 colorimeter and an Orion COD165 Thermo-reactor. The reagent vials used were the Aquafast COD HR (High Range), 0 – 15000 ppm.

7.4.1 Zeta Potential

The zeta potential (ZP) analysis was conducted with a Malvern Zetasizer NanoZS series which uses the electrophoretic light scattering measuring technique.[44] The zeta potential measurements were studied in terms of variations in shear speed and coagulant dosage. The laser used in the Malvern Zetasizer Nano was a 4 mW He–Ne laser of 633 nm wavelength.[44] A dip cell with palladium electrodes (ZEN1002) was used for the determination of zeta potential during this study.

7.4.2 Determination of Total Suspended Solids

Total suspended solids were determined as per ASTM D5907–18. Briefly, a 0.45 µm filter paper was weighed on a watch glass before filtration, thereafter, samples were filtered in a Buchner filter filtration set-up. The post filtered solid samples were placed in an oven at 105°C for 1 hour. Thereafter, the sample was removed from the oven and placed in a desiccator for 30 min to allow the sample to cool in a moisture free environment. Once cooled, the sample was weighed, and the total suspended solids calculated.

7.5 Results at Laboratory scale

7.5.1 Raw effluent composition

The winery crushed a total of 43 500 tons of grapes (38 000 white and 5 500 red) during the vintage period (Mar–April 2021/22) and the average raw effluent composition during this period is illustrated in **Table 1**.

Table 1. Average raw effluent characterization.

Sampling date	pH	Turbidity	EC	Ca	TSS	TDS	COD
	(25°C)	(NTU)	(mS/m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Mar 23rd – 28th 2021	4.0	630	175	130	2275	3546	22620
Apr 9th – 14th 2022	4.5	570	230	222	1840	1476	12400

The values obtained for the chemical composition of the effluent used in this study corresponds with other studies relating to winery effluent composition in South Africa.[18,45,46] Based on the data displayed in **Table 1**, the characteristics of the raw effluent was acidic, showed high levels of total suspended solids (TSS), total dissolved solids (TDS) and chemical oxygen demand (COD).

Previous detailed studies on winery wastewater composition have concluded that 90% of the total soluble organic load is represented by ethanol and sugars (glucose and fructose).[47]
In order for winery wastewater to be disposed of via irrigation, certain legislation limits must be adhered to.[48] These limits are shown in **Table 2**. Comparing **Table 1** and **Table 2**, it is evident that the untreated winery wastewater does not comply with general authorization limits for irrigation water quality in South Africa.

Table 2. General Authorizations for legislated limits for irrigation water quality in South Africa.

	Maximum irrigation volume allowed (m^3/day)		
Parameter	<50	<500	<2 000
pH	6 – 9	6 – 9	5.5 – 9.5
COD (mg/L)	5 000	400	75
EC (mS/m)	200	200	70 – 150
TSS (mg/L)	-	-	<25
TDS (mg/L)*	1300	1300	488 – 975

Chemical Oxygen Demand (COD); Electrical Conductivity (EC); Suspended Solids (TSS), Total Dissolved Solids
*TDS based on EC using a conversion factor of 6.5.

7.5.2 Alkalization

Wastewater discharge permits generally require that acidic waste be alkalised to the range of pH 6.0–9.0.[48] Winery wastewater is known to have an abundance of negatively charged colloids. These colloids remain in suspension due to their net surface repulsive forces. pH adjustment is commonly used to partially destabilize these repulsive forces. To achieve these goals, lime alkalization is a commonly used pH alkalization option.[49–51]

In general, acidic conditions present in winery wastewater favours the production of hydrogen sulphide, which is the dominant malodorous gas associated with wastewater originating from wineries.[52] Raising the pH of stored wastewater can greatly reduce the production of hydrogen sulphide and decrease the impact of mal odours on neighbouring properties. This step is important especially in the context of this case study since the selected winery has had frequent complaints from surrounding neighbours about foul odours being generated by their effluent plant. The relationship between the zeta potential and turbidity with pH is presented in **Figure 2**.

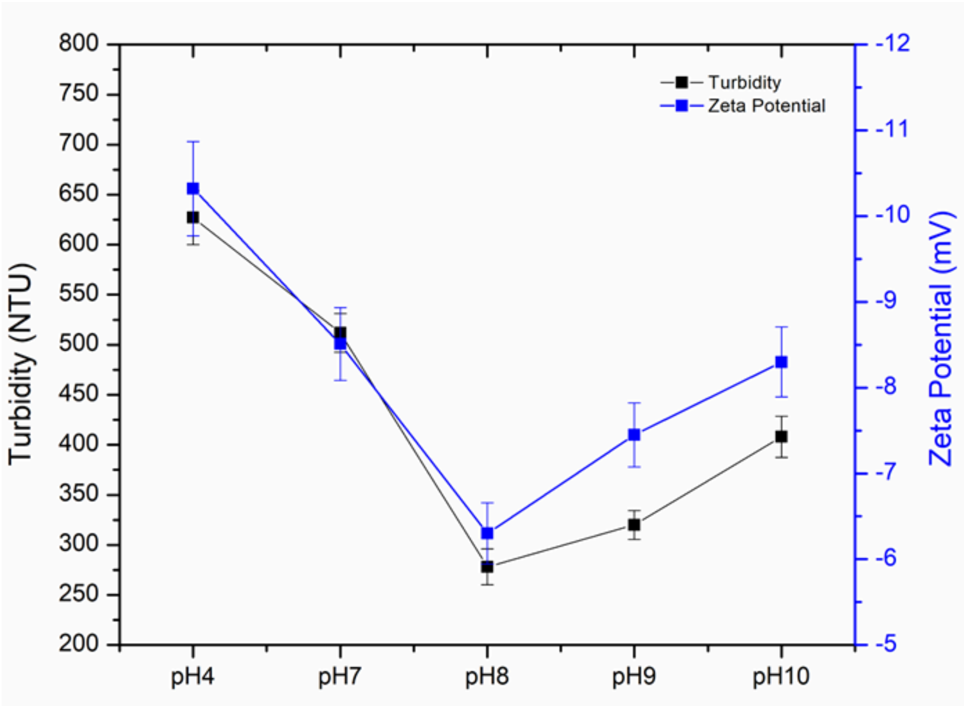

Figure 2. Zeta potential and turbidity as a function of pH.

An observation that can be made from **Figure 2** is that acidic/raw effluent has a larger zeta potential (indicating a greater degree of colloid stability) than the alkalized effluent. This is accompanied by a higher turbidity value since the colloids in suspension of the raw effluent have a lower tendency to agglomerate (and subsequently precipitate) due to higher electrostatic charges (repulsive forces). The optimum pH as determined by zeta potential and turbidity was pH 8 which showed optimal conditions for the particulates to coagulate and precipitate. It is well known the lime does not only act as a alkalizing agent but also as a coagulant, which is why a general decrease in zeta potential is observed upon lime addition.[53] There was a decrease in the turbidity as the pH rises from 4 to 8, this observation was also confirmed in a study conducted by Luz et al., (2021) Their findings indicated that alkalization with lime decreases the turbidity of the effluent from 159 NTU to 2 NTU.[51] At pH values above 8, the zeta potential of the solution decreased, which we believe may be due to an oversaturation of lime dosing. This also resulted in resuspension of particles which is evident with the increase in turbidity values. A similar trend was reported by Awodiji et al., (2020).[54]

Figure 3 illustrates the visual effect of alkalization on turbidity during alkalisation studies. Herein, hydrated lime not only increases the pH of the solution, but also aids in removing suspended matter. The observations made in **Figure 2** and **Figure 3** allowed for the selection of optimum pH (pH 8 – pH 9) for hydrodynamic shear and coagulation studies.

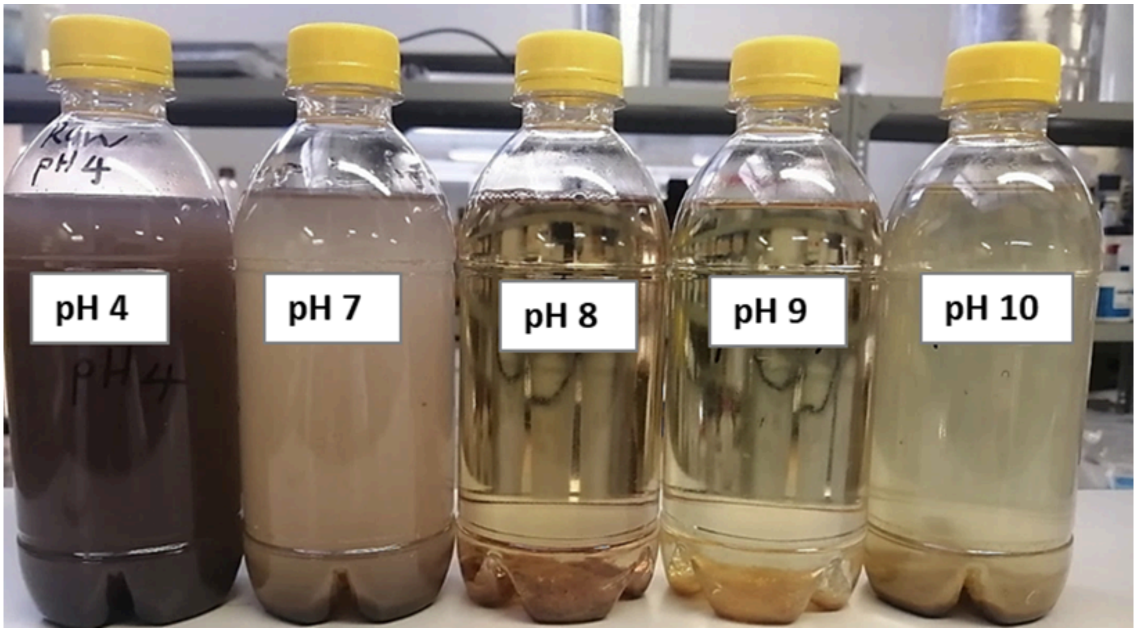

Figure 3. Lime alkalization (visual) studies as a function of pH.

7.5.3 Application of shear

Following pH adjustment studies, the effect of applying hydrodynamic shear to the wastewater was investigated. The alkalized effluent (pH 8) was exposed to different shearing speeds of the mixer for various time periods. One batch of such effluent was exposed to high shear speed (2000, 4000 and 6000 rpm) using a rotor- stator mixer, while another batch was exposed to low shear (250 rpm) using a magnetic stirrer. The samples were sheared for different time intervals, namely: 0 min, 1, 5, 10, 20 and 30 minutes to determine the effect of hydrodynamic shear and shearing speed with increasing time. After the allocated shearing time had elapsed, samples were extracted, 2 minutes after ceasing agitation, from the centre of the container used during the shear experiments (5 cm below surface of liquid) and immediately taken for zeta potential analysis.

Figure 4 illustrates different shearing speeds as a function of time. Here it is shown that aqueous samples exposed to a certain shear environment produced effluent with the zeta potential values closest to 0 mV, which relates to an increased probability for colloid destabilization and subsequent solid/liquid separation to occur. This fast-stirring step destabilizes the colloids in suspension and promotes colloid aggregation via the Van der Waal's forces acting upon the particles. The effect of hydrodynamic shear based on zeta potential analysis shows that shear plays an important role in the colloid destabilization. The basic principle of shear flocculation in this study is based on the creation of colloid collisions of sufficient momentum, where the kinetic energy of the particles is sufficient to overcome the surface repulsive force hence allowing the occurrence of particle agglomeration.[55]

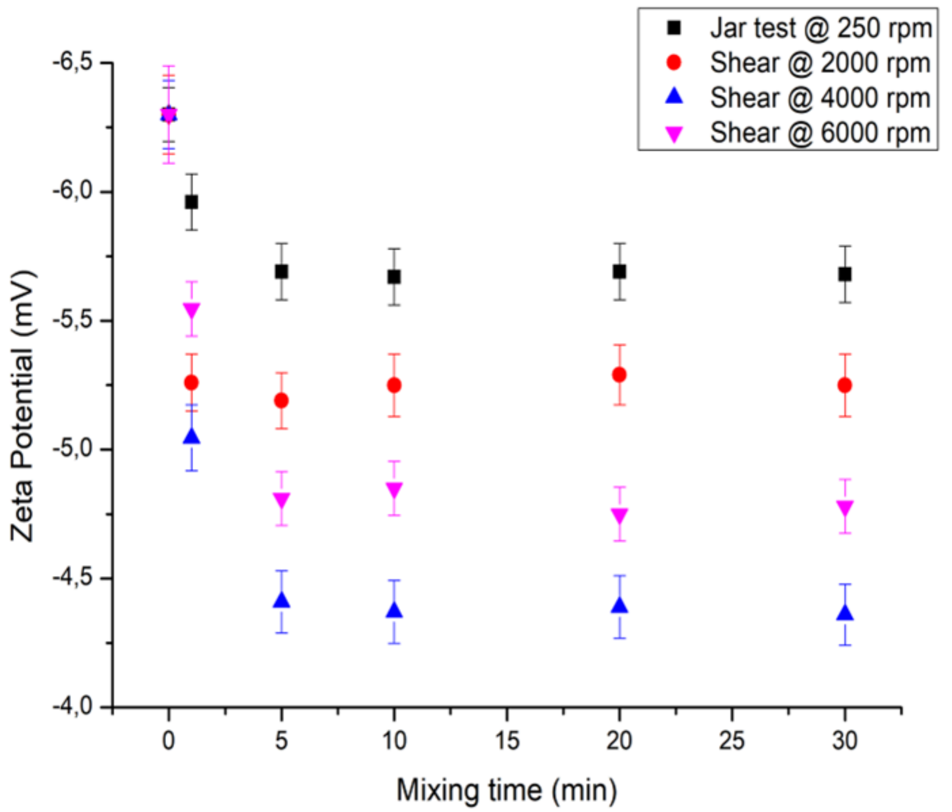

Figure 4. Effect of shearing speed and time (pH 8) oncolloidal stability based on zeta potential.

It should be noted that the purpose of testing zeta potential is to measure the stability of a colloidal suspension. Taking into account that the sample water can be described as a colloidal suspension, the results indicate that at lower mixing speed there is evidence for aggregation of the particles at lower zeta potentials. The optimum shearing speed was observed to be at 4000 rpm, where the lowest zeta potential was obtained. The results indicate that increasing the shearing speed above 4000 rpm caused moderate re-stabilization of the colloids in suspension. In comparison, batch tests conducted at low shearing speeds(250 rpm) displayed a minimal decrease in zeta potential values. The zeta potential results related to the different shearing speed and times illustrate that after 5 minutes of agitation, a plateau is reached. Thus, maximum particle destabilization using shear (both low and high shearing speeds) is obtained after 5 minutes of shearing. At higher mixing speeds, above 4000 rpm there is an increase in the zeta potential inferring a decrease in the colloidal particle size leading to more overall stability.

