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ADVANCING WATER CIRCULARITY: A SIMULATION OF HYDRODYNAMIC CAVITATION AND MEMBRANE PROCESSES FOR SUSTAINABLE INDUSTRIAL WASTEWATER REUSE

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ABSTRACT
Water scarcity is a growing global challenge, exacerbated by population growth, industrialization, and climate change. As freshwater resources become more limited, water reuse has emerged as a promising solution to alleviate shortages. Reusing treated wastewater for agricultural use in arid and semi-arid regions is considered a sustainable approach to conserving freshwater and supporting food production. However, for this to be viable, treated wastewater must undergo rigorous treatment processes to ensure both food safety and environmental sustainability. A water circular economy is central to this approach, emphasizing the recycling and reuse of water in a closed-loop system to minimize waste and maximize resource efficiency. In this model, wastewater is treated, purified, and reused across multiple sectors, reducing overall water consumption. For agriculture, reusing treated wastewater transforms what would be waste into a valuable resource, reducing dependence on freshwater sources. This study examines the integration of advanced treatment technologies into wastewater treatment plants to facilitate the safe and effective reuse of agricultural water. The research focuses on a simulation of a wastewater treatment plant designed for agricultural reuse, starting from a real industrial effluent. The treatment process incorporates innovative methods such as hydrodynamic cavitation, advanced oxidation processes, and membrane filtration to remove organic contaminants and inactivate pathogens. These technologies ensure that the treated wastewater meets the stringent water quality standards required for agricultural irrigation of all types of crops. This work demonstrates how integrating cutting-edge treatment technologies within a circular economic framework can significantly contribute to water sustainability, especially in water-scarce regions.

1. INTRODUCTION

Water scarcity is an increasingly urgent global problem, accentuated by the growth of the world population and climate change (Tow et al., 2021). The need for innovative strategies for water resource management has become essential to ensure a sustainable water supply for agriculture and other sectors (Gupta et al., 2012).

Historically, water reuse has been practiced since ancient civilizations, with examples of the use of urban wastewater in agriculture dating back thousands of years (Goyal & Kumar, 2021). Over time, water reuse practices have evolved from simple irrigation systems to complex wastewater treatment plants. Today, water reuse is a widespread practice in many parts of the world, with applications ranging from agricultural irrigation to industrial use, environmental restoration, and even potable reuse.

Currently, water reuse represents a well-established solution for water scarcity, with thousands of successful projects around the world. Agricultural reuse is widespread, especially in arid and semi-arid regions, where the demand for water for irrigation is constantly increasing. However, water reuse in agriculture requires adequate treatment to ensure food safety and environmental protection (Lazarova, 2020).

Among the emerging technologies for treating wastewater for reuse, hydrodynamic cavitation (HC) and advanced oxidation processes (AOPs) have attracted considerable attention. Hydrodynamic cavitation exploits the

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formation and collapse of microbubbles in a liquid to generate extreme temperature and pressure conditions, capable of degrading organic pollutants and inactivating microorganisms. AOPs, in turn, are based on the production of highly reactive free radicals, such as the hydroxyl radical (•OH), to oxidize and mineralize pollutants.

The effectiveness of hydrodynamic cavitation depends on several operational parameters, including pressure, temperature, residence time, and reactor geometry. Furthermore, it has been shown that HC can act synergistically with other treatment processes, such as ozonation and UV radiation, improving the overall efficiency of the process. Despite the promising results obtained in the laboratory, the large-scale application of hydrodynamic cavitation in wastewater treatment requires further studies to optimize operating parameters and reduce energy costs (Prisciandaro & Innocenzi, 2023).

This work presents the results of a simulation of a wastewater treatment plant (WWTP) designed for water reuse in agriculture starting from a real industrial effluent. The simulation was conducted using the commercial software SuperPro Designer and aims to evaluate the plant's performance under different operating conditions and to identify strategies to optimize process efficiency. The simulated plant integrates a hydrodynamic cavitation and AOP system for tertiary treatment of wastewater to remove organic contaminants and inactivate pathogens, ensuring compliance with quality requirements for agricultural reuse.

2. MATERIALS AND METHODS

The design and simulation of the treatment plant were carried out using the commercial software SuperPro Designer, to optimize the pollutant removal efficiency and evaluate the quality of the treated water for potential reuse in agriculture.

