

Approach in Choosing Suitable Technology for Industrial Wastewater Treatment

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Abstract

The increasing growth of rapid industrial developments causes the formation of huge amount of wastewater loaded with numerous organic compounds unacceptable for the environment and human health as well. Many processes for treating industrial wastewater involve varieties technologies for reduction of toxicity in order to meet environmental-based treatment standards. This article reviews the recent developments and technical applicability of various treatments for the removal of different contaminants from industrial wastewater. A particular focus is given to the factors affecting the selection of appropriate technologies for controlling and managing of a specified industry effluent. Subsequent to the selection of appropriate treatment technology, more pilot-plant scale experiments with real industrial wastewater must be performed on a larger scale. However, there are a very wide variety of technologies for choosing a suitable individual to treat specified wastes; intergradations of more than one technology could be more economic for removal of high strength and toxic industrial. The new integrated technology requires assessing the complete wastewater treatment in order to be reused in the industry itself.

Keywords: Industrial wastewater; Treatment technologies; Biodegradation; Modeling

Introduction

Industrialization has resulted in the formation of huge amount waste products, which are released into the environment in the form of wastewater leading to environmental pollution and deterioration. Pollution and amount of industrial contamination wastes that cause interference with the best usage of the receiving water have begun with the turn of the twentieth century [1]. The wastewater loaded with numerous complex and toxic organics are harmful for the environment. Removal of toxic and hazardous compounds from industrial wastewater (IWW) presents a great issue for protecting natural resources and enables the possibility of reuse of this water, saving the fresh and natural water in the same time, as the priority of sustainable development and environmental protection [2]. New directives and regulations demand the necessity for finding the optimal solution of treatment in order to decrease hazardous compounds below the maximal concentration prescribed by the regulations. The constituents of the IWW are highly variable and specific. The approach used to treat and dispose of IWW is distinctly different from that used for municipal wastes [3]. Many technologies are available for pollution control of IWW. Choice of suitable process needs appropriate methodologies.

This paper reviews the different recent researches and technologies for the decontamination of a wide range of IWW. Special emphasis is placed on recent studies of selection and combination schemes developed for toxic and non-biodegradable wastewater treatment (WWT) and reuse for different kind of industries.

Methodology and Approach of the Study

This paper uses an approach for reviewing of IWW treatment (IWWT) processes with selecting an effective and optimal process for each kind of industry. This methodology includes review methods of treating according to characteristics and the variety of the wastewater inside each industry. Available technologies for treating IWW will be discussed with the new trends of IWWT technologies and special kinds that are only suitable for special wastes. Then, the paper will discuss the methodology and steps that are required for selecting a treatment process for an industrial waste.

Thereafter, the common and the well-known industries will be

reviewed with emphasis on the water uses in each industry, main pollutant produced, characteristics of its wastewater, and main technologies used for treating its wastes. The paper will also discuss modeling of IWWT technologies and its effect in managing and controlling of treatment processes.

Methods for treating wastewaters from industry

Technologies for treating IWW according its characteristics are generally divided into three categories: biological methods, chemical methods, and physical methods. Figure 1 shows candidate technologies for treating IWW based on its characteristics [3].

Waste equalization and pH control are among the most effective waste management procedures of the waste stream. The concentrations and quantity of individual constituents in a given IWW typically vary over wide ranges through the day, as processes are started up, operated, shut down, and cleaned. Sometimes equalization may produce an effluent that warrants no further treatment [1]. Equalization of IWW usually includes pH adjustment for complying with governing regulations and conserving conditions for aquatic-life in receiving waters.

Biological methods of wastewater treatment: The principal applications of the biological processes are: carbonaceous organic material representing in biochemical oxygen demand (BOD) removal, nitrification, denitrification, stabilization, and phosphorous removal. It is convenient to classify biological processes as either aerobic or anaerobic (anoxic and anaerobic). Aerobic biological processes are commonly achieving high degree of treatment efficiency, while anaerobic uses the concept of resource recovery and utilization with

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achieving objective of pollution control. Table 1 shows comparison of aerobic and anaerobic treatment [3,4].