It can be hypothesized based on the zeta potential analyses, that the surface charge of the particles has been altered during the application of a hydrodynamic shear force. The introduction of hydrodynamic shear in wastewater treatment increases the collision probability between particle/particle and bubble/particle. Based on the increase in number of collisions during the application of hydrodynamic shear, the surface chemistry of the particles may be altered to induce aggregation of the suspended particles to form large clusters which can be removed from the medium via the attachment of bubbles (i.e., flotation).[56,57] According to the work by Elizaveta Forbes (2011), hydrodynamic shear assists in the recovery of fine particles and produces particle aggregates that are capable of attachment to air bubbles and being recovered by flotation.[55]

7.5.4 Zeta Potential Studies on Coagulation

Real-time determination of appropriate coagulant dosage of varying raw effluent quality in a treatment plant is a challenging task due to the nonlinearity relationship between coagulant dosage and raw effluent characteristics.[58] In this work, zeta potential results gave insight to the appropriate dosage of chemicals required to achieve maximum destabilization and agglomeration of particles in suspension. The zeta potential after each incremental addition of coagulant was determined where a change towards zero zeta potential indicates that the added coagulant is destabilizing the colloids in the wastewater i.e., shifting towards colloidal aggregation.

During coagulation experiments, an iso-electric point was observed for the AB121 coagulant (1% w/w solution) under the studied pH ranges which is indicated by the dotted line at 0 mV in **Figure 5**. At the iso-electric point, achieved at a dosage of 5 mg/L (250 µL in 500 mL sample), colloidal particles exist in an optimum destabilization zone where the particles no longer repel one another making these conditions ideal for agglomeration and flocculation to occur. Adding a flocculant at this point would improve the floc size and floc stability.

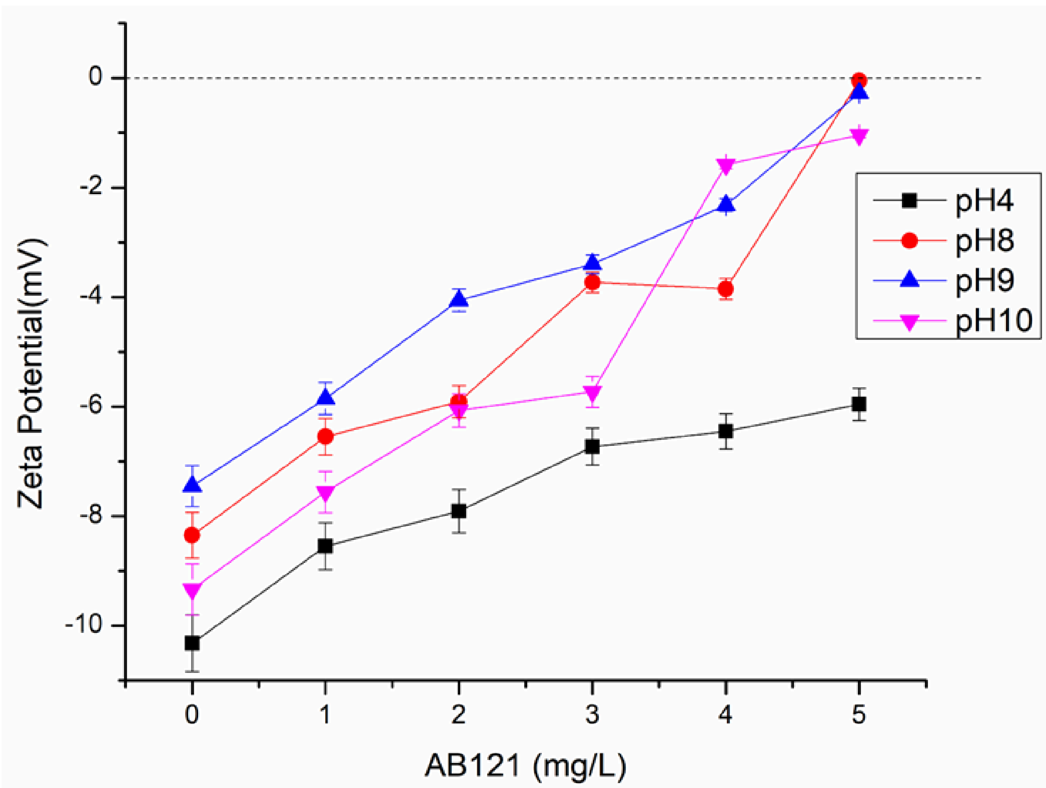

Figure 5. Effect of AB121 coagulant dosage on pH and zeta potential

The coagulant AB121 was thus shown to have effectively neutralized the counterions in solution possibly via the adsorption mechanism as proposed by Lee et al., 2014.[59] Adsorption is possible since this coagulant possesses a specific macromolecular structure containing a variety of functional groups (e.g., carboxyl and hydroxyl) which can interact with the contaminants in the wastewater.[60]

As previously stated, colloids in wastewater are generally negatively charged, but after the addition of a coagulant, these negatively charged colloidal particles are neutralized by the cationic coagulant, resulting in an overall surface charge reduction and formation of micro-flocs. However, the process of coagulation may often result in small and fragile flocs which may break up when subjected to physical forces. To overcome this, flocculant chemicals are added to increase the density and solidity of the flocs formed.59 The following section will investigate the effect of flocculant dosage required to assist the coagulation process. The quality parameters used to evaluate treatment efficiency were total suspended solids and turbidity.

7.5.5 Flocculation

During flocculation studies, the effluent was alkalised to pH 8 using lime, subjected to high shear (4000 rpm) and dosed with 5 mg/L coagulant (AB121). The pre-conditioned samples were subsequently dosed with a flocculant (polyacrylamide polymer, AB796, Abrimix). It is important to note that during the flocculation process, gentle mixing was used (250 rpm using a magnetic stirrer) since a high shear environment used during coagulation experiments would break the formed flocs. Various flocculant dosages (0 – 14 mg/L were investigated. Five minutes after stirring the mixture of flocculant and preconditioned effluent, the stirring was stopped. Two minutes later, the samples were extracted from the centre of the holding container using a micropipette. Both turbidity and the value of total suspended solids (TSS) were measured and results are shown in **Figure 6**. The results illustrate a reduction of 85% in both turbidity and suspended solids when adding 10 mg/l flocculant (500 µL to a 500 mL sample) to the pre-conditioned solution. **Figure 6** also shows the close correlation between turbidity and suspended solids. Further addition of the flocculant (>10 mg/L) appeared to be unnecessary since both the turbidity and TSS remained unchanged.

In a study led by Iakovides et al., (2014) the combined use of polydadmac and hydrated lime (CaOH)2) to treat olive mill wastewater was investigated. Their results indicated that with a lime dose of 20 000 mg/L and between 750 – 2 000 mg/L of polydadmac flocculant, a reduction of 27% in total suspended solids and 43% in total solids was achieved using a mixing speed of 250 rpm.[61] Although the wastewater types were different, the general characteristics of the raw effluent were comparable to that of winery wastewater. Treatment efficiencies of coagulation/flocculation technologies is well documented in literature.[23,24,62,63] A comparison can be made where many authors report on using high doses of chemicals, whilst achieving treatment efficacies generally less than 50% for COD reduction. We therefore postulate that the difference in treatment efficiency may be ascribed to the addition of hydrodynamic shear used in our study.

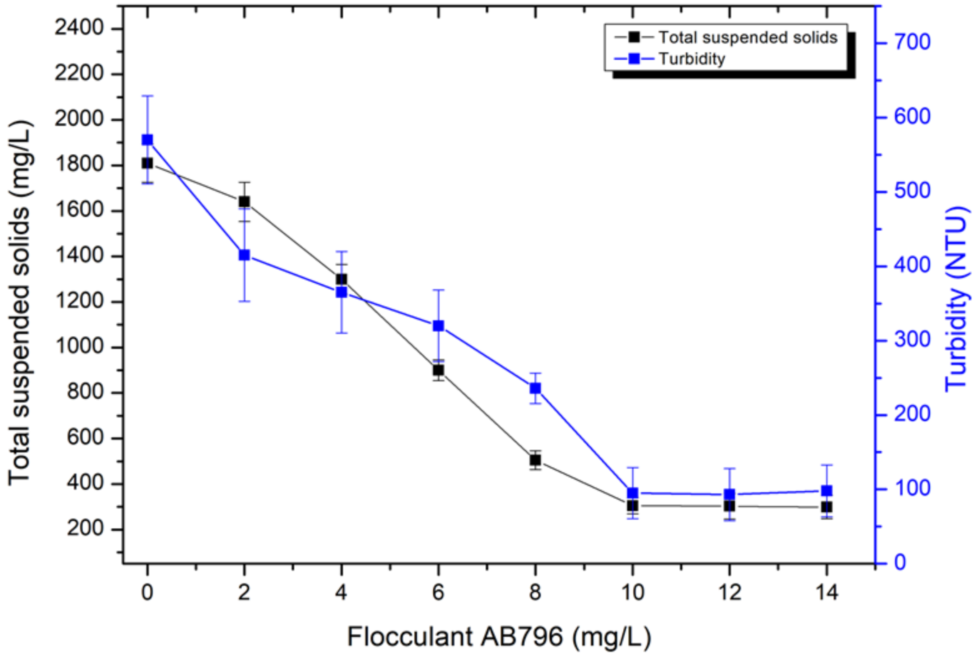

Figure 6. Turbidity and total suspended solids as a function of flocculant dosage

The optimally destabilized particles readily form agglomerates which are "caught" by the polymer chains of the flocculant, resulting in large settling flocs.[64] The flocculant binds the different flocs together and acts as a backbone to the growing floc showing improved mechanical integrity. Most of these flocs settle within the time span of a minute, leaving a clear solution behind with significantly reduced turbidity and TSS values. The process of shear coagulation and flocculation causes the effluent contaminant particles to aggregate sufficiently to allow treatment with dispersed air bubbles to float the aggregates to the surface of the liquid (which can be removed as froth), leaving a clear treated effluent as the subnatant.

7.5.6 Introduction of Air

During the investigation of the final process parameter (the introduction of air in combination with shear/coagulation and flocculation), the effluent was alkalised to pH 8 with lime, subjected to high shear (4000 rpm), dosed with 5 mg/L coagulant (AB121), and finally dosed with 10 mg/L flocculant (AB796). During the shear process air was bubbled into the region of the rotor-stator cavity. Following the addition of coagulation/shear/air, the shear mixer was turned off and the solution was gently mixed at 250 rpm via a magnetic stirrer, in the presence of added air. **Figure 7** illustrates the TSS and the turbidity values of raw effluent (untreated), alkalised (pH 8) and SEFS treated effluents (shear, coagulated and flocculated) with air (i.e., flotation) and without (i.e., sedimentation) the introduction of air (450 L/h) near the rotor stator cavity.

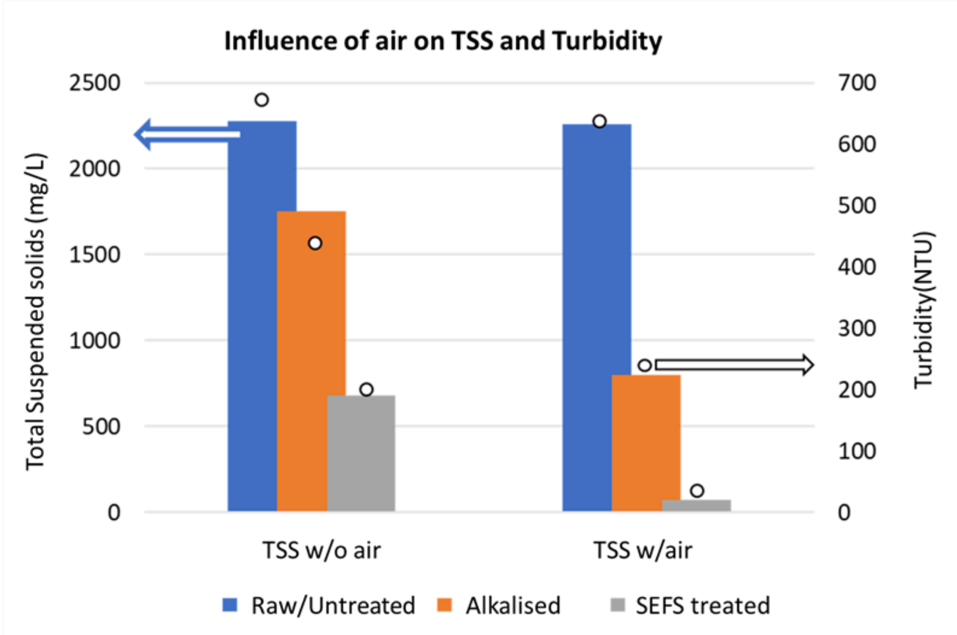

Figure 7. Influence of induced air on turbidity (o) and total suspended solids (blocks)

The small bubbles created by the SEFS rotor were advantageous because smaller bubbles provide a larger surface area which more effectively promotes bubble particle attachment and buoyancy of the suspended solids. Studies have shown that the need to reduce the bubble size is directly related to an increase in the possibility of collision between bubbles and particles.[65]

It is clear that the introduction of air has a positive effect on the quality of treated effluent and confirms that flotation is more effective than sedimentation under the specified conditions (samples were extracted 2 min after the respective procedures, giving very little time for re-sedimentation to occur but sufficient time for flotation). An impressive reduction of 97% and 95% was achieved in TSS and turbidity, respectively when air was introduced during application of shear. Even for the alkalised solution, introduction of (un-sheared) air bubbles lead to a substantial reduction of TSS and turbidity (compare orange blocks in **Figure 7**), possibly facilitated by the well-known coagulating property of lime.[54]

Table 3 shows the values associated with the bar chart shown in **Figure 7**. The raw effluent is effluent sampled from the winery prior to lime, shear treatment, coagulant, flocculant, and air addition. The alkalised sample represents the effluent after lime has been added to increase the pH to 8. The SEFS treated sample represents the alkalised sample which has been exposed to shear (4000 rpm), dosed with 5 mg/L coagulant: AB121, 10 mg/L flocculant: AB796 with and without the introduction of 450 ln/min of air.

Table 3. Total suspended solids (TSS) and Turbidity values of effluent at different stages of treatment.

Sample type	**TSS (mg/L)**		**Turbidity (NTU)**	
	Without air	With air	Without air	With air
Raw effluent	2275	2260	660	635
Alkalized	1750	800	470	280
SEFS treated	680	70	220	30
% Reduction (SEFS vs Raw)	70	97	67	95

The addition of air increased the treatment efficiency of the SEFS reactor. This is shown where a decrease in the suspended solids by 97% (from 2275 mg/L to 70 mg/L) was achieved with the introduction of air compared to the 70% reduction in TSS without air. Similarly, a reduction in turbidity of 95% was achieved with air, whereas only 67% turbidity was reduced without the use of air.

7.5.7 Influence of SEFS on COD

The performance of the SEFS treatment was tested according to its ability to reduce the chemical oxygen demand pre- and post-treatment with and without the addition of air as shown in **Figure 8**. The COD for the SEFS treated effluent yielded a 54% reduction (from 11250 to 5220 mg/L).

