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Original Article

Sustainable Treatment of Industrial Effluents in Oman using an Integrated Aerobic Bioreactor and UV Oxidation System

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Abstract - *Untreated industrial effluents contain complex organic chemicals and heavy metals that pose a major threat to the environment. This study aims to investigate an integrated wastewater treatment system that includes a continuous aerobic bioreactor, algal culture, and a UV downstream reactor. System configuration and operational parameters were defined in Aspen Plus, a process design software, to optimise septic and treatment performance. A system-wide experimental study on parameter sensitivity was designed to characterise the system's physical-chemical properties and to evaluate its treatment and recovery of value through heavy-metal reclamation. Experimental analysis was performed using descriptive behaviour, chemistry, and various mechanistic models to describe the flow systems, the variables, and the reaction models of interest. The experimental results depict the integrated continuous aerobic bioreactor and UV reactor as a system with high operational reliability and consistent performance across a wide range of operational time periods, demonstrating high operational time reliability. The UV (disinfection) and Polishing Efforts, combined with the continuous aerobic bioreactor and algal culture operational system, facilitated an average effluent treatment system (20-7-20) that met stringent limits and average treatment goals for the targeted compliance discharge activities. The system's operational parameters demonstrated high adaptability, as evidenced by the septage/composition super and cut-through to a variety of industry goals and flow treatment targets. Moreover, the integrated system positively impacts sustainable wastewater management by incorporating industrial effluent discharge. Overall, research confirms the integrated aerobic bioreactor–UV reactor approach as practical, versatile, and scalable, and it is optimistically viewed as a sustainable solution for industrial wastewater management. To improve performance, further optimise the system, and broaden its use in industry, a scale-up study is suggested.*

Keywords - *Industrial wastewater, Aerobic bioreactor, Ultraviolet disinfection, Algal bioremediation, Heavy metal removal, AspenPlus, Process simulation and optimization.*

1. Introduction

Water pollution is the contamination of water bodies. It is mostly a result of human activities such as industrial operations, agriculture, municipal wastewater dumping, and accidental spills. Water pollution has a negative effect on the environment as a whole. Contaminated water can kill aquatic flora and fauna. It spreads dangerous diseases and toxins. It can also result in economic losses in the tourism and fishing industries, including job losses and revenue declines. Although there are numerous wastewater treatment options, each one has its pros and cons. Choosing a wastewater treatment method depends on the type and quantity of the pollutants, treatment goals, and available resources. On the other hand, wastewater treatment and management are essential for the protection of the ecosystem, the well-being of the community, and the availability of water for use. The pollution of water due to industrial wastes is an ever-growing problem. The type and quantity of wastewater generated by an industry are of such a volume and complexity that they disrupt the natural systems and the environment's self-regulation.

The textile, pharmaceutical, electrochemical, oil, and metal industries in Oman are fast-growing, with high organic and inorganic content and heavy metals, producing high-strength wastes that are difficult to dispose of or reuse. Due to recent technological advancements, biological aerobic and Ultraviolet (UV) reactors have been widely used for tertiary treatment of high-strength industrial wastewater.

The proposed work will bring numerous benefits and enhance the Sultanate of Oman's profits by enabling the reuse of treated wastewater, minimising desalinated water consumption, and promoting healthy living for humankind living near industrial zones. The project is highly significant for water conservation and the utilisation of treated wastewater. The proposed research project will pave the way for wastewater treatment, enabling treated water to be used for landscaping or other external purposes.

1.1. Problem Statement

The release of untreated waste into the sea and other water bodies, together with the rapid growth of the human population and urban and industrial activities, has had a devastating effect on the environment and the atmosphere. Wastewater treatment before discharge is crucial to curb spiraling water pollution. It is common for industrial effluents to be discharged into water sources, either untreated or inadequately treated. Large quantities of malodorous gases are produced when untreated wastewater accumulates. Moreover, untreated wastewater often contains many pathogenic microorganisms that can cause adverse health effects in the human intestinal tract.

Industrial waste causes water pollution. Due to the accumulation of scientific knowledge and expansion of scientific data, wastewater treatment has increasingly focused on the environmental impact of toxic and potentially toxic chemicals released from domestic and industrial wastewater. High concentrations of inorganic, organic, and heavy metals are produced in the textile, pharmaceutical, electrochemical, oil, and metal industries. Water conservation and wastewater reuse are critical research areas. A good water supply and a pollution-free environment are vital to the Sultanate of Oman. A unique approach to wastewater treatment will be developed to support the national vision and ensure the safety of all people. The treated wastewater could then be used for landscaping and other external purposes. Thus, this study aimed to investigate the feasibility of an integrated continuous aerobic bioreactor and an ultraviolet reactor for treating industrial effluents in Oman. In the latest Sustainable Treatment of Industrial Effluents, researchers are using Artificial Intelligence techniques, including Machine Learning and Deep Learning for parameter prediction, and Digital Image Processing techniques for quality assessment (Poolakkachalil, T. K. et al., 2016) [1]. In the context of data security, when sharing the parameters of the Aerobic Bioreactor and UV Oxidation System for AI processing, there is increasing interest in using federated learning techniques (Vijayalakshmi, K. et al., 2024) [2]. This work introduces AI techniques, but in the future, AI will play a vital role in wastewater treatment.

1.2. Objectives of the Research Work

This study aimed to investigate the feasibility of an integrated continuous aerobic bioreactor and an ultraviolet reactor for treating industrial effluents in Oman. The objectives are as follows.

To examine the physicochemical properties of various effluents in a batch aerobic bioreactor.

To design an integrated continuous aerobic bioreactor and UV reactor for wastewater treatment.

To determine the physicochemical properties and heavy metal removal from the effluents in the integrated system.

To elucidate the kinetic modelling of the degradation of effluents in an integrated continuous aerobic bioreactor and UV reactor.

1.3. Novelty in the Proposed Methodology

Integrated batch-to-continuous treatment framework
This study uniquely establishes a systematic transition from batch aerobic bioreactor analysis to a fully integrated continuous aerobic bioreactor–UV reactor system, enabling improved understanding and optimisation of wastewater treatment performance.

Simulation-driven design of an integrated biological–UV treatment system.

The integrated continuous aerobic bioreactor and UV reactor were designed and configured using Aspen Plus, introducing a process-simulation–assisted approach rarely reported for combined biological and photochemical wastewater treatment systems.

Synergistic Removal of Physicochemical Pollutants and Heavy Metals.

A novel mechanism for removing organic pollutants and heavy metals in a continuous-flow system has been developed through a combination of algal-assisted aerobic biodegradation and Ultraviolet (UV) treatment.

Kinetic modelling of degradation in an integrated continuous system: The research demonstrates a kinetic model of pollutant degradation in an integrated aerobic bioreactor - UV reactor system, enhancing understanding of treatment and system control, demonstrating operational stability and versatility for industrial applications. The integrated system demonstrates sustained performance and compliance with regulations, and its operational adaptability to changes in effluent characteristics illustrates its industrial significance.

1.4. Main Contribution of the Study

This research provides a systematic, pioneering approach to integrated wastewater treatment, with continuous aerobic bioreactors and UV reactors designed, built, and tested to demonstrate wastewater treatment empirically. The research provides insight into the removal of the physicochemical parameters and heavy metals during continuous operation of the system and clarifies the mechanisms using kinetic modeling. By integrating batch study research, continuous system design, and continuous operation to build a long-term performance record, this study provides a scalable, versatile treatment system for broad industrial wastewater treatment. The results promote industrial wastewater treatment technology to improve sustainable management of industrial effluents.

2. Literature Review

2.1. Wastewater Types

Wastewater is water that has been used and is discharged from homes, industries, agriculture, oil and gas, mining, and stormwater systems. Each wastewater source has different contaminants. Domestic wastewater is high in organic matter, nutrients, and pathogens and is treated at municipal facilities, but vermiculture has developed as an alternative to municipal treatment plants [3]. Industrial wastewater has heavy metals and toxic organic compounds and is treated with more advanced methods, such as electrocoagulation and integrated biological–chemical processes (Shahedi et al., 2020; Bahri et al., 2018 [4, 5]). Agricultural wastewater contains high levels of nutrients and animal waste and is treated onsite, usually with systems such as lagoons or anaerobic-aerobic hybrid reactors (Gonzalez-Tineo et al., 2020 [6]). Wastewater from oil refineries contains hydrocarbons and other hazardous substances, and to comply with discharge permits, advanced oxidation and photocatalytic treatments are required (Feroz et al., 2011 [7]; Al Jabri & Feroz, 2015 [8]; Aljuboury et al., 2011 [9]). Runoff from stormwater carries urban contaminants and is increasingly being replenished and reused in water-sensitive urban design systems (Wong and Brown, 2009 [10]).

2.2. Water Pollution Types

Industrial, agricultural, municipal, and urban activities can lead to water pollution through chemical contaminants, nutrients, petroleum hydrocarbons, plastics, and sediments. Pollution from chemicals like pesticides, fertilisers, and industrial chemicals is even detrimental to humans and can poison drinking water sources. Rising levels of nutrient pollution in the Persian Gulf and the Oman Sea are attributed to increased nitrogen and phosphorus pollution, resulting in harmful algal blooms (Mirza Esmaeili et al. 2021 [11]). Transport of oil (oil spills, oil refiners) introduces oil hydrocarbons, Polycyclic Aromatic Hydrocarbons (PAHs), and Volatile Organic Compounds (VOCs) to the seas and oceans, adding to the existing ecological and human health challenges. Due to urban development and unsatisfactory waste management, sediment pollution, including microplastics and other plastics, has been threatening and damaging marine wildlife and people living along the coasts of the Gulf of Oman and the Persian Gulf (Ghayebzadeh et al., 2020 [12]). There are many smart sensors in which we can integrate the AI techniques [13] to identify various parameters, including water pollution. A decline in water quality and wildlife habitat occurs due to sediment pollution in the water, caused by erosion from land development, construction, and agricultural activities. Therefore, there is a need for better erosion and runoff control [14].