The acclimatized activated sludge system had an inherent stability, and was extremely effective at removing complex organics of acetone and methylisobutyl ketone from several 100 mg/L down to 10 µg/L [5]. Constructed wetlands (CWs) are good candidates to biologically treat IWW. Four parallel pilot-scale free water surface CWs, using phragmites communis as emergent plant in media of vesicles ceramic bioballs, indicated (with a 5 day hydraulic retention time -HRT) optimal pollutant removal of 61% chemical oxygen demand (COD), 89% BOD, 81% total suspended solids (TSS), 35% total phosphorous (TP), and 56% ammonia- nitrogen (NH₄-N) for treating IWW [6].

In recent years, high rate anaerobic/aerobic bioreactors have been increasingly employed for degradation high strength IWW with advantage of minimal space requirements, low capital cost and good COD removal efficiencies (in excess of 83%) [4]. An anaerobic upflow blanket filter “UBF” -aerobic membrane bioreactor (MBR) system (Figure 2) was reported to demonstrate an apparent COD removal of 99% in the treatment of high-strength wastewater with COD range of 6000-14,500mg/L at a relatively short HRT of 24 h [7]. While this is impressive, it was noted that membrane fouling was observed and the

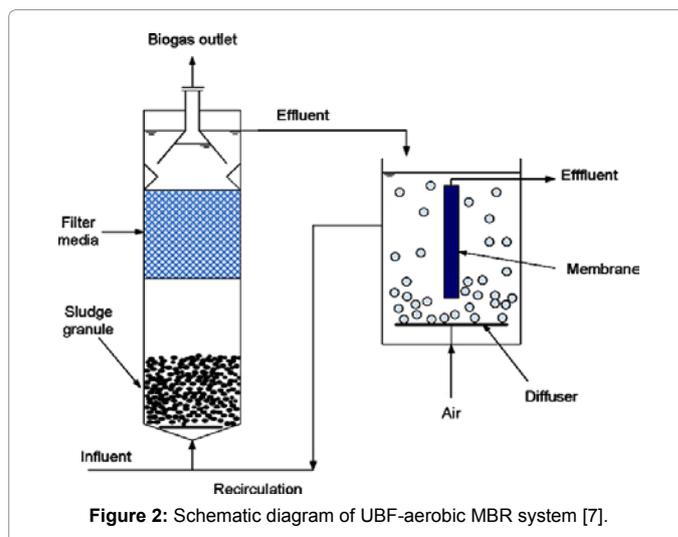
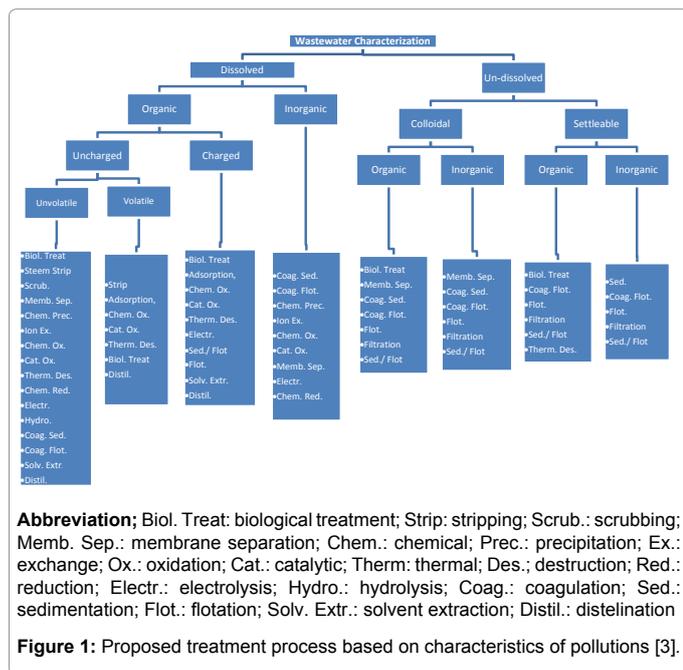


Figure 2: Schematic diagram of UBF-aerobic MBR system [7].

transmembrane pressure was about 9 times higher than that operated under the same conditions. Also, a staged anaerobic/aerobic MBR (Figure 3), in which the membrane module is submerged in the aerobic zone, has been employed successfully in the treatment of high strength synthetic wastewater containing high COD up to 10,500 mg/L and NH₄⁺-N up to 1220 mg/L [8]. Porcelain carriers are installed to prevent the blockade of the orifices.