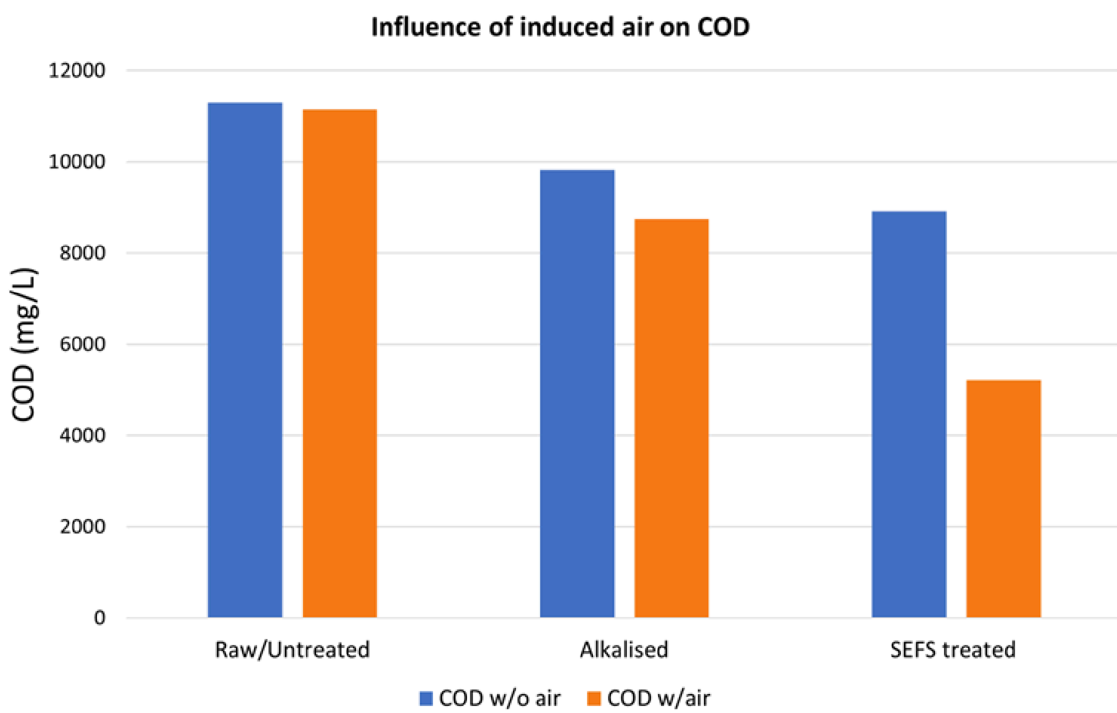

Figure 8. Influence of air on COD reduction.

The optimized particulate destabilization process combined with optimized flocculant dosing, may explain these promising results, especially in relation to suspended solids and turbidity, but not so much for COD. COD value measurements include those originating from both insoluble and soluble organic compounds. The insoluble COD fraction is substantially removed by the synergistic effects of the SEFS process as displayed in **Table 4**. Thus, the smaller reduction in COD compared to the >95% TSS and turbidity is likely SEFS to originate from the continued presence of dissolved organic species after SEFS treatment.

Table 4. COD values of effluent at different stages of treatment

Sample type	**COD (mg/L)**	
	Without air	With air
Raw effluent	11310	11250
Alkalised	9820	8750
SEFS treated	8920	5220
% Reduction (SEFS vs Raw)	21	54

With a COD reduction of 54%, we have shown that SEFS may be considered as an effective primary treatment stage for winery wastewater. Based on both COD reduction and the high reduction values of turbidity and suspended solids, SEFS technology has the potential to be upscaled where a secondary treatment stage such as reverse osmosis can be employed. Through lowering the COD by half and removing most suspended solids using SEFS, upstream biological treatment processes may operate more efficiently.

7.6 Laboratory Study Conclusions

This study focused on the implementation of shear enhanced flotation separation (SEFS) to treat real winery wastewater. We have demonstrated the applicability of this treatment technology with actual wastewater. The individual processing parameters ((pH, chemical dosage, shearing speed and induced air) have been optimized based on the overall treatment efficiency of the SEFS treatment process. A substantial (97%) reduction in total suspended solids (TSS) was achieved using SEFS with initial raw effluent TSS values of 2275 mg/L compared to 50 mg/L for the SEFS treated samples. The reduction in turbidity was (95%) with initial values of 630 NTU for the raw effluent and 25 NTU after SEFS treatment. The results indicate a near linear relationship between turbidity and TSS reductions resulting from SEFS treatment. SEFS technology was also shown to be a suitable technology for the reduction in chemical oxygen demand (COD) of real winery wastewater with reduction values obtained in the study being 54% (raw effluent initial COD: 11250 mg/L versus SEFS treated wastewater COD: 5220 mg/L).

The study highlighted what is achievable with SEFS and shows that this technology may potentially be used as a substitute for conventional primary winery wastewater techniques. Incorporation of an SEFS treatment plant on a winery wastewater treatment site has the potential to alleviate many difficulties in operation turn-around time. SEFS treatment technology may also potentially be used in conjunction with other techniques such as biological treatments and reverse osmosis which will further lower the total COD by reducing the soluble organic content of the treated effluent SEFS.

The optimized results obtained in the laboratory scale were subsequently transferred to the pilot plant situated at the University of the Western Cape. This is discussed in the following section.

8. Pilot Plant Study

8.1 Pilot Plant P&ID

A pilot plant has been designed and assembled to treat winery wastewater at a rate of 5l/min. The Piping and Instrumentation Diagram (P&ID) is illustrated in **Figure 9**, whereas a photograph of the unit is shown in **Figure 10**. The preconditioned winery wastewater (pH adjusted with lime slurry) was introduced and circulated through the unit till the pressure at PG-2 was stabilized at

2.5 bar. At this point only BV-1 and BV-12 were open. After reaching this steady state, various processes and parameters were investigated, which included conventional dissolved air flotation treatment where coagulation (BV-2), flocculation (BV-4) and microbubbles inlet (BV-8, and outlet indicated by the green line (BV-11) and needle valve (NV-1) is opened. A hydrodynamic shear mixing unit was added (pink line) where the wastewater can be exposed to excessive mechanical agitation by way of shear. This is achieved by opening BV-13 and BV-16. The system was designed so that each individual subsystem could be tested as well as to test the synergistic effects of these sub systems.

The sampling points (SP) for each stage of treatment is as follows:

- Coagulation (BV-3 and SP-1)
- Flocculation (BV-5 and SP-2)
- DAF treated wastewater(BV-6 and SP-3)
- Recycled water (BV-7 and SP-4)
- Microbubble infused water (BV-10 and SP-5)
- Sheared wastewater(BV-14 and SP-6)

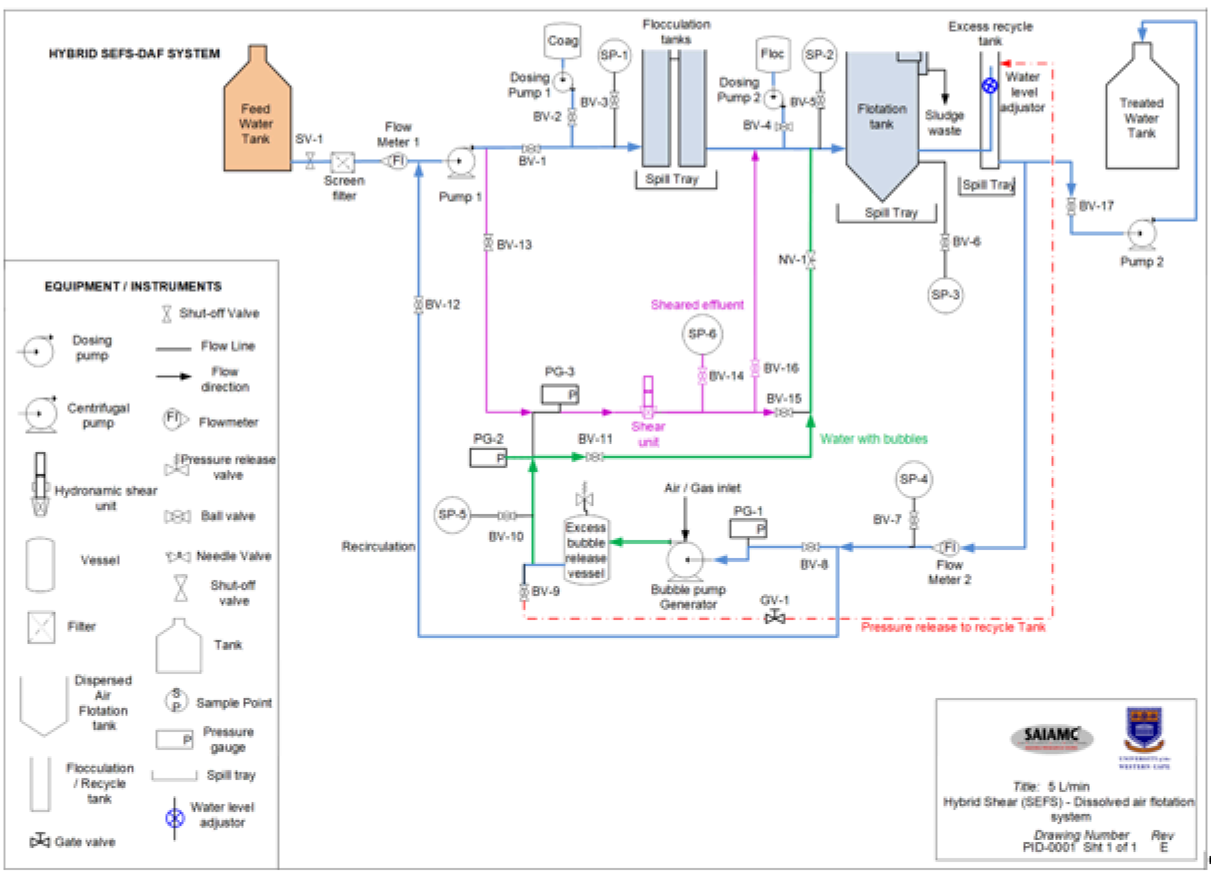

Figure 9. P&ID of the hybrid SEFS/DAF treatment system.

Figure 10. Photograph of Pilot Plant

8.2 High Shear Mixing

The shear unit was fabricated using steel sheets that were assembled to provide a sturdy external framework, accompanied by an internally rotating watertight unit, as illustrated in **Figure 11**. The multi-layered steel structure facilitates the creation of an extended shear gap between the rotor and stator, allowing for the passage of wastewater through an entry and exit point. Rotational speed of the mixer was quantified using a High Precision Tachometer, DT2236E (Addendorff, South Africa). The adopted rotation speed of the shear mixer in this study was determined to be 3250 rpm. This speed was based on optimal changes in surface charge of the particles determined by zeta potential analysis. Increasing the rotational speed of the shear mixer above 3250 rpm had no significant impact on further destabilizing the particles in solution.

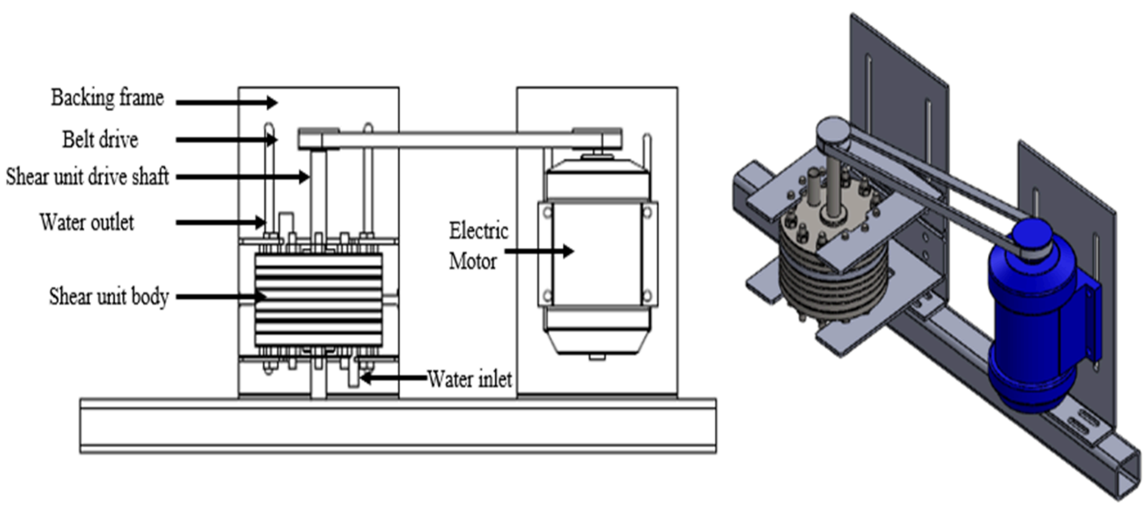

Figure 11. Driving belt connected to the shear unit assembly via an electric motor[28]

8.3 Analytical Methods

8.3.1 Turbidity

The turbidity of the samples was quantified using a Hach TL2350 turbidimeter equipped with a tungsten filament lamp, which was obtained from Agua Africa CC (Hach, South Africa). Turbidity measurements were conducted using the nephelometric method. The turbidity meter allowed for measurement values ranging from 0 to 10,000 nephelometric turbidity units (NTU).

8.3.2 Chemical Oxygen Demand

The term "chemical oxygen demand" generally refers to the quantification of the amount of oxygen required to oxidize the organic matter present in a sample using strong chemical oxidants such as potassium permanganate or potassium dichromate.[66] This test is widely employed as an indicator of wastewater quality.

The COD of the samples was measured using a Thermo Fisher Scientific (Waltham, MA, USA) Orion Aquafast 3140 colorimeter in combination with an Orion COD165 Thermo-reactor. The reagent vials used in this study were the Aquafast COD HR (High Range), 0–15,000 ppm Thermo Fisher Scientific (Waltham, MA, USA).

8.3.3 Zeta Potential

The measurement of zeta potential pertains to the surface charge of particles that are suspended in a medium. Its relevance in the context of wastewater applications lies in its capacity to quantify charge neutralization. The zeta potential is a quantification of the difference in electrical potential between the surface of a particle and the surrounding solution.

The examination of zeta potential (ZP) was performed using a Malvern Zetasizer NanoZS (Malvern Instruments Ltd., Worcestershire, UK) series, which employs the electrophoretic light scattering measurement technique.[44] The investigation focused on analyzing the zeta potential measurements with respect to changes in coagulant dosage and application of various degrees of shear. The laser employed in the Malvern Zetasizer Nano instrument was a 4 mW helium-neon (He-Ne) laser with a wavelength of 633 nm.[44] A dip cell (Malvern Instruments Ltd., Worcestershire, UK) was utilized for the measurement of zeta potential. The dip cell was equipped with palladium electrodes (ZEN1002).

8.3.4 Total Suspended Solids

Total suspended solids (TSS) were determined according to ASTM D5907–18.[67]

8.3.5 Bubble Size analysis

An RS PRO USB Digital Microscope was used to capture images of bubbles produced during the treatment process. This microscope has a magnification ratio of 20× to 230× (optical zoom) and a capture resolution of 1920x1080. The examination of bubble size was performed using the ImageJ software designed for Windows operating system. ImageJ is an open-source Java-based image processing software that is similar to NIH Image, a component of the National Institute of Health in the United States of America.[68]

8.3.6 Particle Size analysis

The particle size of the wastewater was analyzed using a Microtrac S3500 Laser Diffraction Analyzer. Microtrac Laser Diffraction technology uses scattered light from multiple laser beams projected through a stream of particles. The amount and direction of light scattered by the particles are measured by an optical detector array and then analyzed by using Microtrac Software.