2.3. Avoiding Water Pollution

The main aspects of water pollution prevention include reducing pollutant generation, improving the efficiency of pollutant removal, and strengthening governing frameworks. This entails reducing the use of pollutants in farming and industrial practices, enhancing wastewater treatment in municipal facilities, and adopting farming techniques such as cover cropping and reducing fertilizer use, which reduces nutrient loss into water [15]. In the case of Oman, Sudan, and Egypt, Researchers describe the value of public involvement, the role of policymakers, the level of bureaucratic structures, and law enforcement [16]. Monitoring of rivers, as in Indonesia, shows the value of using pollution indices and, in extension, understanding physicochemical parameters to assess pollution and inform management (Bakri and Yushananta, 2023 [17]). In Oman, there is a need to maintain land and marine resources, manage wastewater, brine from desalination, oil spills, runoff from farming, and plastic waste. All of these sustain the need for the management of the integrated coastal zone, the management of environmental impact data (or information), the management of collaboration for the protection of marine ecosystems, and the management of water quality (Choudri et al., 2015 [18]).

2.4. Wastewater Treatment

Wastewater treatment aims to eliminate the harmful impacts of contaminants in wastewater from households, industries, and agriculture. Contaminants can be physical, toxic, and/or biological. For example, physical treatment processes, such as screening, sedimentation, and filtration, remove some suspended solids and debris. Then, chemical processes are used to destroy the remaining colloidal particles and pathogens through coagulation and flocculation, and to disinfect pathogens (Metcalf & Eddy, 2000 [19]).

Biological treatment methods use microorganisms to degrade organic matter (e.g., activated sludge systems, trickling filters, and lagoons). Among advanced biological systems, sequencing batch biofilter granular reactors are noteworthy for effectively removing organic matter from textile wastewater while producing less sludge and requiring less hydraulic retention time (Lotito et al., 2013 [20]). Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are all wastewater treatment processes that use membranes. While membrane bioreactors are the best option for textile wastewater high in dyes, their high operational costs are a hindrance to their use (Jegatheesan et al., 2016 [21]). In the treatment of industrial wastewater, filtration, adsorption, and ion exchange are among the advanced, more expensive methods.

2.5. Aerobic Bioreactor

Because of their elevated biodegradation rates and ability to eliminate organic contaminants, aerobic bioreactors are highly useful for treating high-strength industrial wastewaters. Aerobic MBRs (membrane bioreactors) have been able to almost eliminate COD, suspended solids, nutrients, and colour from wastewater, with 95% or better efficiency for colour in treated wastewaters at different concentrations of certain dyes and biomass concentrations (Khouni et al., 2020 [22]). Aerobic granular sludge systems removed COD and ammonia (colour removal may be limited) (Abdullah et al., 2011 [23]). For the highest-strength wastewaters, integrated anaerobic–aerobic systems represent a further step toward increasing treatment efficiency, yielding 99% COD removal and the added benefit of recovering energy as methane (Show et al., 2020 [24]; Morgan-Sagastume et al., 2019 [25]). Also, with favourable weather conditions, algae pond systems are beneficial for nutrient removal and CO2 sequestration while producing valuable biomass, making them especially helpful for Oman.

2.6. Anaerobic Bioreactor

In the treatment of industrial-strength wastewater that contains dyes, hydrocarbons, and other complex organics, Anaerobic bioreactors are of paramount importance. Although membrane fouling remains a challenge, Anaerobic Membrane Bioreactors (AnMBRs) achieved almost 100% dye removal (Mojiri et al., 2023 [26]). In comparison, hybrid anaerobic-aerobic systems are much better.

Shoukat et al. (2019 [27]); Mustafa et al. (2023 [28]) showed that these systems achieved removals of COD and nitrogen greater than 99%, and, in addition, the quality of the effluent improved due to aerobic polishing. Cao and Mehrvar (2011 [29]) reported that Anaerobic baffled reactors (ABRs) in combination with UV/H_2O_2 advanced oxidation processes can increase the biodegradability and removal of organics by more than 95%. Moving-bed biofilm reactors and sequencing batch reactors have also shown stability and shock-loading resistance, with COD removals over 90% in petroleum refinery wastewater treatment (Lu et al., 2013 [30]; Kutty et al., 2011 [31]).

2.7. Ultraviolet (UV) Reactor

Technologies such as Ultraviolet (UV) reactors and UV-based advanced oxidation processes inactivate microorganisms and treat complex industrial wastewaters. In contrast, degrading dyes and absorbing Azo dye, UV disinfection absorption performance was strongly dependent upon exposure time and dye [32]. Coupling UV with ultrasound eliminates disinfection and reduces odour lamp byproducts, and is a viable alternative to chlorination with no byproducts (Naddeo et al. 2009 [32]). UV photocatalysis with rest TiO_2 composed materials under low conditions effluents ameliorates recalcitrant organic pollutants and has been integrated with membrane systems to treat waste. Fenton and UV/persulfate/Fe^{2+} processes improve COD, TOC, and turbidity removal (Bauer et al. 1999 [33]; Pourehie et al. 2019 [34]).

UV-based reactors are energy-efficient, compact, and versatile for advanced wastewater treatment.

2.8. Wastewater Treatment for Heavy Metal Removal

Effective treatment systems need to be developed to eliminate the risks posed by heavy metals in wastewater streams. Pb, Cd, Hg, Cr, and Ni are the heavy metals of concern, and they mainly stem from municipal/industrial activities. There are physical, chemical, and biological means of metal removal. Metals bound to particulates can be trapped using physical means such as sedimentation, filtration, and adsorption. In the chemical domain, dissolved metals can be converted into insoluble (and removable) entities by means of the coagulation, flocculation, and precipitation processes.

The environmentally sustainable biological methods of metal removal include biosorption, bioaccumulation, and phytoremediation. Advanced methods for the removal of heavy metals include ion exchange, membrane filtration, and some electrochemical processes Studies conducted in Oman show the varying degrees of effectiveness of wastewater treatment systems and the presence of heavy metal pollution in treated wastewater and contaminated seafood (Baawain et al., 2011 [35]; Baawain et al., 2013 [36]; Bazzi et al., 2014 [37]). These studies demonstrate the critical need for enhanced treatment systems, stronger, more consistently enforced policies, and the integration of processes for heavy metal removal.

2.9. Kinetic Modelling

The ability to optimise wastewater treatment processes, especially adsorption and anaerobic digestion systems, is one of the most critical applications of kinetic modelling, regarding different kinetic models. It is noted that these models are likely valid for anaerobic municipal wastewater treatment. Diffusion-controlled and surface reaction-controlled models that consider mass transfer, surface heterogeneity, and reaction rates at the solid-solution interface (Rudzinski and Plazinski, 2007 [38], 2017 [39]) have been used to analyse adsorption kinetics. Because substrate degradation is expected in a well-mixed system, first-order kinetic models are the most common in anaerobic digestion (Cecchi et al., 1991 [40]).

However, these models offer the most extraordinary computational simplicity. In contrast, step-diffusional models are more complex, as they detail hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In terms of greater precision, these models capture spatial and concentration gradients. Proper calibration, validation, and sensitivity analysis are key to providing a dependable kinetic prediction.

2.10. Design Wastewater by Using Aspen Plus

Recent work shows Aspen Plus has been successfully used as a simulation and optimisation tool in the design processes in water and wastewater treatment. In the case of treatment efficiency, energy use, and environmental sustainability, the use of Aspen Plus facilitated systematic evaluation. Chandrasekar et al. (2019) [41] used Aspen Plus for the optimisation of the wet oxidation process of industrial spent caustic wastewater, gaining considerable COD reduction at lower levels of energy and operational costs. Similarly, Tager and Naoushi et al. (2023) [42] utilised Aspen Plus to design and optimise wet air oxidation for hospital wastewater, addressing complex organic pollutants and pharmaceutical residues. Overall, these studies confirm that Aspen Plus facilitates process optimisation, cost-effective design, and environmentally responsible decision-making, supporting the development of sustainable and efficient water and wastewater treatment systems across domestic, industrial, and healthcare sectors.

3. Methodology

The methodology of this study was carried out in four systematic stages. First, the chemical characteristics of soluble and hydro-chemicals of various industrial effluents were studied in a batch aerobic bioreactor to establish baseline performance of treatment. A number of key variables were measured before and after the treatment, and they include pH, COD, BOD, TSS, and some selected heavy metals. Second, the design and construction of an integrated continuous aerobic bioreactor with a UV reactor was undertaken to improve the efficiency of wastewater treatment. The system was developed to enable continuous operation and to ensure adequate exposure of treated effluent to ultraviolet irradiation. Third, the performance of the integrated aerobic–UV system was evaluated by analysing changes in physicochemical properties and the removal efficiencies of heavy metals from treated effluents under steady-state conditions. Finally, kinetic modelling was performed to describe the degradation behaviour of the effluents in the integrated continuous aerobic bioreactor–UV reactor system. Suitable kinetic models were applied to experimental data to evaluate reaction rates and treatment efficiency. Industrial wastewater collected from the Oman Oil Refineries and Petroleum Industries Company (ORPIC), Oman Textile, and National Pharmaceutical Industries Co. (SAOC).