Abbreviation; Biol. Treat: biological treatment; Strip: stripping; Scrub.: scrubbing; Memb. Sep.: membrane separation; Chem.: chemical; Prec.: precipitation; Ex.: exchange; Ox.: oxidation; Cat.: catalytic; Therm: thermal; Des.: destruction; Red.: reduction; Electr.: electrolysis; Hydro.: hydrolysis; Coag.: coagulation; Sed.: sedimentation; Flot.: flotation; Solv. Extr.: solvent extraction; Distil.: distillation

Figure 1: Proposed treatment process based on characteristics of pollutions [3].

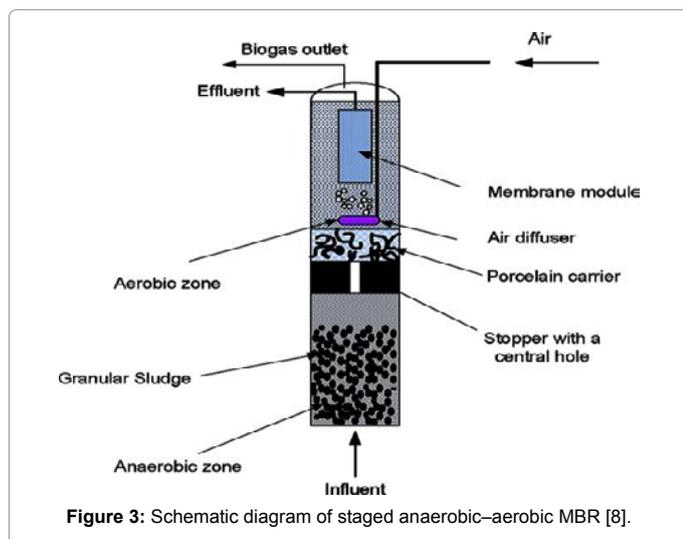
Feature	Aerobic	Anaerobic
Organic removal efficiency:	High	High
Effluent quality:	Excellent	Moderate to poor
Organic loading rate:	Moderate	High
Sludge production:	High	Low
Nutrient requirement:	High	Low
Alkalinity requirement:	Low	High for certain waste
Energy requirement:	High	Low to moderate
Temperature sensitivity:	Low	High
Start up time:	2–4 weeks	2–4 months
Odor:	Less odors	Potential odor
Bioenergy recovery:	No	Yes
Mode of treatment Total:	Essentially	Pretreatment

Table 1: Comparison of aerobic and anaerobic treatment [4].

Industrial ecology has recognized as one step in “waste utilization” rather than “waste treatment” in the late 1990s. Ehrenfeld and Gertler [9] reported on a naturally evolving industrial ecosystem in Kalundborg, Denmark, for treating four main industries comprise the “heart” of the ecosystem: Power station, Oil refinery, Pharmaceutical and enzyme manufacturer, and Plasterboard manufacturer. Also, pellets of white rot fungus were used in air pulsed bioreactor for the continuous treatment of textile wastewater [10]. Continuous treatment of real industrial textile wastewater under non-sterile conditions was carried out during 15 days resulting in dye concentrations of environmentally acceptable to be discharged into a municipal WWT plant (WWTP). The macrofungus *Pleurotus platypus* was investigated in a fixed bed column for removing of cadmium Cd (II) from industrial wastewater [11]. Three cycles of biosorption in the macrofungus fixed bed column were established and proved to be the potential biosorbent for the removal of Cd (II) from industrial effluents.