8.4 Results and Discussion

The average untreated winery wastewater composition during the 2023 harvest is illustrated in **Table 5**. The data displayed is consistent with the characteristics of the untreated winery wastewater reported in literature.

Table 5. Average untreated winery wastewater characteristics

Sampling Date	**pH**	**Turbidity**	**EC**	**TSS**	**TDS**	**COD**
Sampling Date	(25°C)	(NTU)	(mS/m)	(mg/L)	(mg/L)	(mg/L)
3–7 April 2023	3.2	849	430	2620	1740	11,140

The pH, EC, TSS and COD are specifically important when considering using the wastewater for irrigation purposes as outlined by the general water authorizations in South Africa.48 The legislated limits state that, in order to irrigate with wastewater of up to 50 m3/day, the pH, EC, TSS and COD must fall within the limits of 6-9. <200 mS/m, <25 mg/L and < 5000 mg/L, respectively. Based on the wastewater characteristics presented in **Table 5**., it is evident that intervention is required in order to address the environmental impacts should this wastewater be disposed of in its untreated state.

8.4.1 Shear speed

The effect of shear speed was investigated based on the zeta potential of the colloids as illustrated in **Figure 12**. The adopted rotation speed of the shear mixer in this study was determined to be 3250 rpm. This speed was based on optimal changes in surface charge of the particles determined by zeta potential analysis. Increasing the rotational speed of the shear mixer above 3250 rpm had no significant impact on further destabilizing the particles in solution.

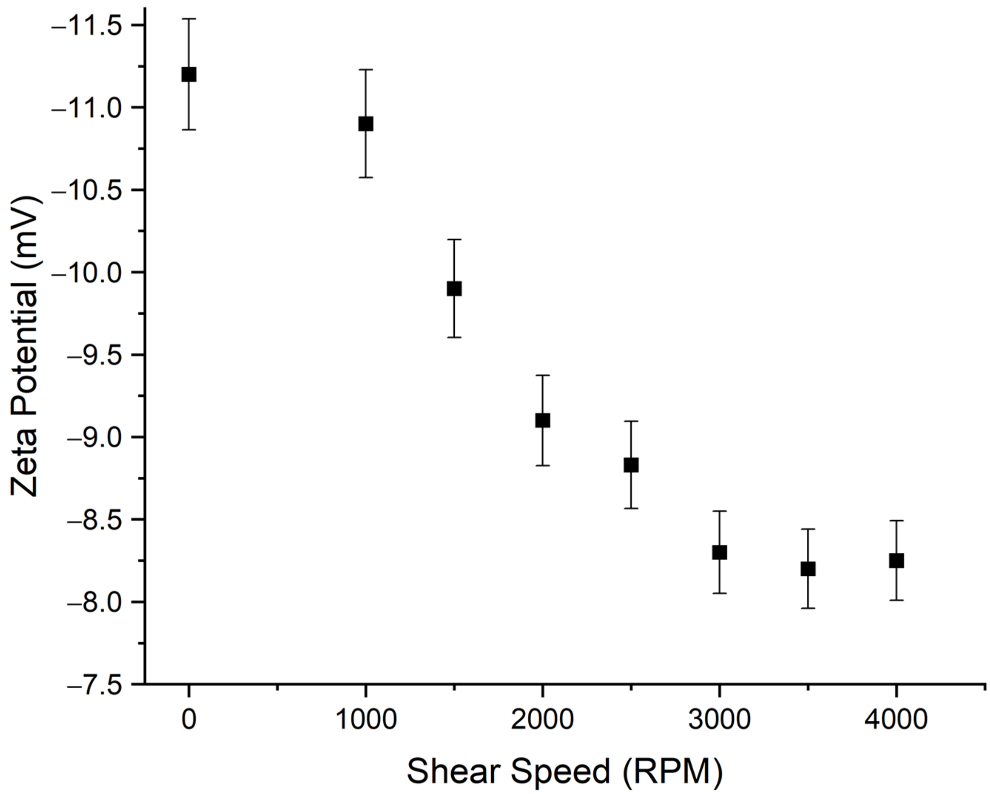

Figure 12. Shear speed as a function of Zeta Potential.

8.4.2 Particle Size Distribution

The particle size of untreated and treated wastewater is shown in **Table 6**.

Table 6. Particle size (in μm) of winery wastewater.

Sample	d10[1]	d50[2]	d90[3]
Untreated	2.205	7.99	34.45
DAF	5.49	15.36	40.79
SEFS	10.49	23.65	56.19

1) Size of particles in microns below which 10% of the sample lies.
2) Size of particles in microns at which 50% of the sample is smaller and 50% is larger.
3) Size of particles in microns below which 90% of the sample lies.

The particle size distribution of untreated, DAF and SEFS treated wastewater is shown in **Figure 13**.

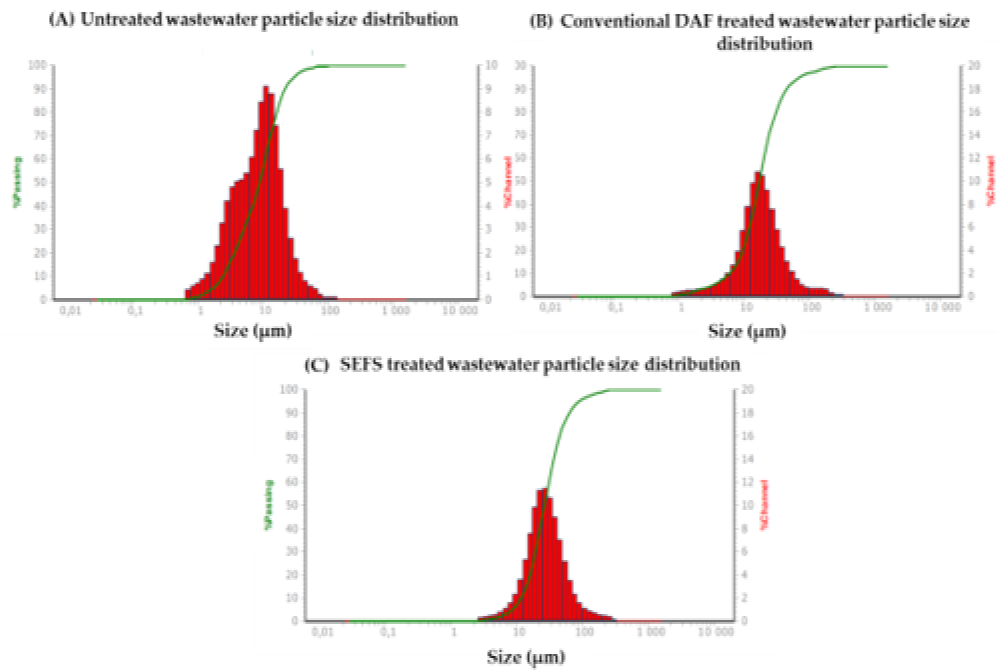

Figure 13. Particle size distribution of (A) Untreated, (B) Conventional DAF and (C) SEFS treated winery wastewater.

The particle size distribution (PSD) from **Table 6** and **Figure 13** displays a general increase in PSD from untreated to conventional DAF and SEFS treated wastewater. The particles contained in the untreated wastewater had mean diameters (D50) of 7.99 µm. When the wastewater was subjected to DAF treatment (in the absence of hydrodynamic shear), the average D50 particle size was 15.36 µm. The increased in particle size may be attributed to the effect of coagulation and flocculation processes which induces the process of particle destabilization by charge neutralization followed by bringing together the destabilized particles form a larger agglomerates which are removed during flotation.[23] The SEFS treated wastewater on the other hand, displayed average D50 particle size values of 23.65 µm. This significant growth in particle size is attributed to the hydrodynamic shear mixing which induces agglomeration and subsequently causes a degree of colloidal destabilization of the particles in solution.[73] It is reported in literature that particles agglomerate faster when exposed to shear due to an increase in particle collisions.[74] This confirms our findings where hydrodynamic shearing altered the particle sizes, subsequently enhancing the separation process.

8.4.3 Zeta Potential Analysis

In aqueous systems, it is common for solid particles to possess various surface charges. These charges are often counterbalanced by oppositely charged counterions present in the solution. The resulting structure is commonly referred to as the electric double layer (EDL).[75] Electric double layers have a significant impact on the physical and chemical properties of heterogeneous systems. The EDL model is a key concept for understanding how electrostatic force works and how it affects the stability of colloids. Therefore, it is important to have methods that can accurately determine the charge state of solid surfaces in relation to key solution factors, such as pH, ionic strength, or solute composition. The zeta potential is often used to deduce and represent significant physical and chemical characteristics of interfacial systems, including aqueous particle suspensions, due to its association with surface charges. This extends to the factors influencing of colloidal stability and aggregation.[76]

Figure 14 illustrates the correlation between the zeta potential and each respective treatment phase.

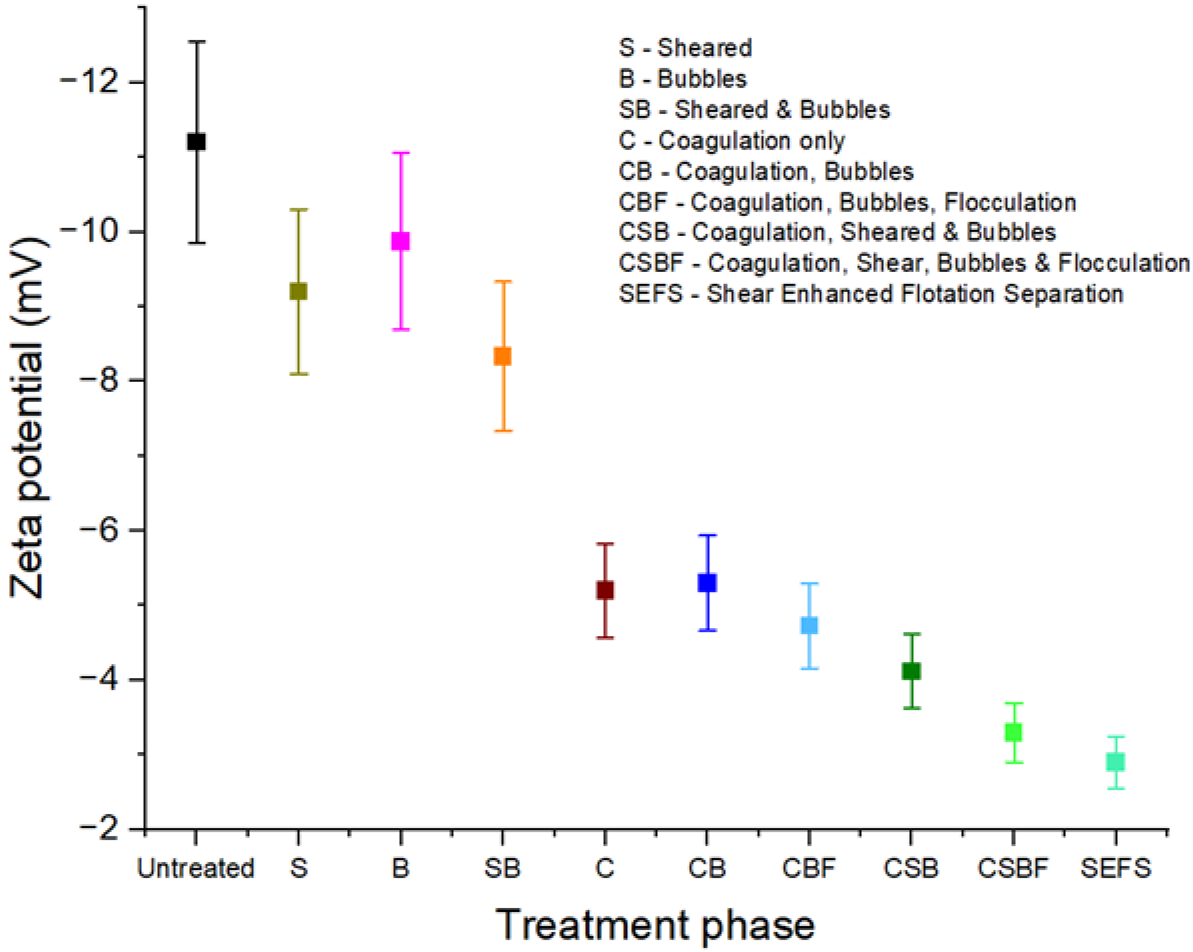

Figure 14. Zeta potential as a function of treatment phase.

The zeta potential as a function of treatment displayed a general trend where each successive treatment phase affected the surface charge of the particles. The raw effluent displayed zeta potential values of -11.4 mV. When exposed to shear, the average zeta potential observed for the solution was -9.2 mV, (a 19% change in zeta potential). In contrast, when bubbles were used, the zeta potential was observed to increase to -9.8 mV (become more negative). The observed negative zeta potential of the microbubbles in water can be attributed to the adsorption of OH− ions at the interface of the bubbles, originating from the water molecules.[77] Microbubbles have a comparatively elevated zeta potential, and empirical findings indicate that the pronounced negative charge of microbubbles restricts their coalescence. Consequently, the structural integrity of the bubbles is preserved at various depths and can remain intact for prolonged durations.[78]

The introduction of the coagulant caused the zeta potential to change significantly from -8.2 mV with shearing and bubbles (in absence of coagulant) to -5.4 mV (after coagulation). This change in zeta potential is attributed to the positive counterions added during coagulation which induces adsorption of ions and subsequent neutralization of surface charges. Conventional DAF samples labelled in **Figure 14** as CBF (coagulation, bubbles and flocculation) caused surface charge reduction to -4.2 mV. The CSBF as denoted in **Figure 14** relates to the post treatment and taken via the recycle sample line (SP-4). The SEFS samples on the other hand were taken directly from the DAF tank exit point (SP-3). Synergistic effects of shear, coagulation, flocculation and flotation (SEFS/CSBF) collectively enhanced the overall destabilization of colloidal particles in the wastewater in comparison to conventional DAF treatment (CBF).