3.1. Preparation of the Algae for Biological Treatment

Microalgae culture (Tetraselmis spp.) obtained from Sultan Qaboos University was used for biological treatment. The microalgae were cultivated in filtered seawater using 250 ml conical flasks. The flasks were placed with LED strip lights and stirred continuously with a magnetic stirrer for 1 week.

The three stocks of nutrients for algae cultivation consisted of N/P (75 g of NaNO3 and 5.6 g of NaH2PO4.H20 mixed in 1 L of distilled water), trace elements (4.36 g of Na2EDTA, 3.15 g of FeCl2.6H2O, 0.0l g of CuSO4.5H2O, 0.022 g of ZnSO4.7H2O, and 0.01 g of CoCl2.6H2O in 1 L of distilled water), and vitamin mixture (0.05 g of cyanocobalamin, 0.1 g of Thiamine HCL, and 0.0005 g of Biotin into 1 L of distilled water) prepared.

1 ml of each nutrient stock was added to the algae culture daily for 10 days. After two weeks, the microalgae culture was transferred to an aquarium for larger-scale cultivation. 300 ml of the aquarium water containing the microalgae population was transferred to 1000 ml of oil effluent wastewater collected from an industrial facility for 10 days of treatment. The cultivation and preparation of algae are shown in Figure 1.

3.1.1. Experimental in a Batch Aerobic Bioreactor

The collected industrial wastewater effluent was filtered to remove solids. Subsequently, 250 g of activated carbon was added to 750 mL of effluent for 24 h. The activated carbon is subsequently filtered and removed from the effluents. 300 ml of aquarium water containing the microalgae was added to 1000 ml of effluent wastewater, and the mixture was stored for 10 days.

Fig. 1 Algae cultivation and preparation

The batch aerobic bioreactor (Figure 2) is supplied with oxygen from a compressor at 2.0 psi. The temperature will be maintained between 20–25°C with a pH range of 6.5–8.5. The retention time is between 2 h and 24 h, and the samples are collected for analysis.

Fig. 2 Batch aerobic bioreactor

3.2. Effluent Physicochemical Properties

3.2.1. pH

The pH values of the effluent samples were measured using a pH meter (Figure 3).

Fig. 3 pH meter

3.2.2. Chemical Oxygen Demand (COD)

COD measurements were performed by pipetting 2 mL of the effluent sample into a COD vial, mixing, and heating at 150°C for 2 h. The HANNA HI 839800 COD reactor was used for digestion, while the HANNA HI 83224 detected colour changes directly, providing COD data in mg O2 L-1. Figure 4 shows the COD analyser.

Fig. 4 COD analyser

3.2.3. Total Suspended Solids (TSS)

The effluent sample was filtered through a standard filter. The residue retained on the filter was dried to constant weight at 175 °C. The increase in weight of the filter represents the TSS, which includes all particles suspended in water that did not pass through the filter (Equation 1)

$$\text{TSS} = \frac{A-B}{V_{sample}} \times 100\% \quad (1)$$

Where

A is the weight of the filter plus dried residue (mg)

B is the weight of the filter (mg)

V_{sample} is the volume of the sample (L)

3.2.4. Total Organic Carbon (TOC)

The TOC of the effluent samples was determined using a TOC analyser (Figure 5).

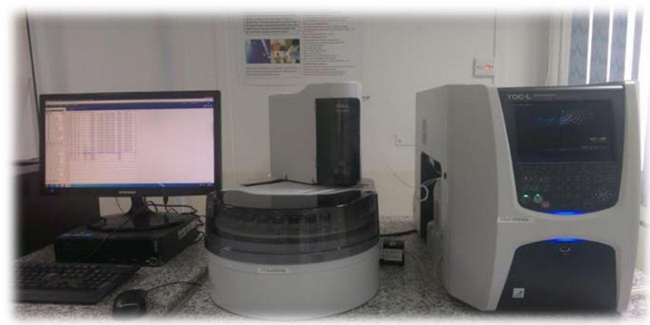

Fig. 5 TOC analyser

3.2.5. Dissolved Oxygen (DO)

The DO concentration of the effluent sample was determined using a DO Meter (Lutron DO5519), as shown in Figure 6.

Fig. 6 Dissolved oxygen meter

3.2.6. Temperature

The effluent samples' temperatures were measured using a temperature meter (Figure 7).

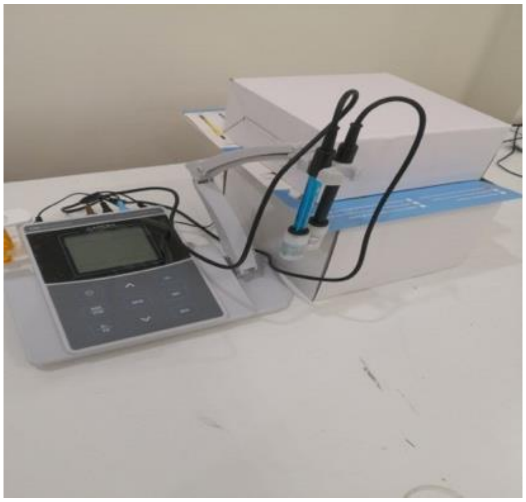

Fig. 7 Temperature meter

3.2.7. Total Dissolved Solids (TDS)

The TDS of the effluent samples was determined using a TDS meter (Lutron DO5519), as shown in Figure 8.

Fig. 8 Total Dissolved Solids (TDS) meter

3.2.8. Heavy Metal Content

The heavy metal content of the effluent samples was determined using an ICPE Plasma Atomic Emission Spectrometer (SHIMADZU ICPE-9000), as shown in Figure 9.

Fig. 9 ICPE plasma atomic emission spectrometer

3.3. Design Calculation of Continuous Aerobic Bioreactor and Ultraviolet Reactor for Treatment Of Industrial

3.3.1. Arobic Reactor

Design of the aerobic reactor made from acrylic with the various dimensions, parameters of the reactor:

Height = 1m= 100cm
The thickness of the wall is given as 1 mm
Diameter (D) = 2 × Radius of the tank (2r) = 12 cm
Radius of the tank (r) = 6 cm = 0.06 m
Material of reactor = Acrylic
Volume of a Cylindrical Tank
$V=\pi\times r^2\times h$
V = Volume of the tank
r= Radius of the tank
h = Height of the tank
$V=\pi\times r^2 \times h$
$= \pi\times (6)^2\times 100$
$= 11309.73\ cm^3 = 11.309$ liter $= 0.011309 m^3$
Surface Area of the Reactor
$A=2\times\pi\times r\times(r+h)$
$=2\times\pi\times (6) \times(6+100)$
$=2\times\pi\times (6) \times(106)$
$= 3996\ cm^2 = 0.3996\ m^2$

3.3.2. Pump / Centrifugal Pump

To determine the power of the pump and the flow rate required to pump fluid into the aerobic reactor with a height of 1 meter and a volume of 11309.73 cm = 11.309 litres = 0.011309m, we need to consider the following factors:

- Flow Rate (Q): The flow rate is the volume of fluid that passes through a given cross-sectional area per unit time. It is usually measured in litres per minute (L/min) or cubic meters per second (m^3/s).
- Power (P): The power required by the pump to move the fluid through the system. It is typically measured in watts (W) or horsepower (hp).
- Density of the Fluid (ρ): The density of the fluid being pumped affects the amount of mass that needs to be moved to achieve the desired flow rate.
- Acceleration Due to Gravity (g): Gravity plays a role in determining the pressure and energy required to lift the fluid to a certain height.
- Height (h): The height factor in the formula accounts for the elevation or head through which the fluid is being pumped. It represents the vertical distance the fluid must be lifted.

Given:
Height of the reactor, h=1 meter = 100 cm
Volume of the reactor, $V=11309.73\ cm^3 = 11.309$ litter $= 0.011309 m^3$
Density of fluid (ρ) = 1000 kg/m
Acceleration due to gravity (g) = 9.81 m/s

Flow Rate

To calculate the flow rate, we need to consider the time it takes to fill the reactor to maintain the volume V = 11309.73 cm^3 = 11.309 litres = 0.011309 m^3. Let us assume we want to fill the reactor in 1 hour (3600 seconds)
Time (t) = 1 hour = 3600 second

- Flow Rate = 3.14 m /s

Work Done by the Pump, Force (Weight Of The Water), Power Of The Pump, and Efficiency Of The Pump

- Work.= Force× Distance
- Force.=Weight of the fluid= Density ×Volume× Acceleration due to gravity

Power = Work/Time
Force = Weight of the fluid = Density ×Volume× Acceleration due to gravity
= 1000 × 0.011309 × 9.81 = 110.94N
Work= Force× Distance = 110.94 × 1= 110.94 J
Power = Work/Time =110.94/3600
= 0.0308 (J/S) KW = 30.8 W

Therefore, the power required to lift the wastewater to a height of 1m in 1 hour is approximately 0.0307W, and the flow rate needed is approximately 3.14 m/s.
The power and flow rate can be adjusted based on the timeframe (1 hour / 2 hours / 4 hours, etc.).