Chemical methods of wastewater treatment: This treatment can be used for removing substances through: 1) producing insoluble solids and gas, 2) producing coagulation of a colloidal suspension, 3) producing biological degradable substances from nonbiodegradable, 4) destroying or deactivating chelating agents, and 5) producing nonobjectionable substances that can be removed more easily. Coagulants allow the colloidal particles to join together by slow stirring. Some highly objectionable substances can be chemically oxidized to produce non-objectionable substances, such as CO₂ and water. For biorefractive compounds in IWW that are not completely removed by biological treatment, additional physical and/or chemical treatments are necessary to enhance their biodegradability. Electro-coagulation could quickly coagulate and remove the colloidal and suspended particles, then electro-oxidation oxidizes the remaining organics. The coupled process eliminates COD, BOD, color, turbidity, and coliforms in a practical HRT (2h) [12].

Advanced Oxidation Processes (AOPs) are considered a highly



competitive IWWT technology for the removal of organic pollutants that not treatable by conventional techniques [13]. Free radicals (hydrogen peroxide- H_2O_2 , UV, fenton's reagent, ozone- O_3) are powerful oxidizers that can convert many organics all the way to CO_2 , water, and fully oxidized states of other atoms that were part of the original organic pollutants, including sulfates and nitrates [13]. Many oxidation treatments have traditionally been studied for this purpose, including photo-chemical degradation processes (UV/ O_3 and UV/ H_2O_2) [14,15], photo-catalysis (TiO_2 /UV, Fenton and photo-Fenton process) [16], and chemical oxidation processes (O_3 , O_3/H_2O_2 , and H_2O_2/Fe^{2+}) [17,18].

Combination of AOPs/biological technologies for treatment of certain difficult (or impossible) IWW were used and have greatly increased the removal of difficult pollutants [19]. The ability to increase biodegradability and detoxify effluent streams containing polar and hydrophilic chemicals by alternative treatment with AOPs, such as photo-catalysis, ozonation, and ultrasound-oxidation has been extensively studied in the recent years [20-24]. A wide variety of Fenton's reagent applications have already been reported for treating many kinds of IWW [25]. Table 2 shows the operating conditions in different Fenton processes for treating different IWW. Pre-treatment of simulated IWW containing organic and inorganic compounds by oxidative degradation using homogeneous Fenton type processes (Fe_2^+/H_2O_2 and Fe_3^+/H_2O_2) conducted to removal of up to 94% of initial total organic carbon (TOC) after 120 min [2]. Ferrous sulfate was found to be the most appropriate reagent for Fe_2^+ and H_2O_2 to reduce the TOC and sludge production.

Dopar et al. [16] used photo-Fenton process operated with artificial UV-C irradiation and solar light UV-A application for biodegradation of complex organic compounds. Hydrodynamic cavitation induced by a liquid whistle reactor has been used in conjunction with the advanced Fenton process for treatment of bio-refractory materials where their toxicity be decreased, then conventional biological oxidation can be employed for final treatment [26].

Physical methods of wastewater treatment: This treatment accomplish removal of substances by use of naturally occurring forces, such as gravity, electrical attraction, and van der Waal forces, as well as physical barriers. Physical methods of WWT include sedimentation, flotation, and adsorption, as well as barriers such as bar racks, screens, deep bed filters, membranes, electro dialysis and ion exchange.

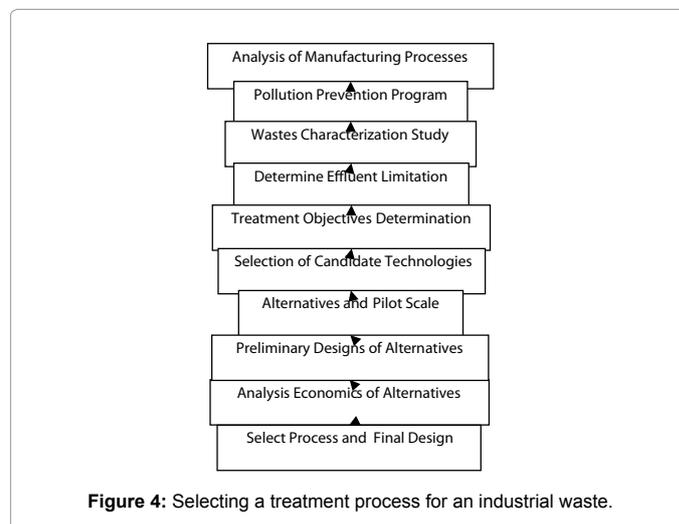
Segregation of TSS from any industry's waste plays an important part in its overall waste treatment program for elimination a major portion of the contaminant and for separation of one type of contaminant for more easily and economically further treatment. Flotation of small particles in suspension can be flocculated and buoyed to the liquid surface and removed by skimming. Membrane processes can enhance conventional processes by concentration of components in the reactor, such as in a MBR. Membrane processes have a good efficiency of water recycle and reuse to meet water reusable request in many industries (foodstuff, leather, textile, electronic industry) [27].