The following effluent quality metrics were monitored in both plant configurations (with and without Hydrodynamic Cavitation): COD, BOD_5, TOC, TSS, TKN, TP, NO_3-NO_2. The results were compared to the regulatory limitations for agricultural reuse (Classes A and B under European Union Regulation (UE-2020/741). The percentage reduction of each parameter in the Hydrodynamic Cavitation section was also calculated to determine the efficiency of the advanced oxidation process.

TABLE 1: Properties of the effluent to be treated.

Parameter	Value
Flow rate	100
Chemical Oxygen Demand (COD)	2500
Biochemical Oxygen Demand (BOD_5)	1000
Total Kjeldahl Nitrogen (TKN)	17
Total Protein (TP)	3,10
Chlorine (Cl^-)	490
NO_3-NO_2	37,3
pH	8,5

3. PLANT DESCRIPTION

This plant layout is intended to treat real industrial wastewater with the composition described in Table 1. The system depicted here can handle a current of 100 m^3/h of effluent (35000 E.I.).

3.1 Wastewater treatment plant description

The basic scheme, shown in Figure 1, is intended to discharge effluent to municipal wastewater collection and treatment plants following Italian legislation (Italian Republic, 2006).

The wastewater to be treated is finely screened to remove particle materials. Given the effluent's initial composition, it is added with chemicals to supplement nutrients and balance the pH. Thus, 33% HCl is added until a concentration of 45 mg/l (pH 7,6) is obtained. In addition, nitrogen and phosphorus sources are provided in quantities of 20,5 mg/l and 4,4 mg/l, respectively. The overall consumption of these combinations will be 4,55 kg/h of HCl (33%) and 13,5 l/h of nitrogen/phosphorus mixture (18%).

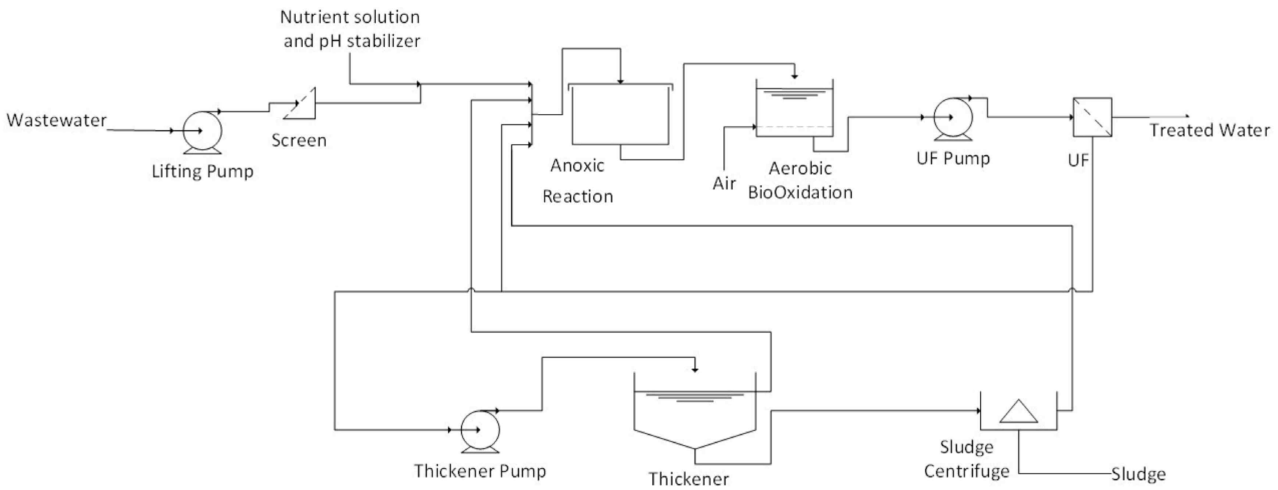

FIGURE 1: Process flow diagrams for the basic wastewater treatment plant.