3.3.3. Efficiency of Centrifugal Pump

The efficiency of a given pump is the ratio of the output power to the input power. This ratio indicates the extent to which a given pump converts the input power to output power. The efficiency of a pump is usually less than 100%, and thus, in any given system. This implies that the output power is always less than the input power because of the losses in the system.

However, in real-world situations, pumps are not 100% efficient. Various factors, such as friction losses, mechanical inefficiencies, and heat losses, can reduce the output power relative to the input power. This is where the concept of pump efficiency comes into play. In an ideal scenario with no losses in the system, the input power to a pump should equal its output power. This means that all the power supplied to the pump is effectively transferred to the fluid being pumped, with no losses due to friction, inefficiencies, heat, or other factors.
To calculate the efficiency of a centrifugal pump that pumps water with a density of 1000 kg/m^3 to a height of 1 meter with a flow rate of 3.14 m^3/s and a power of 0.0308 W,

Given:
Density of water (ρ) = 1000 kg/m^3
Height (h) = 1 m
Flow rate = 3.14 m^3/s
Power of the pump = 0.0308 KW = 30.8 W
Acceleration due to gravity (g) = 9.81 m/s^2

In an ideal system, input power is equal to output power
Efficiency (%) = 100%

3.3.4. Compressor of Air in an Anaerobic Reactor

For the compressor pressure required to pressurise the air in the aerobic reactor to a certain depth, we need to consider the height of the water column in the reactor, the reactor volume, and the reactor area.

Given:

- Height of water column (h) = 1m
- Volume of the aerobic reactor = 11.309 liters = 0.011309 m^3
- Area of the reactor = 0.3996 m^2

The pressure required to fill the reactor with air can be calculated using the ideal gas law:
P= Nrt/V
n= number of moles of air
R is the ideal gas constant (approximately 8.314 J/(mol•K))
T is the temperature in Kelvin = 25 °C = 298 K
V=Volume of the Reactor

Molar Mass of Air

The molar mass of air is the composition of dry air, which is primarily nitrogen (N_2) and oxygen (O_2), with smaller amounts of other gases such as argon (Ar) and carbon dioxide (CO_2), and traces of different gases.
Given the composition of dry air: (Fraction)

- Nitrogen (N_2): 78.08%
- Oxygen (O_2): 20.95%
- Argon (Ar): 0.93%
- Carbon Dioxide (CO_2): About 0.04%

And the molar masses of these gases:

- Nitrogen (N_2): ~28.02 g/mol
- Oxygen (O_2): ~32.00 g/mol
- Argon (Ar): ~39.95 g/mol
- Carbon Dioxide (CO_2): ~44.01 g/mol

Molar mass of air as follows:
Molar mass of air= (Fraction of Nitrogen× Molar mass of Nitrogen) + (Fraction of Oxygen× Molar mass of Oxygen) + (Fraction of Argon× Molar mass of Argon) + (Fraction of Carbon Dioxide× Molar mass of Carbon Dioxide)
= (0.7808×28.02)+(0.2095×32.00)+(0.0093×39.95) +(0.0004×44.01)
= 21.878 + 6.704 + 0.371 + 0.0176
= 28.9706 g/mole

Molar mass of air = 28.9706 g/mole

Convert Molar Mass to Mole of Air

molar mass of air from 28.9706 g/mol to moles, following the

formula:
Number of moles = Given mass/ Molar mass
Given:
- Given mass = 28.9706 g
- Molar mass = 28.9706 g/mol

Substitute these values into the formula:
Number of moles= (28.9706) g /(28.9706) g/mol
Number of moles=1mole
Therefore, if the molar mass of air is 28.9706 g/mol, then 28.9706 g of air corresponds to 1 mole of air.

Pressure of Air
P = P= $\frac{nRT}{V}$ = $\frac{1\times 8.314\times 298}{0.011309}$ = 219079.6 pa
= 21.9076 Kpa

3.3.5. Calculation Of Storage Tank (Rectangular Tank 15liters)

15 litres is the maximum capacity required for the storage tank.
To calculate the dimensions of a rectangular tank with a volume of 15 litres = 15000cm
The possible set of dimensions that could work:
- Volume (V) = 15 liters
- 1 litre is equal to 1000 cm^3
- V=15×1000=15,000 cm^3

Dimensions of the tank are:
- Length (l) = 50 cm
- Width (w) =30 cm
- Height (h) = 100 cm

The formula for the volume of a rectangular
V= L×w×h = 50 × 30×100= 15000 cm^3

Therefore, a rectangular tank with dimensions of 50 cm in length, 30 cm in width, and 100 cm in height would have a volume of 15 litres (15,000 cm³).

3.4. Design Using Aspen Plus

Specialised software tool for designing and analysing hydraulic systems, particularly those involving pneumatic and hydraulic circuits.

Aspen plus+:
- Helps engineers model and simulate fluid power systems (hydraulic and pneumatic)
- Supports components like pumps, valves, cylinders, accumulators, and piping.
- Calculates pressure losses, flow rates, and efficiency in hydraulic circuits.
- Useful for optimising system performance and avoiding cavitation or excessive pressure drops.
- Assists in selecting appropriate tubing, hoses, fittings, and valves based on system requirements.
- Simulates both steady-state and dynamic (transient) conditions in hydraulic systems.
- Can export data for further analysis or integration with CAD software.

The experimental setup consists of an aerobic reactor, a UV reactor, a compressor, a feed tank, and a pump (Figure 10). The aerobic reactor made from an acrylic pipe of custom dimensions shows outcomes that surpass the expected values. We are going to install a decanting unit above the reactor zone. Sample ports are distributed at the height of the reactor (aerobic reactor). For a closed tank, the feed is pumped into the column. An outlet is positioned about 1 m from the base of the column. A provision was made to return the effluent from the column to the feed tank through a recycle line. The effluent sample was cooled in open tanks to room temperature and then fed to the aerobic reactor individually at 2 LPM (3.14 m³/s). Air is passed from the compressor to the reactor in the bottom portion using an air diffuser at approximately 3.168 psi. The system operated continuously, and after the filter, the feed flow was maintained at a specific rate to the aerobic reactor and subsequently to the UV reactor. The physicochemical properties (COD, TOC, DO, TSS, TDS, pH, and heavy metals) of the treated effluent were measured and compared with those of the initial effluent. Aspen Plus was used to design the system, and the full-dimensional size was determined.

3.5. Physicochemical Properties and Heavy Metals Removal from the Effluents in the Integrated System

3.5.1. Preparation of Effluents

Industrial oil effluent collected from the Oman Oil Refineries and Petroleum Industries Company (ORPIC). The collected industrial oil effluent was filtered to remove solids. Subsequently, 250 g of activated carbon was added to 750 mL of effluent for 24 h. Activated carbon is subsequently filtered and removed from the effluent. 300 ml of aquarium water containing microalgae was added to 1000 ml of effluent wastewater, and the mixture was kept for 10 days.

Synthetic wastewater was prepared by adding different concentrations of Cu, carbon, Cd, Pb, Ni, Zn, and Cr to 1000 mL of distilled water at 25 °C for 24 h, as shown in Table 1.

Table 1. Synthetic wastewater content constituents concentrations (mg/L)

Constituents	Concentrations (mg/L)
Copper	10
Carbon	100
Cadmium	0.5
Lead	5
Nickel	5
Zinc	10
Chromium	1

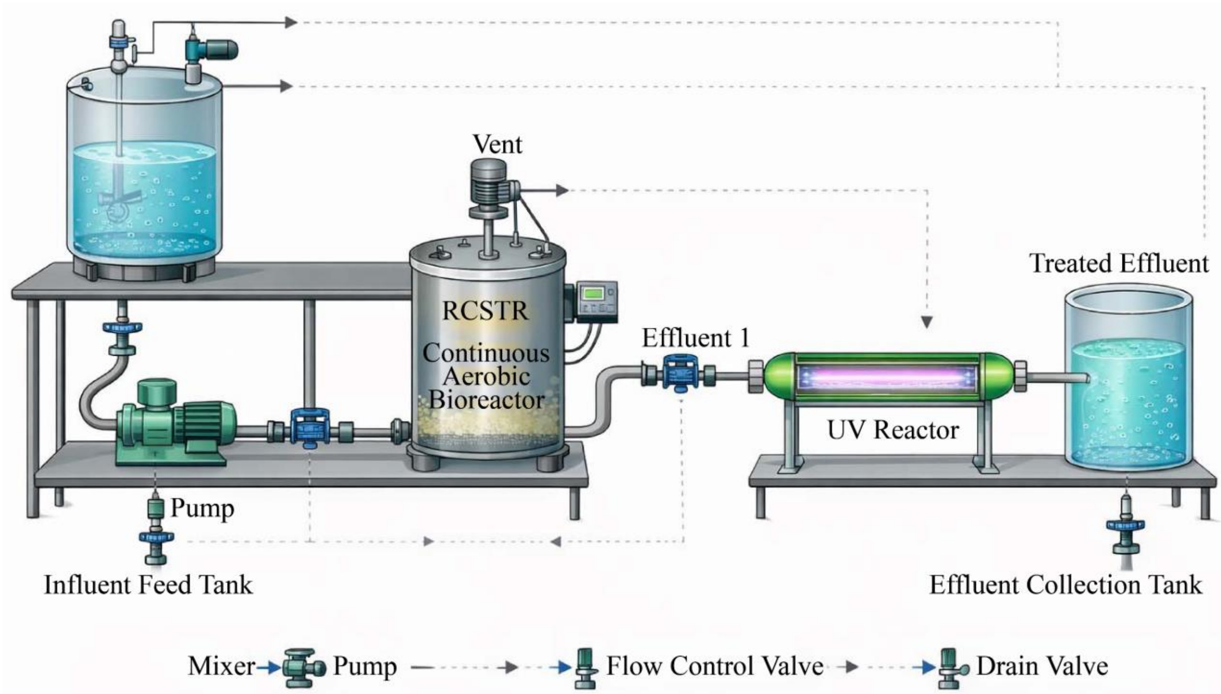

Fig. 10 An integrated continuous aerobic bioreactor and UV reactor fabricated to study the degradation of synthetic and real wastewater

3.5.2. Experimental Parameters

The temperature in the integrated system ranges between 20 and 25°C, with a flow rate of 2 L/min (3.14 m³/s) and a pressure of 3.17 psi. The retention time varied from 2 to 10 h.