Adsorption on activated carbon may be used for removal many compounds from wastes such as: pesticides; 2, 4-D herbicides and carbamate insecticides, DDT, chlorobenzene, and p-chlorobenzene sulfonic acid. Low cost and non-conventional adsorbents include agricultural by-products (which are renewable and inexpensive) such as nut shells, wood, bone, peat, coconut shells, processed into activated carbons [28]. Bansode et al. [29], have reported the important of adsorbents for the removal of heavy metals (HMs) and organics from municipal and IWW. Ion exchange can be used to remove undesirable ions from IWW as a final treating step, as treatment for isolated process streams in a waste minimization program, or prior to recycle and reuse of IWW. Superconducting magnetic has combined with magnetic seeds for treating paramagnetic and diamagnetic pollutants [30].

Land application of several versions is used for WWT method, including spray irrigation, wetlands treatment, overland flow, and hyponics. Deep-well injection has been used to dispose of organic solutions from chemical, pharmaceutical, petrochemical, paper, and refinery; in addition, many inorganic solutions may be disposed of in this manner [1].

Selecting a treatment process for an industrial waste

The main goal of design an IWWT process is to minimize the volume and toxicity and the final treatment residue, since final disposal can incur significant cost and liability. Regardless of the industry, the evaluation and selection of waste treatment technologies typically follows a logical series of steps that help to meet the goal of minimizing waste toxicity and volume. In scope of an IWWT plant (IWWTP) design, multiple process alternatives which suit all related law and regulations should be considered and the technical and economical aspects of these alternatives should be evaluated by detailed comparative cost analysis, which should include investment, operation,



Origin of the wastewater (WW)	Initial load	Operational conditions						Removal (%)
		pH	Temp °C	H ₂ O ₂ conc.	Fe ₂ ⁺ conc.	H ₂ O ₂ / Fe ₂ ⁺	COD/ H ₂ O ₂	
Textile WW	2400 mg/L COD	3	50	385 g/L	5.5 g/L	95–290	NMa	95% COD
Laboratory WW	1037 ± 136 mg/L COD	4	24 ± 1.5	NM	NM	4.5	1:9	92.3% COD
IWW and domestic ww	1750–3323 mg/L COD	3±.2	40	550 mg/L	400 mg/L	NM	NM	>90% COD
Cosmetic WW	1215, 785 mg/L TOC	2–3	25–75	9040 mg/L	200 mg/L	45	1/2.12	45–60% TOC
Dyes	0–2000 mg/L COD	3	25	1.2–4.4mM	NM	0.20–0.37	NM	48–70% COD
Synthetic dyebath	2746 mg/L COD	3	50	30mM	10mM	3	NM	30% COD
Landfill leachate	1000,4000 mg/L COD	2.5	25	0.15 mol/L	0.05 mol/L	3	NM	89.2, 68.2% COD
Leachate	132–177 ± 8 g/L COD	3	25	NM	NM	NM	1	75%, 77 ± 8% COD
Pesticide (atrazine)	0.01mM atrazine	2	25	NM	0.01–0.2mM	0.33–3.0	NM	15–98% atrazine
Green olives	31, 7.5 g/L COD	2–3	25	1.0M	0.03M	NM	0.54–0.13	14.4 5 g/L COD
Pharmaceutical	900–7000 mg/L COD	3.5	25	0.3M	0.002M	155	NM	45–65% COD
Cork cooking WW	5000 mg/L COD	3.2	30	10.6 g/L	NM	5	NM	87.3% COD
Pulp mill effluents	110 mg/L TOC	5	25 ± 2	50mM	2.5mM	20	NM	87.5% TOC