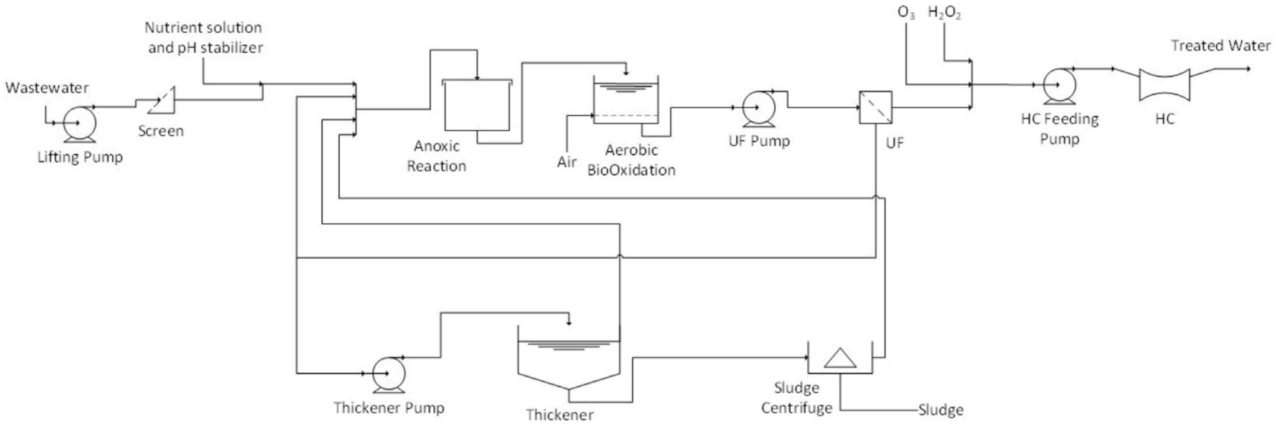

FIGURE 2: Wastewater Treatment Plant equipped with the Hydrodynamic Cavitation section.

Then, the effluent is sent to the biological treatment section to undergo denitrification in the first tank and aerobic oxidation in the second.

3.2 Hydrodynamic Cavitation Section

The same plant can be equipped with an advanced oxidation section, as shown in Figure 2.

Specifically, the advanced oxidation section includes hydrodynamic cavitation treatment, composed of a pump and a Venturi tube. HC is a process of generation, growth, and subsequent collapse of vapor-filled cavities within a liquid due to variations in local pressure. The cavities are generated in a low-pressure region, as in the throat of a Venturi tube. When these cavities travel to a region of higher pressure, they implode. The cavity collapse under certain conditions results in very high pressure and temperature near the location of collapse. These extreme local temperatures (> 2000 K) and pressures (> 100 MPa) result in the generation of highly reactive radical species (from water and dissolved air), with extreme physio-chemical effects that have been of interest to engineers and scientists due to their potential to damage equipment. On the other side, the strongly oxidizing hydroxyl radicals and local hot spots can be used for treating pollutants in water as well as for intensifying a variety of organic reactions in water (Capocelli et al., 2014). Therefore, among various AOPs, the •OH yield, removal efficiency, and energy efficiency are the main evaluation indicators. In general, less •OH is produced and higher energy consumption is required by hydrodynamic cavitation alone, but it can remarkably enhance oxidative degradation of organics by promoting the mass transfer and •OH formation in combination with other AOPs, such as Fenton oxidation (Innocenzi et al., 2019) and ozonation (Wu et al., 2012). Several studies also by this research group have confirmed the synergistic effect of hydrodynamic cavitation and oxidants like ozone and hydrogen peroxide, (Ayedi et al., 2024; Innocenzi et al., 2022) to create a hybrid advanced oxidation process that achieves significantly greater degradation in a shorter period. In this treatment scheme, the inlet water stream of hydrodynamic cavitation is enriched with 7.5 mg/l of ozone and 0.3M of hydrogen peroxide. These are average concentrations used in previous studies carried out on polluted water streams with different organic loads.

The permeate from ultrafiltration is thus first added up with hydrogen peroxide (0,5 kg/h) and ozone (1 kg/h). It is then pumped into a Venturi tube-type hydrodynamic cavitation reactor via a pump. This pump must produce a sufficient Dp to initiate cavitation, with the ensuing synergistic effects on the previously supplied oxidants. 99% bacterial degradation was assumed for the simulation of this section, consistent with results found in the literature (Sun et al., 2020).