3.5.3. Post-Treatment Sample Analyses

The post-treatment physicochemical analysis of the sample (COD, TOC, DO, TSS, TDS, pH, and the heavy metal content) was determined based on Section 3.2.4 Effluent Sample Analyses discussed previously.

3.6. Kinetic Modelling on the Degradation of the Effluents

The experimental data obtained from the integrated continuous aerobic bioreactor and UV reactor were compared with those from the batch system, fitted to the first-order, diffusional, and Singh models.

3.6.1. First Order Model

The following Equation expresses the first-order model.

$$-\frac{dC_s}{dt} = k_f C_s \tag{2}$$

The above model becomes the following Equation after integration.

$$\ln\left(\frac{C_{S0}}{C_S}\right) = k_f t \tag{3}$$

where

Cso = initial substrate concentration (mg COD/L)
Cs = substrate concentration (mg COD/L)
t = degradation time (h)
kf = first-order rate constant (h−1).

3.6.2. Diffusional Model

The diffusional model is given as follows.

$$-\frac{dC_s}{dt} = = k_d C_s^{0.5} \tag{4}$$

The above model becomes the following equation after integration.

$$C_s^{0.5} - C_{s0}^{0.5} = \frac{k_d}{2} t \tag{5}$$

where
Cso = initial substrate concentration (mg COD/L)
Cs = substrate concentration (mg COD/L)
t = degradation time (h)
kd = rate constant for the diffusional model.

3.6.3. Singh Model

The Singh model is shown as follows.

$$-\frac{dC_s}{dt} = \frac{k_S C_s}{1+t} \tag{6}$$

The above model becomes as follows after integration.

$$\ln\left(\frac{C_S}{C_{S0}}\right) = k_S \ln(1+t) \tag{7}$$

where
Cso = initial substrate concentration (mg COD/L)
Cs = substrate concentration (mg COD/L)
t = degradation time (h)
ks = rate constant for the Singh model

3.7. Aspen Plus–Based Design of an Integrated Continuous Aerobic Bioreactor and UV Reactor

3.7.1. Description of Processes

A continuous aerobic bioreactor with an incorporated UV reactor, as illustrated in Figure 11, was simulated in Aspen Plus for industrial wastewater with high organic load and a few trace heavy metals. While the aerobic bioreactor was the primary biological treatment unit for organic degradation, the UV reactor was the polishing unit for advanced oxidation and pathogen inactivation.

3.7.2. Set Up for Aspen Plus Simulation

Process simulation was carried out using Aspen Plus V12. The property method for NRTL was chosen to model behaviour in the aqueous phase. The influent wastewater stream was characterised based on empirical measurement of COD, BOD, TSS, and dissolved metals. A surrogate compound was used to represent organic matter (e.g., glucose or acetic acid), and an air stream supplied dissolved oxygen.

3.7.3. Modelling of the Continuous Aerobic Bioreactor

In Aspen Plus, the aerobic bioreactor was modelled using a CSTR (RCSTR) block. Biological degradation was modelled using stoichiometric equations for the aerobic oxidation of organic matter. Operating conditions for the reactor were as follows:

Temperature: 30 degrees Celsius
Pressure: 1 standard atmosphere
Hydraulic retention time (HRT): 8 hours
Aeration rate controlled to keep dissolved oxygen above 2 mg/L
The reactor performance was evaluated based on COD and BOD removal efficiencies.

4. UV Reactor Modelling

The UV reactor was modelled using an RPLUG reactor block, representing plug-flow behaviour. Advanced oxidation reactions were introduced to simulate UV-induced degradation of residual organics and heavy metals. UV intensity and residence time were incorporated as kinetic parameters. The UV reactor achieved further reduction in COD and enhanced effluent quality.

5. Process Evaluation

Aspen Plus simulation results showed that the integrated system achieved over 95% COD removal and a significant reduction in heavy metal concentrations. Energy consumption, reactor sizing, and operating parameters were optimised to ensure cost-effective and sustainable operation.

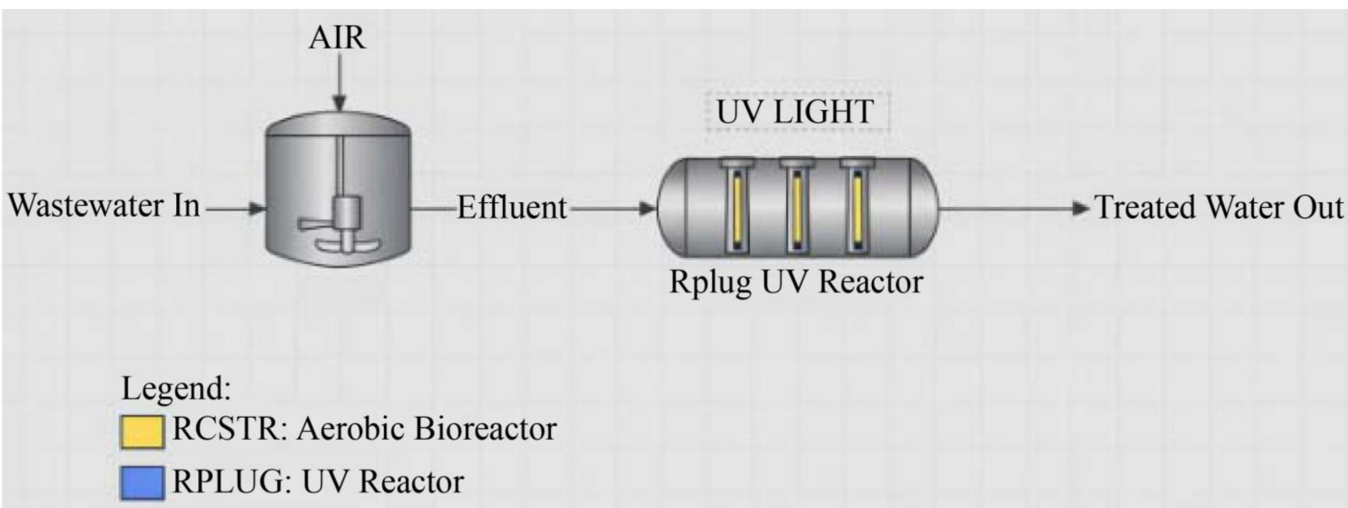

Fig. 11 Aspen plus model for the proposed methodology

6. Result and Analysis

6.1. Analyses of the Physicochemical Properties of Various Effluents Treated in a Batch Aerobic Bioreactor

The changes in the physicochemical properties (pH, COD, TDS, and TSS) of various industrial effluents (textile, pharmaceutical, and oil industries) were investigated using aerobic treatment in a batch system.

The samples were collected every 4 h, and the treatment efficiency was determined by analysis.

6.2. Chemical Oxygen Demand (COD)

Figure 12 shows the changes in COD removal percentage for various industrial effluents (textile, pharmaceutical, and oil industries) over time in a batch aerobic system.
The highest COD removal was observed at 24 h: 78.0% for pharmaceutical effluents, 87.6% for textile effluents, and 87.7% for oil effluents, with initial COD concentrations of 3532, 6672, and 8987 mg COD/L, respectively. The COD removal percentage increased with operation time for all initial concentrations.