Table 2: shows the operating conditions in different Fenton processes [25].

maintenance and rehabilitation costs, in order to determine optimum treatment for the industry [31]. Figure 4 illustrates the approach for developing a well-operating, cost-effective treatment system for IWW as described in detail in the following text.

Step 1) Analysis of manufacturing processes: It is to show the raw material for processes, supply of water to each manufacturing process, how contributes wastewater generation and all other processes parameters. The first step achieves familiarity with the manufacturing processes themselves through literatures review, site visits and interviews to gain an understanding of how wastewater is produced.

Step 2) Wastes minimization and wastes characterization study: Wastes minimization (pollution prevention) should be studied for optimizing raw materials and chemical usage, preventing leakage, reuse and/or recycling wastes, improvements in housekeeping, and implementing wastes reduction program. Waste strength reduction is a major objective for an industrial plant concerned with waste treatment. The strength of wastes may be reduced by: 1) process changes; 2) equipment modifications; 3) segregation of wastes; 4) equalization of wastes; 5) by-product recovery; and 6) monitoring waste streams. Thereafter, wastewater characterization studies should be carried out to provide the accurate and complete information on which to base the design of the treatment system. The characterization of IWW should include parameters that environmentally have bad effect on the natural resources; including: BOD, COD, acid, alkaline, metals, colored and turbid materials, nitrogen and phosphorus compounds, solids (dissolved, suspended), volatile, oil and grease, and other pollutants (chlorine, chlorides, hardness, etc.).

Step 3) Determine treatment objectives: These objectives will depend on where the wastewater is to be sent after treatment. If the treated wastewater is discharged to another body of water or released into the environment, it must comply with pretreatment requirements and regulations. In the case of industrial water recycling and/or reusing, the effluent must have water of a quality appropriate to its designated use, then there should be no barrier to its introduction and deposition of the existing freshwater supply [32].

Step 4) Select candidate technologies: The right approach for an IWWT pollution abatement program is one which reveals all opportunities and alternative for inplant WWT. Accordingly advantages and disadvantages of each alternative, candidate technologies for treatment can be selected. The selection should be based on one or more of the following: successful application to a similar wastewater; knowledge of chemistry, biochemistry, and microbiology; knowledge

of available technologies, as well as knowledge of their respective capabilities and limitations. The main factors which must be considered in the decision on the WWT technologies to be applied are: 1) quality of the original wastewater, 2) removal of parent contaminants, 3) treatment flexibility, 4) facility decontamination capacity, 5) final WWT system efficiency, 6) economic studies, 7) life cycle assessment of the treatment technology, and 8) potential use of treated water [13].

Step 5) Bench-scale investigations: They are required to develop new technologies and generate information on new IWWT processes for the purpose of quickly and efficiently determining the technical feasibility and a rough approximation of the financial feasibility of a given technology [3,13]. Bench-scale studies range from rough experiments, in which substances are mixed in a beaker and results observed, to rather sophisticated continuous flow studies of small treatment devices that are models of the full-size equipment.

Step 6) Pilot-scale investigations: They are studies of the performance of a given technology using the actual wastewater to be treated, usually on site and using a representative model of the equipment that would be used in the full-scale system. During the pilot plant operation period, observations should be made to determine whether or not performance predicted from the results of the bench-scale investigations and try to determine the cause for the performance difference if it is not confirmed [3].

Step 7) Prepare preliminary designs: A meaningful cost-effectiveness analysis can take place only after the completion of preliminary designs of the technologies that produced satisfactory effluent quality in the pilot-scale investigations to enable accurate estimation of the costs for construction, operation, and maintenance.