4. RESULTS AND DISCUSSION

The findings of this study focus on the reuse of industrial wastewater for irrigation purposes, while future research will investigate plant energy use. The described plant configurations produce a treated water flow rate of 71.23 m^3/h.

4.1 Plant Characteristics

Table 2 summarizes the main characteristics of the wastewater treatment plant equipment.

Advanced Oxidation Processes increase the quality of treated water by mineralizing chemical species that can pass through traditional wastewater treatment without

TABLE 2: Wastewater treatment plant equipment.

Equipment	Main Characteristic
Lifting Pump	5
Screen Number	1
Anoxic Tank	3450
Aerobic BioOxidation	5200
Ultrafiltration Pump	50
UF Membrane Type	Dft Membrane
UF Membrane Number	86
Thickener Charging Pump	1
Thickener	8.5
Sludge Sentrifuge	15
Venturi Feeding Pump	15

degradation (Prisciandaro and Innocenzi. 2023). In this study, a hydrodynamic cavitation system with a Venturi tube is proposed. As demonstrated in various investigations, hydrodynamic cavitation has a synergistic effect on conventional oxidants when combined with the output of earlier treatments (Wang et al. 2021).

4.2 Treated water composition

Table 3 depicts the characteristics of water discharge from the two alternative system setups. The table also indicates the constraints imposed by current European guidelines on water reuse for irrigation applications (EUROPEAN PARLIAMENT, 2020).

As demonstrated in Table 3, the water leaving the ultrafiltration treatment may be appropriate for reuse as irrigation water for crops classified as Class B water applications. However, EU Regulation 741/2020 mandates that the water be disinfected before its reuse; therefore, the water exiting the Ultrafiltration section is not appropriate for irrigation reuse. The environmental parameters of this stream should be attributed to bacterial or viral remnants in the treated effluent.

Advanced oxidation methods are also covered in the guidelines for potable water reuse issued by the USEPA in 2017 as a disinfection method (USEPA, 2017).

According to EU 741/2020, hydrodynamic cavitation treatment yields Class A water suitable for all forms of culture. It has also been demonstrated in the literature that such a process can be efficient at removing numerous pathogens with great efficiency (Sun et al.,2020).

The reduction efficiency in environmental parameters (TOC, TP, TKN, COD, BOD_5, TSS) of the current output from the cavitation section resulted always higher than 98%. This performance can be also attributed to the degradation of residual bacterial or viral load in the output current from Ultrafiltration (Mazziotti di Celso & Prisciandaro, 2013).

5. CONCLUSIONS

In this study, modeling results for two possible layouts of an industrial wastewater treatment facility are provided. In the first plant design, the discharge meets all the standards for discharge to the municipal wastewater management network. This is mostly owing to the Ultrafiltration portion, which enables complete compliance with current Italian rules on the issue. The outflow from the ultrafiltration section contains COD, BOD_5, and TSS concentrations that would allow the reuse of Class B water for irrigation purposes under current European Union regulations. Still, the lack of a disinfection step makes them unsuitable for the purpose.

The literature indicates higher than encouraging yields for wastewater disinfection using Advanced Oxidation Treatments, specifically Hydrodynamic Cavitation in combination with other oxidants. The implementation of one stage of Hydrodynamic Cavitation to the initial plant scheme, in addition to disinfecting the effluent, enables further reductions in COD and TSS levels, as well as the reuse of Class A water for irrigation applications under European Union regulations.

However, the treated wastewater retains residual chlorine, making it suitable for certain crops. This limitation could be readily addressed with a Reverse Osmosis step. This operation ensures that the water is of adequate quality to be reused for processing. However, the topic stems from the current study's objectives.

Future research will focus on energy optimization using simulation tools, as well as assessing the environmental impact of the schemes employed through Life Cycle Assessment.

TABLE 3: Characteristics of the effluent from the two different plant configurations and limits for irrigation reuse in Europe.

Parameter	UF Section	UE 741/2020 Class B Water	HC Section	UE 741/2020 Class A Water
TOC	5,655		0,081	
TP	0,529		0,005	
TKN	1,28		0,014	
NO_3-NO_2	25,217		25,202	
COD	15,323	≤125	0,234	≤10
BOD5	8,157	≤25	0,114	≤10
TSS	11,180	≤35	0,152	≤10

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