8.4.4 Influence of Microbubbles

Many researchers have debated the definition of microbubble sizes. For example, Agarwal et al., (2011), described these as small bubbles with sizes ranging from 10 to 50 µm.[79] Interestingly, Takahashi et al., (2007) classified these particular bubbles as having diameters less than 50 µm.[80] In a separate investigation by Terasaka et al., (2011), the microbubbles were categorized as small bubbles, with dimensions ranging from 10 to 60 µm, according to their specific field of use within a study examining physiological activity.[81]

Relating the bubble size presented in **Figure 15** to the particle size in **Figure 13**, it can be inferred that the separation process is more effective when the bubble size and the particle size are at the same order of magnitude. For example, the average bubble size of the conventional DAF treatment was 126 µm. In comparison, that of the SEFS treated wastewater was 62 µm. The shear unit creates a highly turbulent environment and increases the collision probability between colloids and bubbles which effectively enhances the solid/liquid separation process as opposed to that without shearing in conventional DAF treatment. By increasing the collision frequency between bubbles and particles and capture efficiencies, greater separation efficiencies can be achieved.[57]

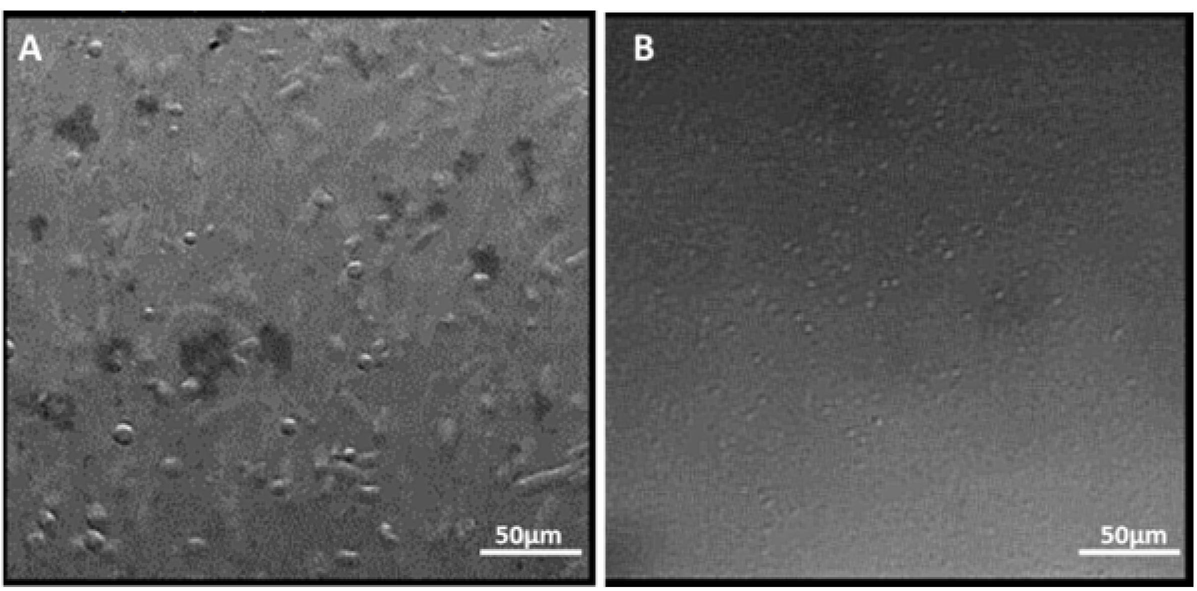

Figure 15. Snapshot of Bubble Size analysis of (A) Conventional DAF and (B) SEFS treatment.

A total of 1456 bubbles were quantified and the different bubble size bins are illustrated in **Figure 16**. The mean conventional DAF bubble size (**Figure 16A**) fell within the bin range of 50 – 150 µm, representing roughly 60% of the bubble's sizes. According to various literature studies, these bubble sizes are well within the reported range for DAF treatment of wastewater.[53,82,83] When the wastewater was exposed to hydrodynamic shear (**Figure 16B**), the frequency of smaller microbubbles was observed to increase. The bubble size in the range 50 –

100 μm was 30% more with shear treatment than conventional DAF treatment. Furthermore, unlike the DAF treated wastewater, the SEFS treatment generated bubbles with sizes less than 50 μm. The enhancement in the frequency and quantity of smaller bubbles (< 100 μm) may therefore explain the higher removal efficiencies using a shear mixer. Wu et al., (2015), similarly stated that smaller gas bubbles and their ability to increase the contact area (spreading of the gas bubble on the particle) creates an environment where the hydrodynamic disruptive shear force remains stable.[84] In other words, microbubbles induced by hydrodynamic shear selectively attach to micron size particles while still keeping their mechanical strength and integrity.

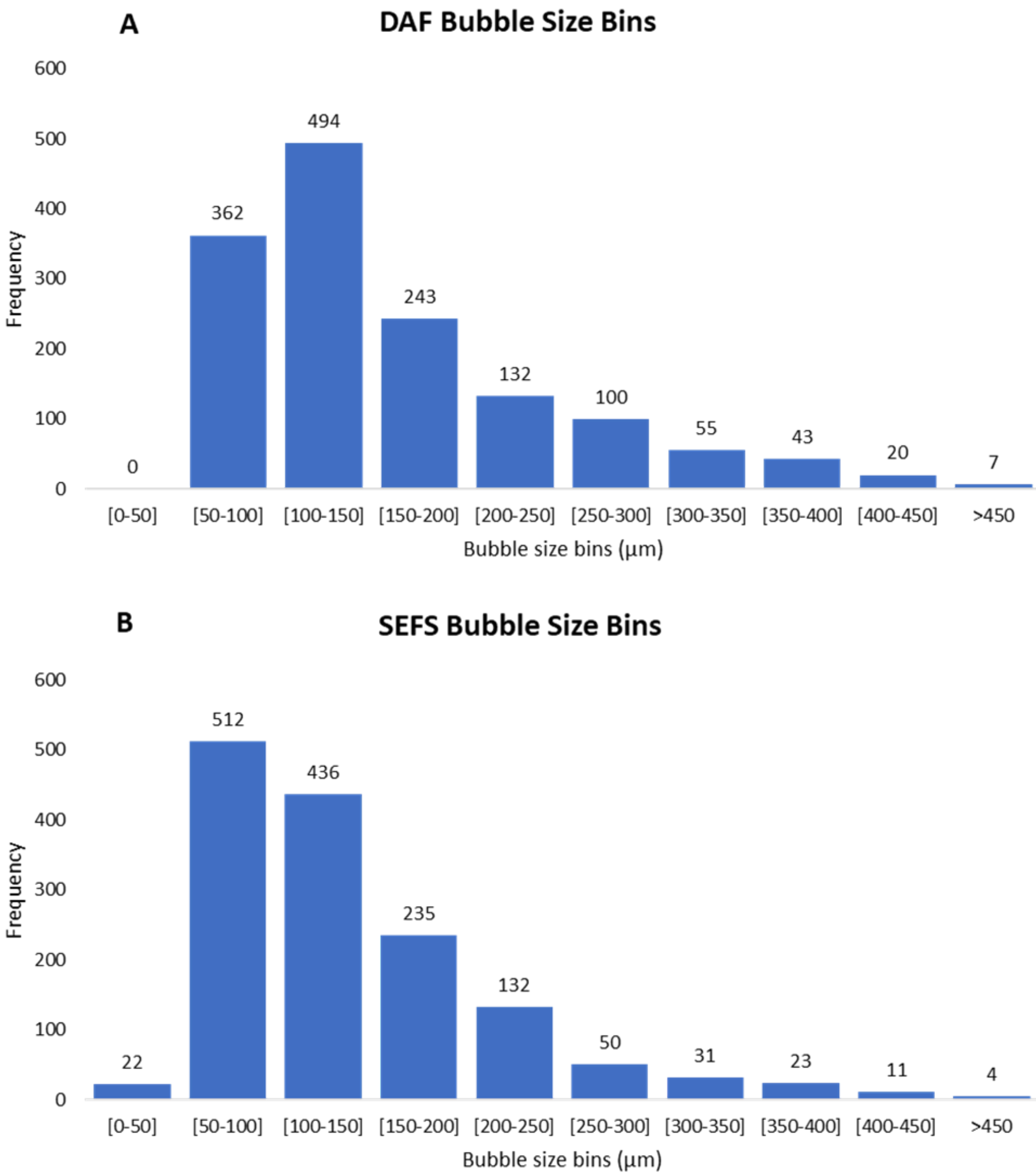

Figure 16. Histogram of bubble sizes for (A) conventional DAF and (B) SEFS treated wastewater.

The beneficial nature of the smaller sized microbubbles generated by the shear mixer stems from its ability to offer a larger particle surface area, which enhances the attachment of particles to the bubbles and facilitates the buoyancy of the suspended solids. Research findings indicate that a clear correlation exists between the necessity to decrease bubble size and the heightened likelihood of collisions occurring between bubbles and particles.[65] The importance of bubble size and particle size in relation to treatment efficiency is evident during turbidity and total suspended solids studies in the following sections.

8.4.5 Turbidity and Total Suspended Solids

Figure 17 illustrates turbidity values as a function of the treatment phase. Turbidity refers to the measurement of the relative transparency of a liquid and quantifies the optical property of water. More specifically, the quantification of light scattering caused by the presence of particulate matter within a water sample, when illuminated by a light source. High concentrations of particulate matter affect light penetration, subsequently leading to elevated turbidity values.
Turbidity values depicted in **Figure 17** show that with each treatment phase, the turbidity systematically decreased, with untreated wastewater having turbidity of 849 NTU, whereas the final (SEFS) treated wastewater had values similar to that of drinking water (3 NTU). The slight increase in turbidity for the samples only exposed to bubbles (labelled as B in **Figure 17**) can be explained by the flotation mechanism free of chemical additives, disturbing the solution equilibrium which leads to a higher degree of suspended particles in solution.

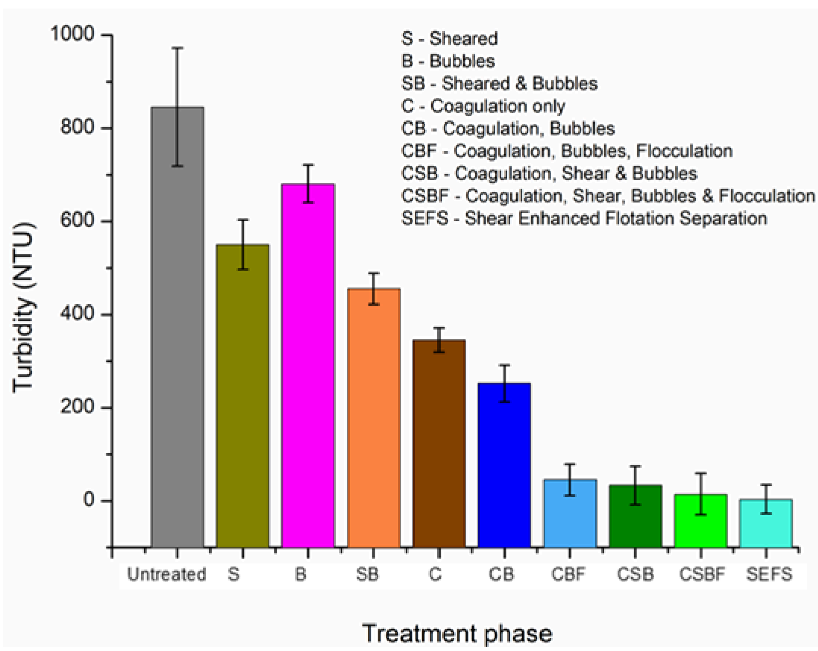

Figure 17. Turbidity studies as a function of treatment phase.

Table 7 shows the TSS and turbidity treatment values of the wastewater and compares the difference between conventional DAF treatment and the addition of shear during SEFS treatment.

Table 7. Total suspended solids (TSS) and Turbidity values of wastewater at different stages of treatment.

Sample Type	TSS (mg/L)		Turbidity (NTU)	
Sample Type	Conventional	SEFS	Conventional	SEFS

	DAF		DAF	
Untreated	2620	2620	849	849
Treated	75	17	35	3
% Treatment Efficiency (Treated vs. Untreated)	97	99	96	99

The data presented in **Table 7** illustrates that a significant reduction in both TSS and turbidity was achieved with both treatment methods. However, when exposed to shear, the treatment efficiency increased for both TSS and turbidity quality parameters. These values are further complemented with the visual differences in haziness as depicted in **Figure 18**.

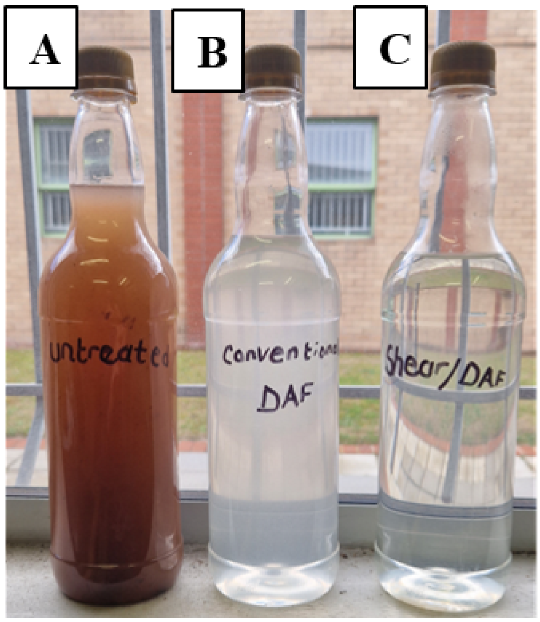

Figure 18. Visual comparison between (A) Untreated, (B) Conventional DAF, and (C) SEFS treated wastewater.

8.4.6 Chemical Oxygen Demand

The efficacy of the SEFS treatment was evaluated by assessing its capacity to decrease the chemical oxygen demand before and after treatment is depicted in **Figure 19**. The chemical oxygen demand (COD) of the wastewater treated with conventional DAF displayed values of 5490 mg/L with initial COD for the untreated wastewater having a value of 11,140 mg/L. The SEFS treated wastewater resulted in a significant reduction of 66%, decreasing from an initial concentration of 11,140 mg/L to 3,800 mg/L.

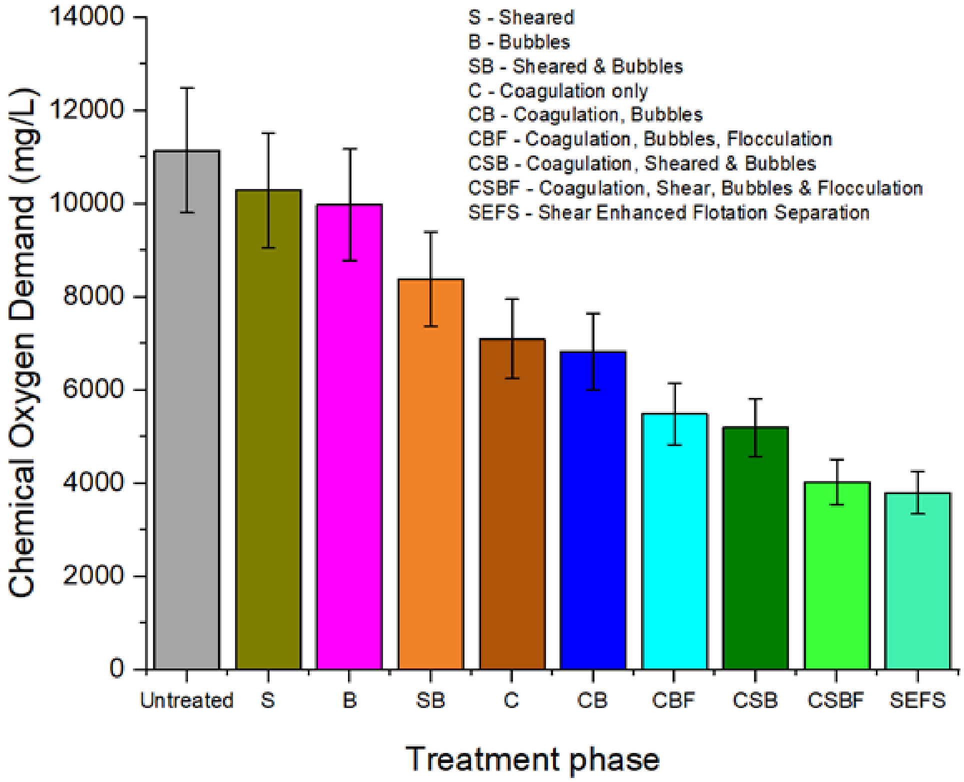

Figure 19. Chemical Oxygen Demand as a function of treatment stages.