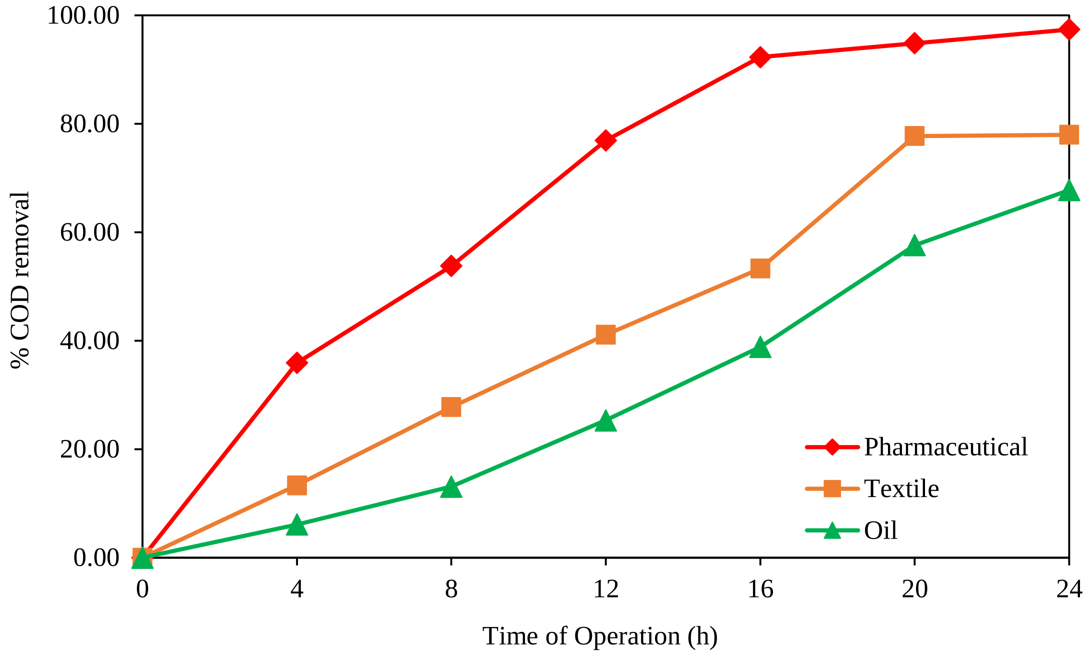

Fig. 12 COD removal (%) of the effluents (textile, pharmaceutical, and oil) using a batch aerobic system with respect to time (h)

6.3. Total Dissolved Solids (TDS)

Figure 13 shows changes in TDS for various industrial effluents (textile, pharmaceutical, and oil) over time using a biological aerobic batch system. It was observed that the TDS decreased for all effluents over time, with the lowest TDS obtained after 24 h. The TDS significantly reduced from 2900 mg/L (textile effluent), 3670 mg/L (pharmaceutical), and 3700 mg/L (oil) to 365 mg/L (textile), 1003 mg/L (pharmaceutical), and 1000 mg/L (oil) after 24 h.

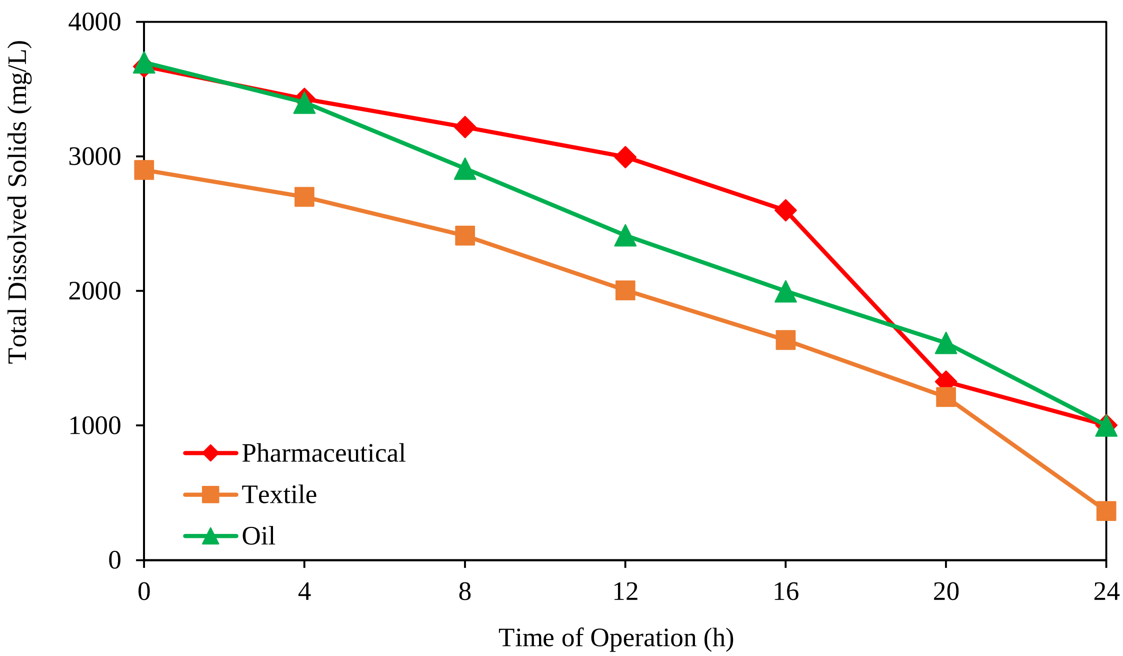

Fig. 13 TDS of the effluents (textile, pharmaceutical, and oil) using a batch aerobic system with respect to time (h)

6.4. Total Suspended Solids (TSS)

Figure 14 shows the changes in TSS for various industrial effluents (textile, pharmaceutical, and oil) over time in a biological aerobic batch system. Similar to the TDS of effluents reported previously, the TSS decreased for all effluents, with the lowest TSS obtained after 24 h. TDS significantly reduced from 1597 to 816 mg/L in the textile effluent after 24 h. In contrast, the TDS of the pharmaceutical effluent decreased from 2080 mg/L to 912 mg/L. Finally, TDS decreased from 2800 mg/L to 918.9 mg/L for the oil effluent.

6.5. PH

Figure 15 shows the changes in pH of various industrial effluents (textile, pharmaceutical, and oil industries) over time in a biological aerobic batch system.

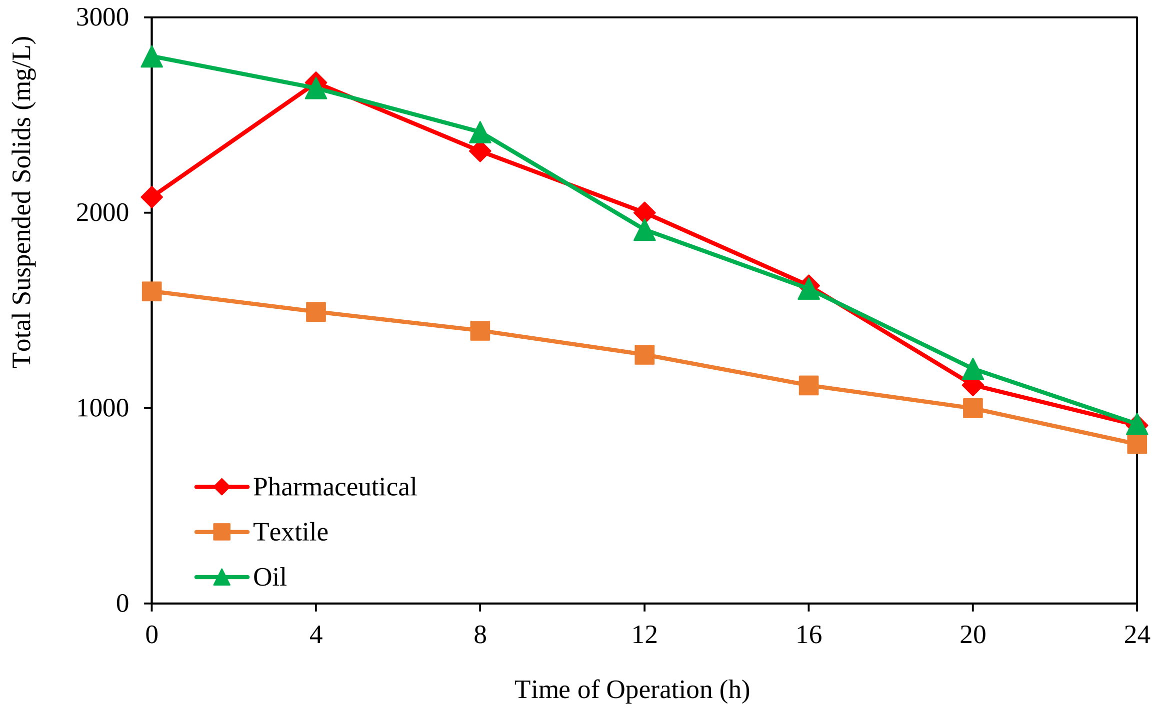

Fig. 14 TSS of the effluents (textile, pharmaceutical, and oil) using a batch aerobic system with respect to time (h)

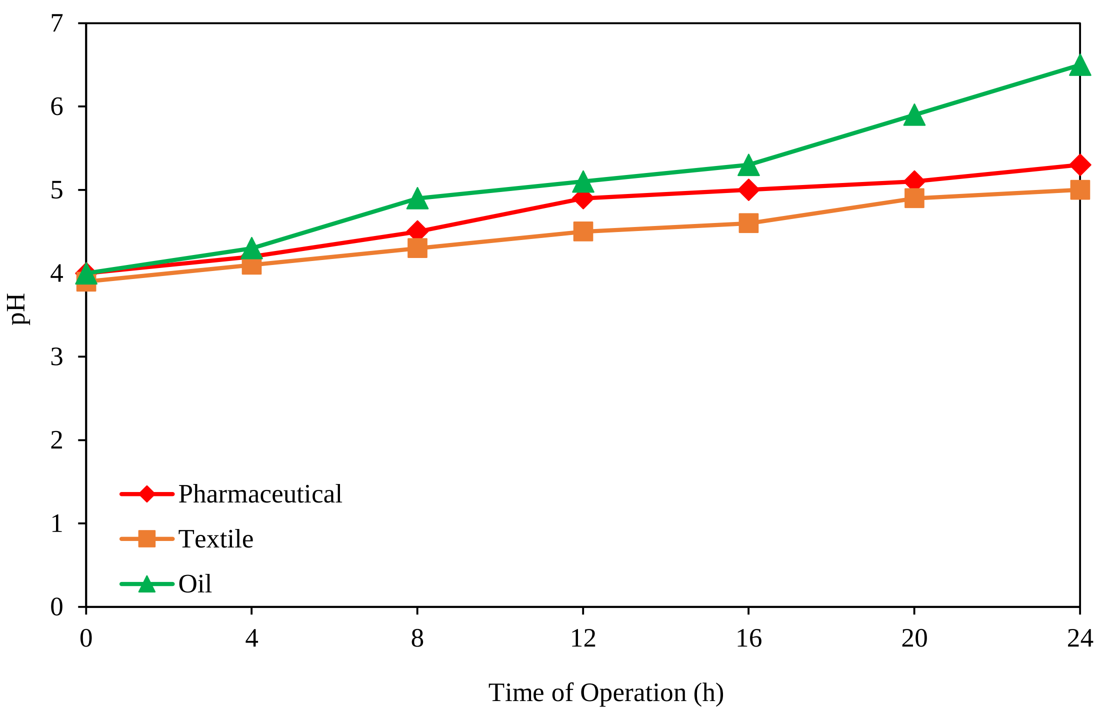

Fig. 15 pH of the effluents (textile, pharmaceutical, and oil) using a batch aerobic system with respect to time (h)