The positive results, particularly in terms of suspended solids and turbidity, can primarily be attributed to the synergistic effects of the enhanced particle destabilization process and the flotation phenomenon. However, it is worth noting that the impact on COD levels appears to be less pronounced than on the TSS and turbidity. The SEFS procedure effectively eliminates a significant portion of the insoluble COD component, as demonstrated by the data presented in **Table 8**. Hence, the relatively lower percentage decrease in chemical oxygen demand (COD) in comparison to an average of 96% reduction in total suspended solids (TSS) and turbidity, respectively, for conventional DAF and average of 99% reduction in TSS and turbidity for SEFS treated wastewater is likely attributable to the residual dissolved organic compounds present in the wastewater.

Table 8. COD values of wastewater at different stages of treatment.

Sample Type	COD (mg/L)	
Sample Type	Conventional DAF	SEFS
Untreated	11,140	11,140
Treated	5490	3800
% Treatment Efficiency (Untreated vs. Treated)	51	66

A comparison between chemical requirements with and without shear is presented in **Table 9**. The differences observed can be explained by the different mechanisms of aggregation. During conventional DAF treatment, the aggregation is governed by the Brownian motion of the particles (perikinetic aggregation). In contrast, the formation of aggregates when an external flow field is applied such as shear mixing, produces orthokinetic aggregates. Orthokinetic aggregation has been shown to enhance the aggregation rate of colloids compared to Brownian mechanisms.[85] Furthermore, hydrodynamic shearing has the advantage of intensifying chemical reaction processes with fast inherent reaction rates but relatively slow mass transfer rates.[86]

Table 9. Chemical requirements: Conventional DAF versus SEFS.

Parameter	Conventional DAF	SEFS	% Difference
Shear Speed (RPM)	0	3250	-
Coagulant Concentration (ppm)	4.4	2.8	36.4
Flocculant Concentration (ppm)	10.3	7.1	31.1

Cagnetta et al., (2019) conducted a study to evaluate the efficacy of dissolved air flotation (DAF) in combination with a pilot-scale high-speed activated sludge system at the municipal water treatment plant in Aartselaar, Belgium. Following activated sludge and DAF treatment, their findings indicated a reduction of 78% in TSS and 68% in COD.[87] In comparison, the results of our study indicate that the SEFS treatment caused a significant reduction in chemical oxygen demand (COD) of 66% compared to 51% using conventional DAF treatment, without using any other additional technologies (such as activated sludge in the previously mentioned study by Cagnetta et al., (2019). Our findings suggest that SEFS treatment holds promise as a viable and efficient method for treating winery wastewater. SEFS technology exhibits promising potential for upscaling, as seen by its effective COD reduction and high reduction values for turbidity and total suspended solids. This suggests that SEFS technology could be successfully implemented on a larger scale, particularly in conjunction with a secondary treatment stage such as membrane bioreactors.

8.4.7 Froth Analysis

The general process of DAF treatment produces various quantities of froth. In the process of dissolved air flotation, the initial step involves pressure to achieve air saturation. Subsequently, the water that has reached its saturation point undergoes pressure release to atmospheric level leading to the creation of microbubbles.88 The introduction of microbubbles in the flotation tank facilitates their interaction with the contaminants present in the water. Ultimately, the bubbles become affixed to the contaminants and ascend to the water's surface, forming a foam composed of complexes composed of bubbles and pollutants. This froth theoretically should consist of a vast majority of the particulate material that was floated during winery wastewater processing. A dense and concentrated form of froth was generated as shown in **Figure 20**.

Figure 20. Froth produced during the SEFS treatment process.

The soil used by the winery in our case study mostly contains sand and 1% stone. At a depth of 30cm, the soil has a pH of 6.1 and is saturated with Na (5.6%), K (3.5%), Ca (45.9%) and Mg (20%). As with any crop, grapevine development and output depend on proper nutrition. The primary nutrient influencing grapevine health and quality is nitrogen. The incorporation of potassium has been found to enhance grape productivity, primarily by enhancing both grape cluster quantity and weight.[89] Both calcium and magnesium are essential nutrients, required for optimal grapevine performance. Generally, these nutrients are abundant in soils with pH values within the optimal range, making fertilization of these nutrients unnecessary.[90] In order to consistently produce grapes of high quality, fertilizers are primarily used in agriculture. One of the aims of this research was to investigate the contents of the froth to determine its potential suitability for use as fertilizer. **Table 10** displays the characteristics of the froth as well as that of a commercially available fertilizer.

Table 10. Macronutrient chemical composition of froth and commercial fertilizer.

Element	Unit of measurement	Conventional DAF	SEFS	Commercial Fertilizer
Ca	(%)	1.7	1.9	8.2
Mg	(%)	3.1	3.4	5.7
S	(%)	7.9	7.8	8.1
N	(%)	6.1	5.8	17.1
P	(%)	4.2	3.9	14.2
K	(%)	2.6	2.8	18.5

The values depicted in **Table 10** suggest that regardless of adding shear to the treatment process, the composition of the froth remained similar. The commercial compost showed ideal values for crop growth. In comparison, the pilot plant treated water does not meet the requirements for the solid waste to be used as fertilizer in its current state. A study was conducted by Conradie et al., (2020) which investigated the annual nutrient requirements to produce 30 tonnes of grapes per hectare in South Africa. They stated that the macronutrients (N, P, K, Ca and Mg) required to produce one tonne of grapes is (N) 3.93 kg/ha, 0.7 kg/ha (P), 3.2 kg/ha (K), 2.77 kg/ha (Ca) and 0.77 kg/ha (Mg).[90] Our froth analysis results in **Table 10** showed the presence of important nutrients for crop growth albeit in small percentages in comparison to the commercial fertilizer. The effects of adding dried foam to the soil will, however, need to be investigated in a future study. The elements, particularly nitrogen, phosphorus, potassium and sodium in the froth did not show alarmingly high levels which may be harmful to the soil and the environment if mixed with commercial fertilizer.[91] The breakdown of organic matter in the soil releases nutrients that plants may absorb, such as potassium, phosphate, and nitrogen, which lowers the amount of fertilizer needed by the vines.

8.4.8 Pilot Plant Energy Requirements and Cost to Treat Winery Wastewater

The treatment efficiency of both conventional DAF as well as SEFS have been discussed in section 5.3. **Table 11** displays the power consumption values for each parameter during treatment.

Table 11. Energy consumption during wastewater treatment.

	Power Consumption(kWh/m^3)
Inlet Pump	0.032
Coagulant Dosing Pump	0.048
Flocculant Dosing Pump	0.076
Microbubble Generator	0.418
Shear Mixer	0.478
Outlet Pump	0.034

The energy consumed to treat 1 m^3 of winery wastewater using conventional DAF amounted to roughly 0.6 kWh/m^3 whereas the SEFS treatment energy was 1.1 kWh/m^3, as also illustrated in **Figure 21**. The quality of the treated wastewater may outweigh the total energy expenses even though SEFS treatment requires more energy than DAF treatment, as shown in **Table 11**.

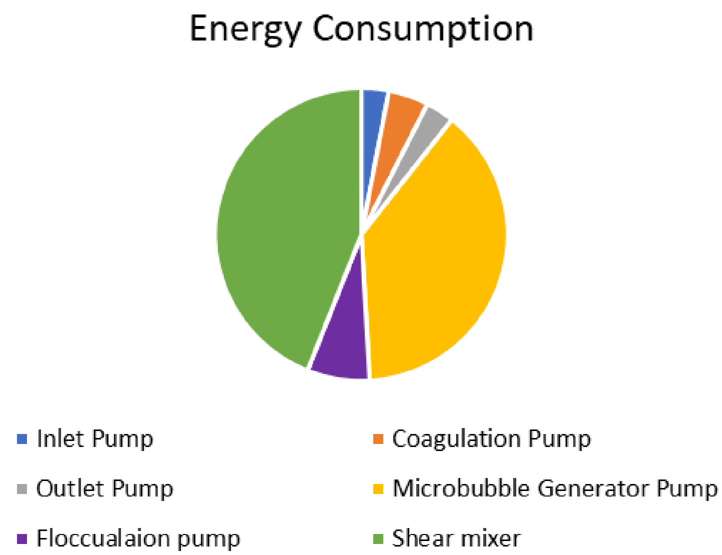

Figure 21. Energy consumption of individual treatment process

Table 12 illustrates the operational and materials costs during the treatment of 1 m^3 of winery wastewater. Considering the achieved outcomes, particularly the treatment efficiency, the added energy input expenses of the SEFS treatment system are thus considered reasonable. More specifically, the results highlight the cost saving during chemical treatment with SEFS. Wineries that opt for SEFS treatment have the potential to reduce both their overall energy expenditures (e.g., from secondary treatment processes) and their expenses related to wastewater disposal.

Table 12. Material and operational costs to treat 1 m^3 of winery wastewater.

Material and Operational Costs			
	Units	DAF	SEFS
Energy consumed	kWh/m^3	0.6	1.1
Coagulant	ZAR/ m^3	R0.86	R0.37
Flocculant	ZAR/ m^3	R0.34	R0.13
Energy cost in ZAR	ZAR */kWh	R1.09	R1.95
Total cost per/m^3	R	R2.29	R2.45
Treatment Efficiency			
TSS	%	97.1	99.4
Turbidity	%	95.8	99.6
COD	%	51	66

8.4.9 Pilot Plant Study Conclusions

This chapter focused on the development and implementation of a hybrid shear enhanced flotation separation (SEFS) pilot plant for the treatment of winery wastewater. It comprised of the individual and synergistic effects of chemical additives and microbubbles, with and without shear. To the best of the author's knowledge, this study represents one of the first instances in which hydrodynamic shear has been incorporated as a treatment component in winery wastewater treatment. Hydrodynamic shear has been demonstrated to be a component that improves treatment efficiency overall. The energy consumption for DAF treatment was 0.6 kWh/m^3, whereas that of SEFS treatment was 1.1 kWh/m^3. Total material and operation costs are R2.29/m^3 for DAF and R2.45/m^3 for SEFS. Nevertheless, the small additional costs of SEFS are justified by the improved treatment efficiencies achieved by SEFS when compared to DAF.

The SEFS treatment resulted in a significant reduction of 99.6% in turbidity (from 849 NTU to 3 NTU) and 99.4% in TSS (from 2620 mg/L to 17 mg/L). In comparison, the conventional DAF achieved a reduction of 95.9% in turbidity (from 849 NTU to 35 NTU) and 97.1% in TSS (from 2620 mg/L to 75 mg/L). The SEFS treatment furthermore achieved a 66% reduction in chemical oxygen demand values, decreasing them from 11,140 mg/L to 3800 mg/L. The conventional DAF treatment system achieved a 51% decrease in COD, reducing it from 11,140 mg/L to 5490 mg/L. However, the remaining concentration of COD in the wastewater may be attributed to the soluble portion, which could not be eliminated through the use of SEFS or DAF treatment.

It was demonstrated that shear not only improves treatment effectiveness, but it also requires 33% less coagulant and 37% less flocculant compared to conventional DAF treatment. Another advantage of SEFS is that you do not need to go through floc tanks for flocculation to be successful. The differences in COD reduction between the two treatment methods can be ascribed to the increased agglomeration of particles and the generation of smaller bubbles during shear, resulting in an increased likelihood of collision between bubbles and particles. The higher frequency of microbubbles within the 0 – 100 µm range in SEFS treatment resulted in an enhancement in flotation and overall improvement in the separation of solids and liquids compared to DAF treatment.

The analysis of solid waste indicated that the froth produced during the treatment procedure may be a viable fertilizer component due to the presence of valuable nutrients such as sodium, nitrogen and phosphorus. Prior to utilizing this solid waste as a component for commercial fertilizers, it is important to conduct an in-depth study on the potentially detrimental or advantageous characteristics of the froth when applied to soil.

The value of SEFS technology in treating agricultural wastewater has been demonstrated, and it may also be useful for treating other types of wastewater, such as pharmaceutical and municipal wastewater.

8.4.10 Overall Lab and Pilot Plant Conclusion

The results obtained during the SEFS lab and pilot plant study indicated that:

- The research team developed a solid understanding on the mechanisms involved in the destabilisation of suspended solids in winery wastewater, including the analytical techniques to verify these mechanisms.
- Optimal laboratory scale SEFS conditions for winery wastewater were established leading to 97% and 95% reduction of SS and turbidity respectively when compared to

the raw effluent. These values are achieved within minutes of operation.

- Optimal pilot scale SEFS conditions for winery wastewater were established leading to an excess of 99% reduction of both SS and turbidity.
- Optimal flotation conditions for winery wastewater were established leading to 54% and 66% reduction of COD for experiments conducted at laboratory and pilot scale respectively.
- The solid (froth) generated after winery wastewater processing presented potential use as fertilizer, however, the effects of adding the dried froth to the soil will need to be investigated in a future study.
- The PhD regarding this section has been finalized and David Vlotman will be graduating in September 2024.

9. Economic analysis of the Shear enhanced Flotation Separation (SEFS) technology for winery wastewater treatment

9.1 Introduction

From an accounting perspective, wastewater treatment plants at businesses, including wineries, are treated as cost centres. This is due to the fact they are primarily associated with the management and disposal of wastewater generated by the wine making operations. These facilities are essential for environmental compliance and the avoidance of potential liabilities, such as fines; however, they do not contribute directly to revenue generation.

Wastewater treatment operations and facilities at wineries, typically fall under the maintenance department and don't contribute directly to the overall financial bottom line. These facilities play a crucial role in the overall functioning and facilitate the smooth operation of the revenue generating departments. Like all cost centres, wastewater treatment facilities don't generate profits, effective management of these units is vital for controlling costs and optimizing operational efficiency. By managing wastewater treatment costs efficiently, the winery can enhance their overall profitability and environmental compliance. Additionally, cost centres are essential for meeting regulatory compliance, maintaining employee satisfaction and ensuring the smooth functioning of the overall winery.

Reasons why wastewater treatment plants are often classified as cost centres:

- Regulatory Compliance: Wineries are required to adhere to environmental regulations that dictate the proper treatment and disposal of wastewater. Wastewater treatment plants are necessary to meet these regulatory standards, however as highlighted above compliance does not generate revenue.
- Operational Costs: Running and maintaining a wastewater treatment plant involves various costs, including labour, energy, chemicals, equipment maintenance and monitoring. These costs are considered necessary for the proper functioning of the plant but do not contribute directly to revenue.
- Risk Mitigation: Proper wastewater treatment is crucial for mitigating environmental risks and avoiding potential legal and financial consequences associated with environmental violations. While avoiding these risks is important, it also does not generate revenue.
- Corporate Social Responsibility (CSR): Maintaining a wastewater treatment facility is

often part of a company's commitment to corporate social responsibility and sustainable business practices. While this can enhance a company's reputation, it doesn't necessarily result in direct financial gains.

That being said, some wineries often explore ways to optimize their wastewater treatment processes to reduce costs and improve overall processing efficiency. Wineries in certain areas may explore opportunities to recycle and reuse wastewater and in turn saving cost.