The pH of all the effluents increased over time, initially from acidic to near-neutral. This indicates that aerobic batch treatment is suitable for increasing effluent pH.

6.6. Kinetic Modelling of the Degradation of the Effluents in a Batch Aerobic System

Kinetic modelling has also been proposed for the degradation of effluents to determine the best model to explain the degradation mechanism of effluents (textile, pharmaceutical, and oil) in a batch aerobic system.

6.6.1. First Order Model

Figure 16 shows the kinetic plot for the degradation of textile, pharmaceutical, oil, and effluent waste based on the first-order model.

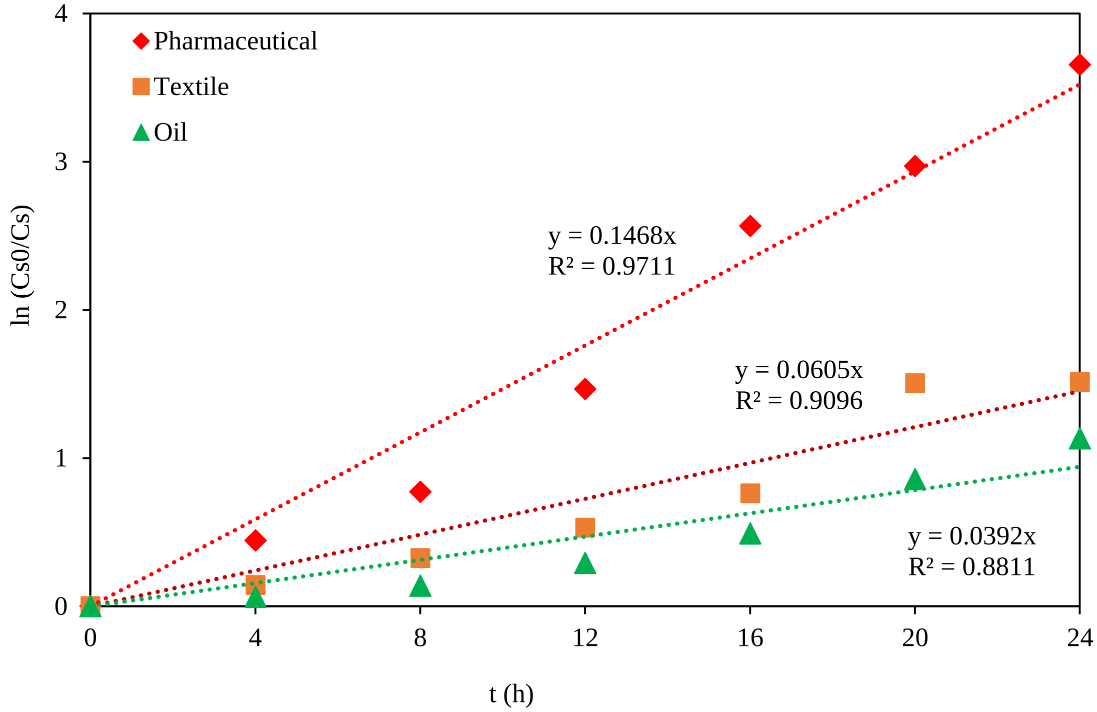

Fig. 16 Kinetic plot for the degradation of the effluents (textile, pharmaceutical, and oil) using a batch aerobic system based on a first-order model

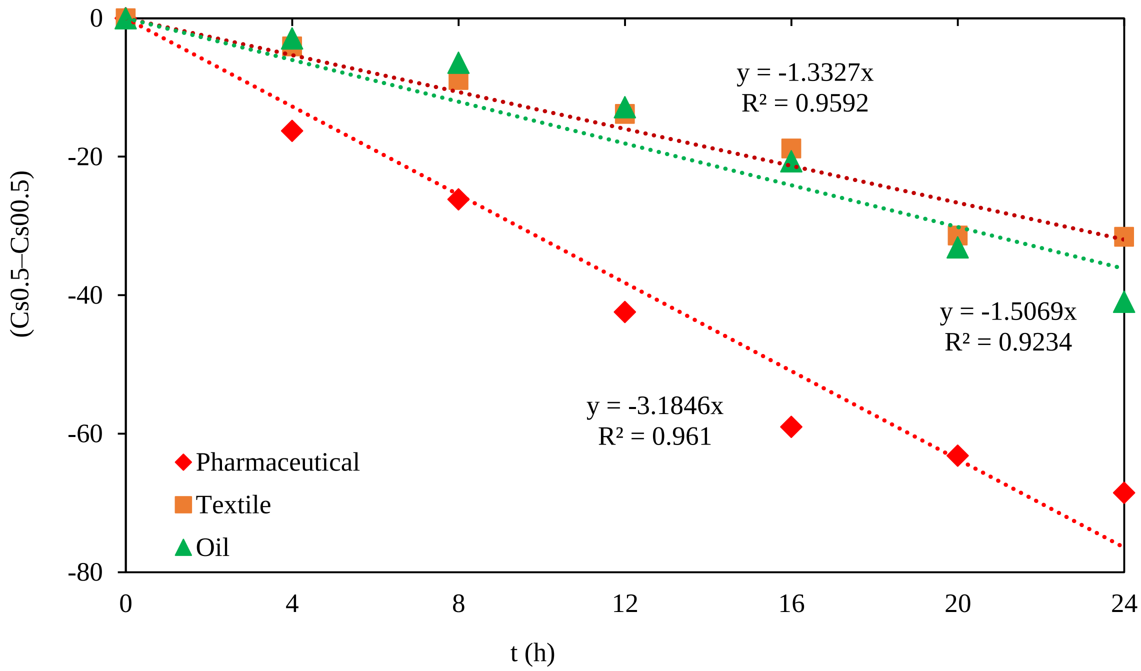

Fig. 17 Shows the kinetic plot for the degradation of textile, pharmaceutical, and oil effluents based on the diffusional model

From the kinetic plot of the first model for the effluents (textile, pharmaceutical, and oil), the determination coefficient (R2) values were 0.9895 (pharmaceutical), 0.9628 (textile), and 0.9446 (oil), which were approximately 1. The high R2 value for the first-order model indicated the model's fitness for the degradation of effluents (textile, pharmaceutical, and oil).

6.6.2. Diffusional Model

Figure 17 Kinetic plot for the degradation of the effluents (textile, pharmaceutical and oil) using a batch aerobic system based on a diffusional model From the kinetic plot of the diffusional model for the effluents (textile, pharmaceutical, and oil), the determination coefficient (R2) values were 0.9894 (pharmaceutical), 0.9854 (textile), and 0.9672 (oil), which are approximately 1.

6.6.3. Singh Model

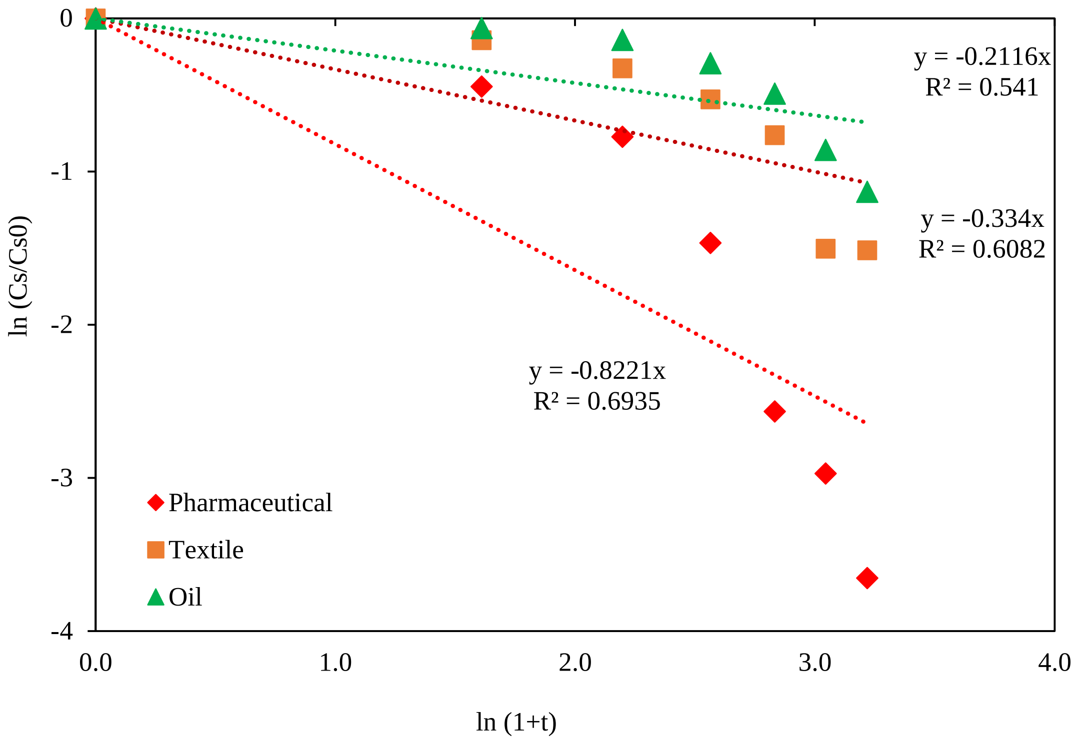

Fig. 18 Shows the kinetic plot for the degradation of textile, pharmaceutical, and oil effluents based on the singh model

Figure 18 Kinetic plot for the degradation of the effluents (textile, pharmaceutical, and oil) using a batch aerobic system based on the Singh model. From the kinetic plots of the Singh model for the effluents (textile, pharmaceutical, and oil), the determination coefficient (R2) values are lower than those of the previously discussed models (first-order and diffusional).

The R-squared values were 0.8882 (pharmaceutical), 0.8388 (textile), and 0.7864 (oil). The low R2 value for the Singh model indicates its inability to describe the degradation of effluents (textile, pharmaceutical, and oil) using a biological aerobic batch system.

Table 2 suggests that the first-order model best described effluent degradation (textile, pharmaceutical, and oil) using a biological aerobic batch system. The negative rate constant in the diffusional model, as well as the low R2 values for the Singh models, show that the models fail to capture the process in question.

Table 2. Kinetic analysis for the degradation of the effluents (textile, pharmaceutical, and oil) using a batch aerobic system based on first order, diffusional, and the singh model

Kinetic Models	Pharma- -ceutical	Textile	Oil
First Order Model			
kf (h-1)	0.1468	0.0605	0.0392
R2	0.9895	0.9628	0.9446
Diffusional Model			
kd	–1.5923	–0.6664	–0.7535
R2	0.9894	0.9854	0.9672
Singh Model			
ks	0.8221	0.3340	0.2116
R2	0.8882	0.8388	0.7864

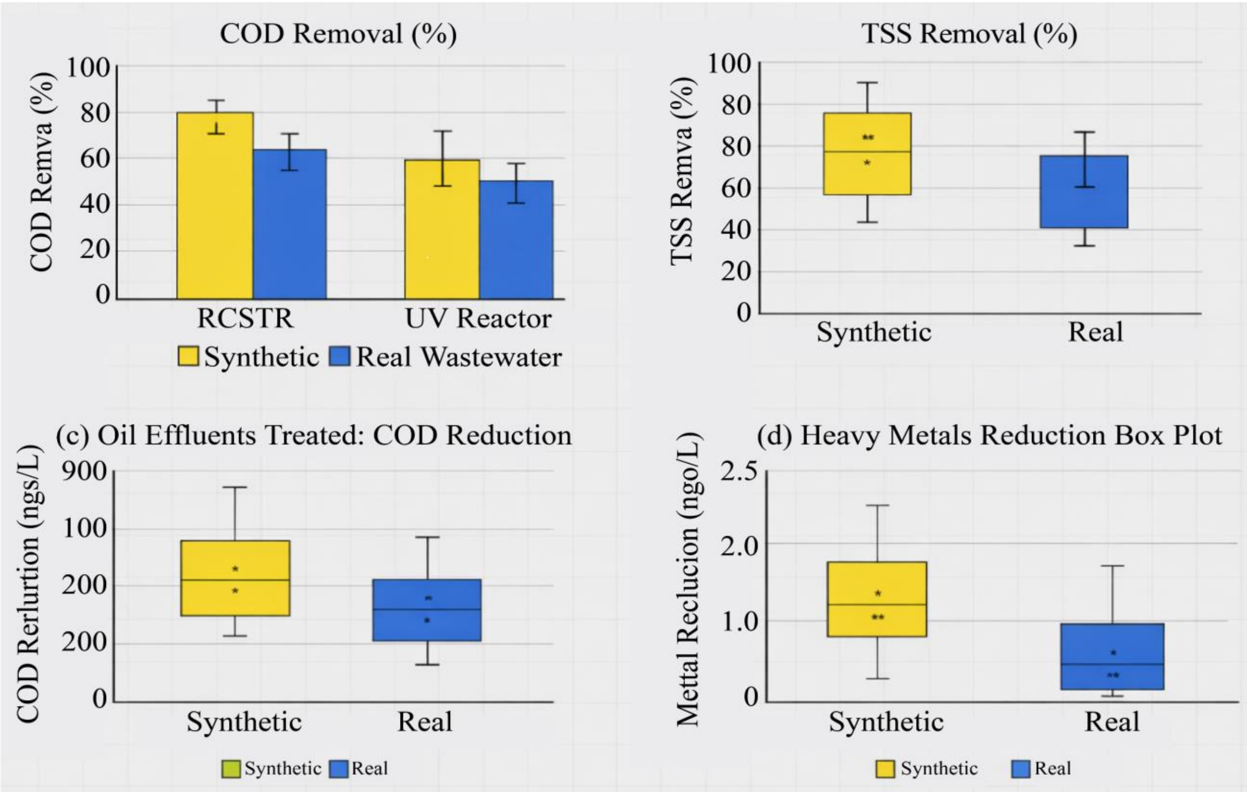

Fig. 19 Statistical analysis based on the physicochemical properties

Figure 19 presents a trend analysis of the efficacy of treatment integrated with a Continuous Aerobic Bioreactor and UV reactor of synthetic and real oil effluents. The analysis compared the physicochemical properties of the real and synthetic oil effluents. In the COD removal analysis, RCSTR achieved around 80% reduction of synthetic wastewater and 65% reduction of real sewage. UV reactor further reduced cod by 60% and 50%, respectively, thus UV treatment alone was not good enough.

However, the combination of biological and chemical treatment improved the overall removal. In real wastewater, TSS removal was in the 55 to 70 percent range. However, this was higher (75 to 80 percent range) in synthetic wastewater. The higher percentage removal in synthetic effluents suggested less complex oil matrices. In the COD reduction analysis of oil effluents, median values were higher in synthetic wastewater. However, in real effluents, there was a greater spread of values, which indicates variability in the organic load and the treatment resistance.

The heavy metal reduction (bottom-right) indicates partial removal, with synthetic wastewater achieving higher median reductions (~1–1.5 mg/L) than real effluents (~0.5–1 mg/L). In summary, the data show that synthetic effluents perform better in COD and metal removal than real wastewater, with greater variability, indicating that the process requires optimisation for complex industrial effluents.

7. Conclusion and Future Scope

The integrated system of a continuous aerobic bioreactor and a UV reactor shows promising potential for treating industrial oil effluents. The physicochemical analysis revealed that real and synthetic oil effluents showed COD reductions of 65–80% and 75–85%, respectively, and TSS removals of 55-75%. Standard deviations indicated that the system performed reliably across the different experimental runs. Substantial removal and efficiencies were modelled for the heavy metals Cu, Zn, and Pb, with removal ranging from 40% to 70% across different influent concentrations. Modelling showed that, for the most part, the degradation followed pseudo-first-order kinetics, and the step-diffusion models accounted for the bioreactor, which was further in line with the treatment mechanism. UV light contributed to polishing the effluents by killing more than 90% of the microorganisms, thereby ensuring compliance with effluent standards and regulations at both the national and international levels. The study showcases the system's adaptability, enabling it to adjust retention time, algal inoculum, and UV exposure across different wastewater compositions. The system's ability to statistically remove pollutants demonstrates its prospects for industrial-scale use. Future research should investigate scalable studies that integrate real-time tracking and automated management systems to maximise treatment effectiveness and energy optimization with the support of image processing [43]. Sophisticated modelling incorporating machine learning may be able to estimate effluent quality under different operational parameters. Moreover, the addition of membrane filtration and/or advanced oxidation processes to synergistic treatment may further improve the removal of heavy metals and the degradation of organics. Implementing these techniques would expand the integrated system's capacity to handle various industrial effluents, thereby enhancing sustainable wastewater management and environmental protection. The role of Artificial Intelligence in the treatment of industrial effluents is a new area of research that offers the potential to measure multiple parameters in cyber-physical systems (Vijayalakshmi, K., 2011 [44]). Artificial Intelligence (AI) and Machine Learning (ML) in Industrial Effluent Treatment have enabled the development of control processes, predictive modelling of treatment performance, and increased contaminant removal efficiency [45]. Machine learning (ML) in real-time management and fault-detection systems can identify and mitigate COD, BOD, and wastewater toxicity. AI-based optimisations have improved the even distribution of chemicals and reduced energy consumption while supporting advanced treatment technologies for sustainable management of industrial wastewater.

In addition, the ML application will help reduce the costs associated with optimizing wastewater treatment parameters [46], which will be the subsequent extension of the research.

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