9.2 Estimating the costs and benefits of upgrading the Winery X effluent plant.

The cost benefit analysis method with its estimation tools is to assist the Winery's management team in understanding the upsides and downsides of remaining with the current wastewater treatment system or to make a capex (capital expenditure) investment to upgrade it. This analysis method seeks to guide Winery X to understand possible benefits and limitations of adopting a new system to improve their environmental wastewater compliance levels.

Winery X has an average wine production capacity of 30,000 m^3/a and a wastewater effluent stream of 49,000 m^3/a, which is approximately 163% of the wine production, indicating that Winery X is doing better than many other wineries.

Winery X is currently confronted with compliance challenges, where it is required to comply with set municipal discharge limits. For example, the chemical oxygen demand (COD) levels of post-treated wastewater at Winery X are currently 2,000 ppm while the legal limit is set at 400 ppm. Data collected from Winery X in 2020 indicated that the wastewater discharged by Winery X had a COD and electrical conductivity (EC) exceeding the limits for 9 months, while the pH of the discharged wastewater was above the municipal limits for 3 months. Currently the winery does not incur any compliance costs; the municipality only acknowledges their efforts on striving to comply with the limits.

Apart from complying with municipal standards, the effluent also produces a foul odour, which the winery has been trying to eliminate for the last few years. The treated wastewater is not potable or not reusable and is currently discharged to a field.

Winery X approached SA WIne to assist with a possible solution to these issues. SA WIne in partnership with the University of the Western Cape which has analysed the existing system and has proposed possible alternatives to the winery.

The proposed systems to improve the compliance levels of the discharged wastewater involves a capex investment for all scenarios modelled. The three options modelled for Winery X includes:

- ☐ Option 1, keep the existing system and do nothing, continue with non-compliance and emit a stench. This option was also modelled with fines for non-compliance of the treated wastewater.

- ☐ Option 2, involves upgrading the existing system, which includes an installation of a flotation device between the neutralisation pit and dam 3. Winery X would have to invest a capital amount and incur additional running costs to keep the plant running with an annual maintenance of 10% of the initial capital investment. This process is expected to treat the winery wastewater and produce effluent that is compliant with the local municipal limits for irrigation to barren land.

- ☐ Option 3, is to install an advanced upgrade on the existing system, which involves the addition of a flotation system plus an automation of the neutralisation pit. Likewise, Winery X would have to sustain the investment costs and running costs with a 10% annual maintenance, with the installation of reverse osmosis (RO). This would result in the quality of water that could be re-used, this would also realize an effluent treatment recovery rate of 75% would be achieved.

- The commercial analysis and modelling focused on a comparative analysis of the three options.

9.3 Commercial inputs and assumptions

The commercial analyses for the three options was done over a period of ten years utilising an inflation rate of 4.80% and a discount rate of 10%.

The annual cost structure, capex and opex (operating expenditure), of the wastewater treatment process for the three options based on actual 2020 cost and quotations received is presented in **Table 13**.

This existing treatment process, Option 1, includes chemicals, service agreement, labour electricity and maintenance. According to Winery X, the use of chemicals forms the largest part of the running cost calculated at R427,660. The rest of the operating expenses, which includes maintenance, labour electricity and service agreements summed up to R173,963. The total running cost for the year ending in 2022 was R601,623. The resulting running cost normalised to treated wastewater volume was R12.28/m^3.The capex and opex estimates for Options 2 and 3 are presented in **Table 14**.

Table 13. Capex and annual opex costs for the wastewater treatment options.

	Option 1 **(R/a)**	**Option 2** **(R/a)**	**Option 3** **(R/a)**
Capex Investment cost	0	600,000	1,100,000
Chemicals related to effluent treatment – Lime	140,847	140,847	140,847
Chemicals related to effluent treatment – Bacteria	154,602	77,301	77,301
Chemicals related to effluent treatment - CaCo3	132,211	132,211	132,211
Total cost of chemicals	**427,660**	**350,359**	**350,359**
Service agreements (Nano Bubblers)	56,428	56,428	56,429
Solid/sludge removal (Lime ponds)	6,334	6,334	6,334
Electricity cost effluent (Nano bubblers and pumps)	21,479	10,739	10,739
Electricity cost for the SESF		7,200	14,400
HR - salaries for temp workers during harvest season	49,185	49,185	49185
Maintenance on pH instruments	10,005	10,005	10,005
Maintenance on pumps and motors	30,533	30,533	30,533
Maintenance (10% of Capital)		60,000	110,000
Additional annual running costs		100,000	200,000
Total expenses to run the wastewater treatment plant	**601,624**	**680,783**	**837,984**

For the cash flow analysis all opex costs were inflated with inflation. For Option 1 a fine was included and modelled. As a sensitivity, a base case fine of R2/m^3 of non-compliant wastewater was used. Sensitivities were also modelled for fines at R8/m^3 and R16/m^3.

Table 14. Annual opex savings associated with the wastewater treatment options.

	Option 1 (R/a)	Option 2 (R/a)	Option 3 (R/a)
Lime savings as a results of more efficient mixing using a flotation device		30,000	30,000
Total cost of chemicals		**30,000**	**30,000**
Water savings as a result of a reduced amount or lime water		1,500	1,500
Water reuse as a result of RO produce water meeting potable water specifications			55,125
Total expenses to run the wastewater treatment plant		**1,500**	**56,625**

9.4 Results of commercial analysis

The cash flows analysis highlighting the annual net cash flows and cumulative net cash flows for each option at imposing a fine of R2/m^3 for non-compliant wastewater is presented in **Figure 22, 23 and 24**. The cash flows analysis highlighting the annual net cash flows and cumulative net cash flows for each option at imposing a fine of R8/m^3 for non-compliant wastewater is presented in Appendix B.

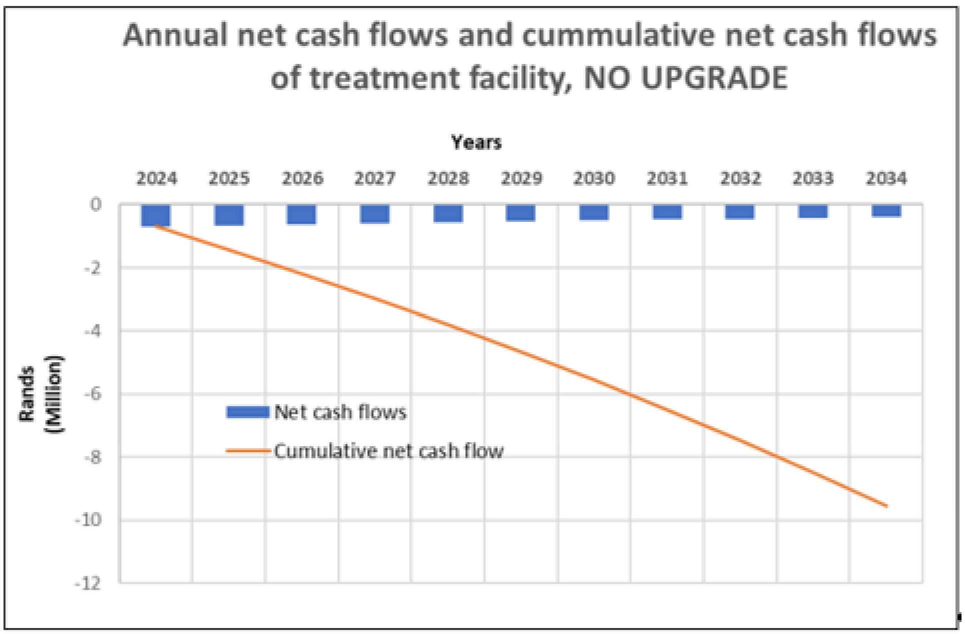

Figure 22. Annual net cash flows and cumulative net cash flows for Option 1, with a fine of R2/m^3 for non-compliant wastewater.

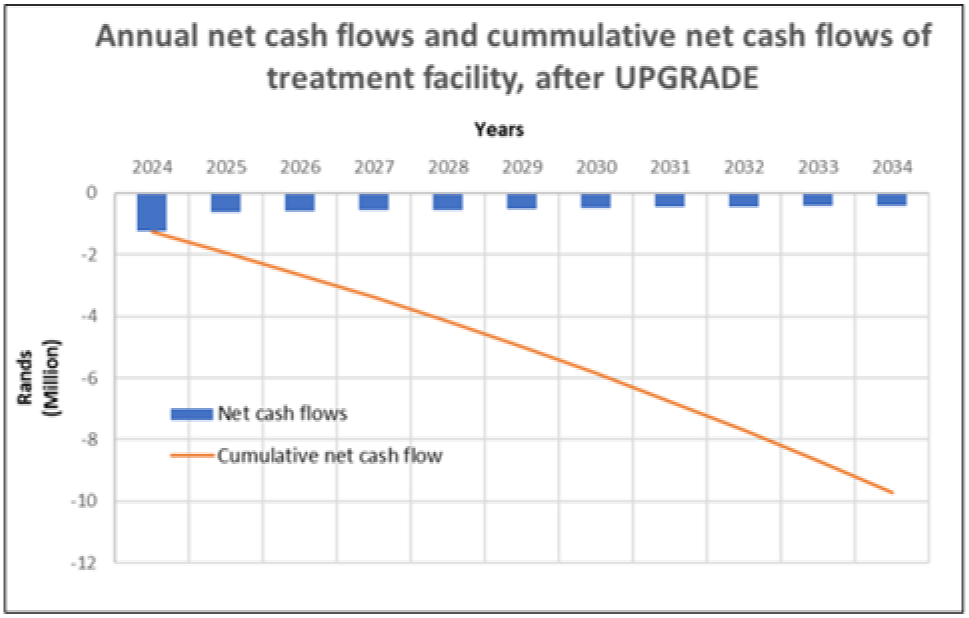

Figure 23. Annual net cash flows and cumulative net cash flows for Option 2, with a fine of R2/m^3 for non-compliant wastewater.

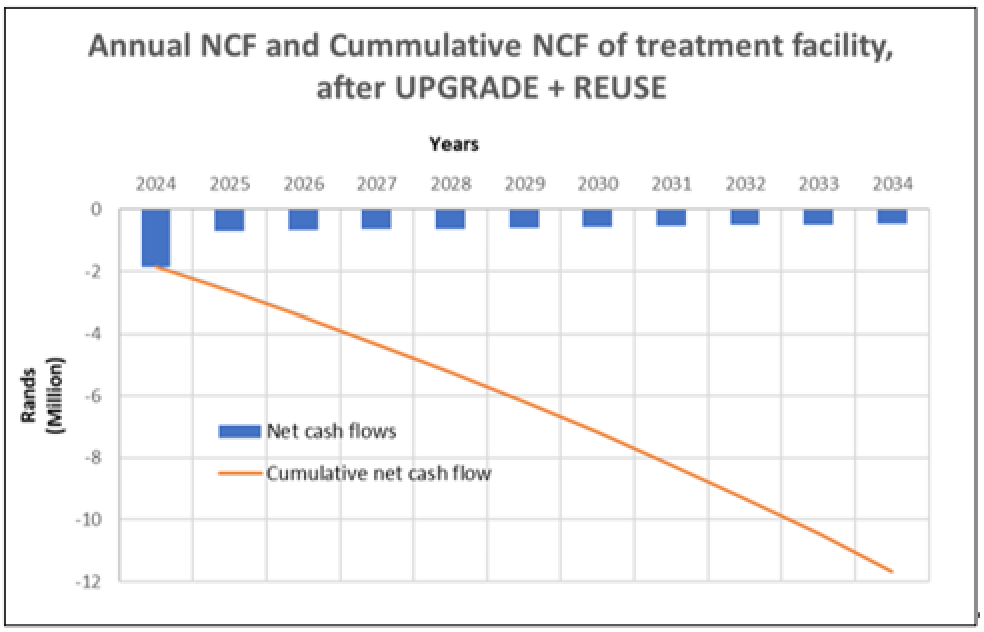

Figure 24. Annual net cash flows and cumulative net cash flows for Option 3, with a fine of R2/m^3 for non-compliant wastewater.

The cumulative net cash flows, the associated NPV's and the cost savings relative to the base, Option 1, for a fine of R8/m^3, R12/m^3 and R16/m^3, for non-compliant wastewater is presented in **Table 15, 16 and 17**.

Table 15. Cash flow analysis of the wastewater treatment options utilising a fine of R2/m^3.

Parameter	**Option 1**	**Option 2**	**Option 3**
Cumulative net cash flow (RM)	-9.5	-9.7	-11.7
NPV (RM)	-6.0	-6.3	-7.7
Cost savings relative to the base case (RM)		**-0.3**	**-1.7**

Table 16. Cash flow analysis of the wastewater treatment options utilising a fine of R8/m^3.

Parameter	Option 1	Option 2	Option 3
Cumulative net cash flow (RM)	-12.8	-9.7	-11.7
NPV (RM)	-8.1	-6.3	-7.7
Cost savings relative to the base case (RM)		**1.8**	**0.4**

Table 17. Cash flow analysis of the wastewater treatment options utilising a fine of R16/m^3.

Parameter	Option 1	Option 2	Option 3
Cumulative net cash flow (RM)	-17.2	-9.7	-11.7
NPV (RM)	-10.9	-6.3	-7.7
Cost savings relative to the base case (RM)		**4.6**	**3.2**

At a fine level of R2/m^3 for non-compliant wastewater, there is a commercial benefit to upgrading the plant. Investment in Options 1 and 2, do not result in a savings to the winery, as per **Table 15**.

With an increase in the fine level to R8/m^3 and R16/m^3 there is a commercial benefit to investing in upgrading the treatment plant, which will result in overall cost savings, **Table 16** and **Table 17**. At fine levels of R8/m^3 and R16/m^3, the upgrading to Option 2, gives the most cost savings and there is a commercial rationale to upgrading the existing wastewater treatment plant at Winery X, **Table 16** and **Table 17.**

10. Membrane Capacitive Deionisation (MCDI)

10.1 Introduction

The term capacitive deionisation is derived from the words capacitive and deionisation. Deionisation refers to the removal of charged molecules or atoms in the form of ions (cations and anions) and capacitive refers to the capacitor used to facilitate the removal of ions. A capacitor is a device composed of one or multiple pairs of electrodes that are oppositely charged. An electric potential is applied over the electrodes, resulting in positively and negatively charged poles. Salts dissolved in water exist as positively and negatively charged ions. Cations are attracted by electrostatic force to the negatively charged electrode while the anions are attracted to the positively charged electrode. Hence, the ions are separated from the water solution. Cycles of regeneration and purification are alternated to produce both brine and desalinated water streams. Limitations of capacitive deionisation (CDI) would manifest during polarity reversal/electrode regeneration. When the adsorbed ions are desorbed, the cations and anions are attracted to the opposite electrode. Therefore, the regeneration of the electrodes is compromised, limiting the electrode sorption capacity for the subsequent desalination run. This limitation is resolved by a system modification known as membrane capacitive deionisation (MCDI). An MCDI cell is created by placing ion exchange membranes between the cathode and anode. Regeneration/charge efficiency is improved by the selective transport of cations and anions by the ion-exchange membrane when the polarity is reversed.

10.2 Research Update

The work relating to MCDI was completed in 2022. The student developed an appropriate understanding of MCDI and submitted his thesis in 2023 and will graduate in September 2024. To date 24 electrodes were produced and tested.

Based on the observed selectivity towards mono-valent ions, MCDI could still be considered as desalination technology for winery wastewater, but more research is required to study the desorption cycles.

11 Appendix

11.1 APPENDIX A: Diagram of the wastewater treatment facility at Winery X

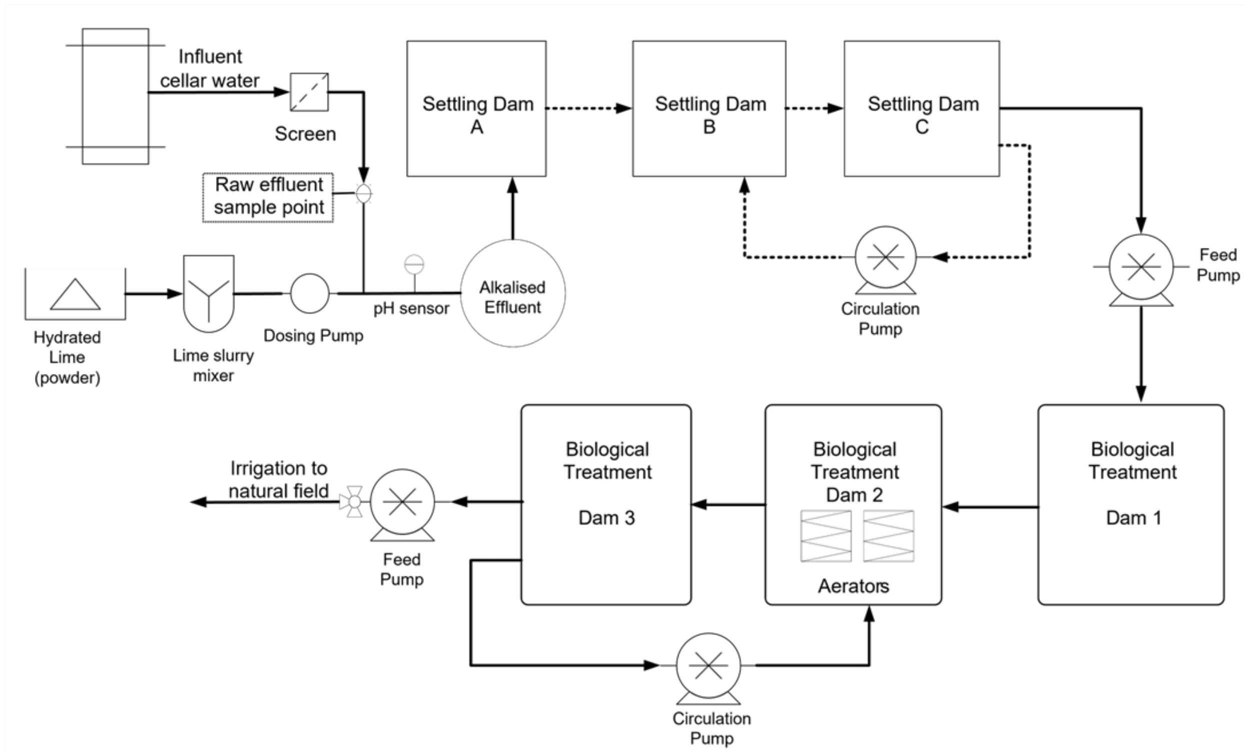

Figure A1. Wastewater treatment plant at Winery X.

11.2 Appendix B: Cash flows analysis for each option at imposing a fine of R8/m3

The cash flows analysis highlighting the annual net cash flows and cumulative net cash flows for each option at imposing a fine of R8/m^3 of non-compliant wastewater is presented in **Figure B1, B2 and B3**.

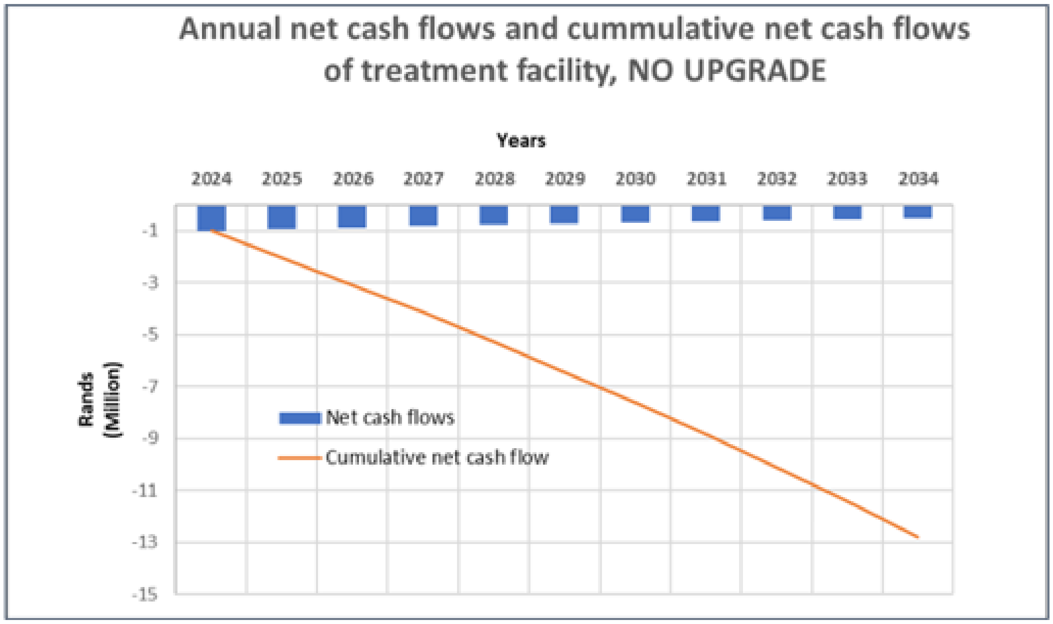

Figure B1. Annual net cash flows and cumulative net cash flows for Option 1, with a fine of R8/m^3 for non-compliant wastewater.

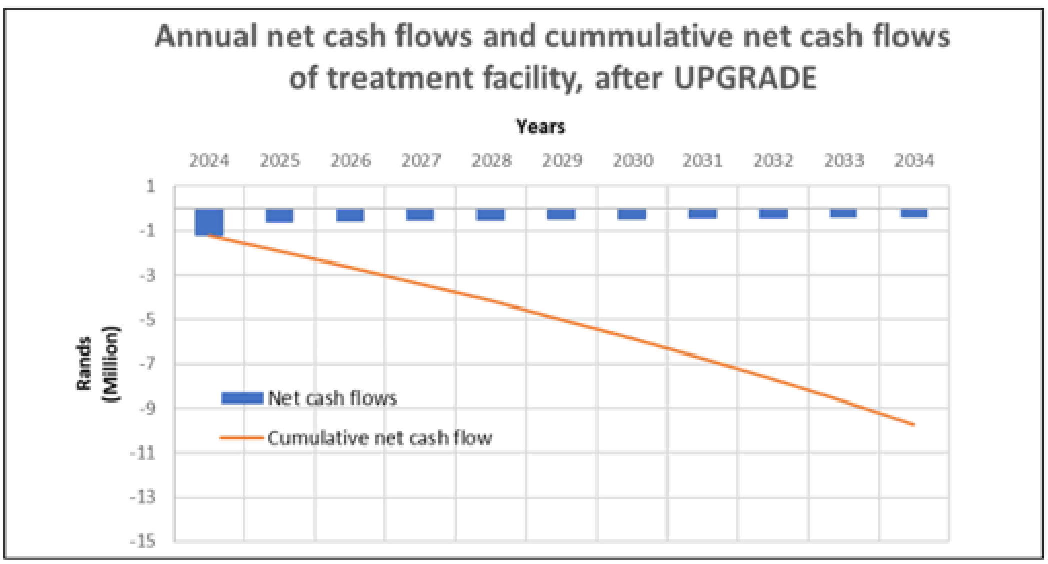

Figure B2. Annual net cash flows and cumulative net cash flows for Option 2, with a fine of R8/m^3 for non-compliant wastewater.

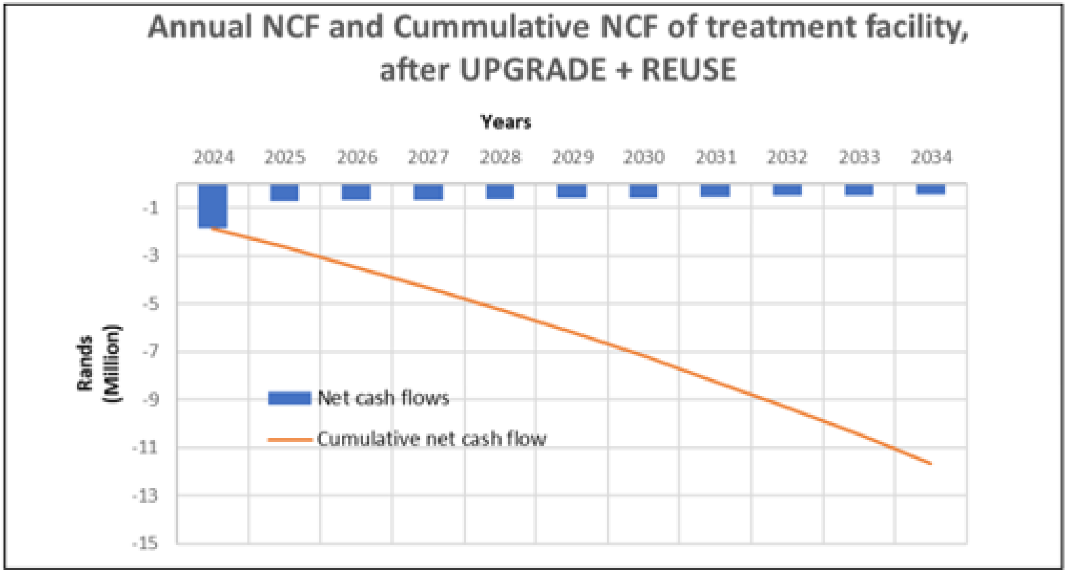

Figure B3. Annual net cash flows and cumulative net cash flows for Option 2, with a fine R8/m^3 for non-compliant wastewater.

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13. CONCLUSIONS AND RECOMMENDATIONS

We have successfully designed, fabricated and modified an upscaled version of the lab-scale SEFS technology (a DAF/Shear hybrid treatment plant)

Our results suggest that this pilot plant is capable of reducing the TSS, turbidity and COD by 99%, 99.6% and 66%, respectively. The treated water has been shown to be chemically fit to be used as a source of irrigation water (up to 50 m3 since the COD falls within the 400 - 5000 mg/L range).

14. PLANNED OUTPUTS

a) TECHNOLOGY DEVELOPMENT, PRODUCTS AND PATENTS

The potential of this project, once optimized technologically towards the treatment of winery wastewater, is significant in terms of overall benefit to the environmental and production economics. However, as long as; A) wineries are not consistently penalized for discharging non-compliant effluent and B) the consequences of water restrictions are not stopping the winery from operating, the incentive for investing in SEFS treatment technology is difficult to justify.

b) SUGGESTIONS FOR TECHNOLOGY TRANSFER

c) HUMAN RESOURCES DEVELOPMENT / TRAINING (STUDENTS)

Student Name and Surname	Student Nationality	Degree (eg Hons, MSc)	Level of studies in final year of project	Total Bursary Cost for Industry for entire project
Honours				
Y Augustine	South African	Hons	Hons	R 17978
L Macutyana	South African	Hons	Hons	R 16000

S Pesula	South African	Hons	Hons	R 17680
A.Masela	South African	Hons	Hons	R 10000
M.Arendse	South African	Hons	Hons	R 10000
Masters				
C.Theron	South African	MSc	MSc	R 0
T.S. Mgudlwa	South African	MSc	MSc	R 171670
PhD				
D.Vlotman	South African	PhD	PhD	R 538663.33
Postdocs				
B. Cerff	South African	PhD	PhD	R 376590

d) LIKELY PUBLICATIONS (POPULAR, PRESS RELEASES, SCIENTIFIC)

- Vlotman D.E., Key D, Bladergroen B.J. Technological Advances in Winery Wastewater Treatment: A Comprehensive Review. South African Journal of Enology and Viticulture, 43(1), 58-80. https://doi.org/10.21548/43-1-4931
- Vlotman, D.; Key, D.; Cerff, B.; Bladergroen, B.J. Shear Enhanced Flotation Separation Technology in Winery Wastewater Treatment. Water 2023, 15, 2409. https://doi.org/10.3390/w15132409
- Vlotman D., Key D., Cerff, B., Bladergroen B.J. Wastewater Treatment Using Shear Enhanced Flotation Separation Technology: A Pilot Plant Study for Winery Wastewater Processing. Processes 2023; 12, 3. https://doi.org/10.3390/pr12010003

e) PRESENTATIONS/PAPERS THAT COULD BE DELIVERED

Young Chemist Symposium Presentation (UWC) September 2023.

15. PROJECT OUTCOME AND IMPACT

New Knowledge	Benefits Supply Chain	Direct Grower Application	Direct Packhouse/Winery/ Cellar Application	Other
X	X	X		N/A

Other is: N/A

The Value of the project to industry

SEFS is envisaged to make the wine industry more competitive and sustainable. technology eliminates costs related to raw effluent discharge, subsequently reducing the wastewater processing costs of the winery and benefitting the supply chain. It enables the treated effluent to be more compliant and as a source of irrigation water.

16. PERSONS PARTICIPATING IN THE PROJECT:

INITIALS AND SURNAME	HIGHEST QUALIFICATION	RACE (B,C,I,W)	GENDER (M,F,X)	INSTITUTE DEPARTM	POSITION	TOTAL COST TO PROJECT
RESEARCH PERSONNEL						R 345000
Prof Bladergroen	PhD	W	M	SAIAMC	Project Lead	R 315000
Prof Ocran	PhD	B	M	Economics	Professor	R 30000
SUPPORT PERSONNEL						R 90825
A.Mbaxa	BSc Chemistry	B	F	Chemistry	Assistant	R 85675
M.De Kock	BSc Chemistry	W	F	Chemistry	Assistant	R 5150

POSITION: Co = Co-worker (other researcher at your institution)
Coll = Collaborator (participating researcher that does not receive funding for this project from industry)
PF = Post-doctoral fellow
PL = Project leader
RA = Research assistant
TA = Technical assistant/ technician

17. TOTAL COST OF PROJECT

TOTAL ANNUAL COSTS (ALL YEARS)	CFPA	RAISINS SA	HORTGRO	SATI	SA WINE	ARC	OTHER	TOTAL
2019 and before	R 0	R 0	R 0	R 0	R 0	R 0	R 0	R 0
2020	R 0	R 0	R 0	R 0	R 850000	R 0	R 0	R 850000
2021	R 0	R 0	R 0	R 0	R 900000	R 0	R 0	R 900000
2022	R 0	R 0	R 0	R 0	R 750000	R 0	R 0	R 750000
2023	R 0	R 0	R 0	R 0	R 400000	R 0	R 0	R 400000
2024	R 0	R 0	R 0	R 0	R 0	R 0	R 0	R 0
TOTAL	R 0	R 0	R 0	R 0	R 2900000	R 0	R 0	R 2900000