Step 8) Conduct economic comparisons: The choice of treatment technology between two or more systems proven to be reliably capable of meeting the treatment objectives should be based on a thorough analysis of all costs over the expected life of the system. Operational and maintainal (O&M) costs must include as much detail as capital costs, if not more [3].

Step 9) Final design process: It is for the selected technology in both a formality, during which standardized documents (including plans and specifications) are produced, and a procedure, during which all of the fine details of the facility that is to be constructed are worked out. These steps complete the normal sequence of events for the identification, selection, and construction of an IWWT system, either for pretreatment or final treatment of wastewater.

Treatment of Different Kinds of Industrial Wastewater with Different Technologies

IWW characteristics vary not only with the industry that generates them, but also within the industry itself. Treatment of IWW is a complex due to the wide variety of compounds and concentrations it may contain. The next paragraphs will discuss common kinds of IWW and their treatment technologies.

The power industry and cooling water

Significant quantities of water are needed for power generation and cooling applications, greatly exceeding the quantities of water used for all other purposes (in USA, about 47% of water that is consumed annually) [32]. To control the quality of the recirculating stream, water is removed as blowdown water, and water is added to the recirculating stream as make-up water to compensate for loss of water through blow-down, evaporation and drift. A key unit process of a zero effluent discharge (ZED) is vapor compression evaporation which can recover about 95% of the waste stream as distillate. However, the process is very expensive due to dissolved solids (DS). A combination of electro dialysis reversal and reverse osmosis (RO) was adopted to pretreat the waste flows prior to evaporation [32]. Cokes wastewater contains ammonia, cyanide, thiocyanate, sulfides, and a wide variety of complex hydrocarbons. Cyanide is a highly toxic organic compound even at low concentrations and its presence in aqueous media is severely restricted by regulations [33]. Conventional treatment of toxic cokes wastewater comprises expensive caustic treatment and steam stripping to reduce the pollutant loads, followed by biological treatment [34,35]. The coke WWTP at a steel making company in Korea is a conventional activated sludge process for the removal of toxic organic pollutants (Figure 5) [35]. A bioreactor system with 30 packed gel envelopes containing *Nitrosomonas europaea* and *Paracoccus denitrificans* cells was also used for nitrogen removal in a thermal power plant wastewater for removing 95% of the total inlet nitrogen [36].

The pulp and paper industry

During the 20th century the specific fresh water consumption has fallen dramatically from around 300 m³/ton of paper products at the turn of the century to about 30 m³/ton today in the new processes. The effluents from this industry cause slime growth, thermal impact, scum formation, coloration, non-biodegradable organic materials, killing aqualife due to toxic substances, and loss of aesthetic beauty in the environment.

Since pulp and paper IWW characteristics vary in a wide range; different treatment options such as chemical, aerobic and anaerobic biological processes; adsorption, advanced oxidation and membrane filtration has been used for their pollution control [37-39]. Chemical coagulation followed by sedimentation is a probed technique for the treatment of high suspended solids pulp wastewater especially those

formed by colloidal matters. Coagulants with alum and polyaluminum chloride (PAC) were used for reduction of 99.9% turbidity, 99.5% TSS and 91.3% COD from pulp and paper mill wastewater at the optimum dosage PAC of 500 mg/L and pH 6.0 [40]. Several researchers have investigated the membrane processes, such as microfiltration (MF), ultra-filtration (UF), nanofiltration (NF), and RO in the treatment of pulp and paper industry effluents [39,41,42]. Membrane processes effectively reduce BOD, COD, TSS, DS, AOX (adsorbable organic halides), and color from pulp and paper effluents. Buyukkamaci and Koken [31] concluded that the most economic and technically optimal pulp and paper IWW treatment processes were found as extended aeration activated sludge process with or without up-flow anaerobic sludge blanket (UASB). Anaerobic biological processes are widely preferred treatment options in pulp and paper industry effluents because of toleration, protection against the deleterious effects caused by shocks of pH, loading, zero fibre and other solids that would otherwise clog the reactor [38]. Buzzini et al. [43] used an UASB reactor for the treatment of cellulose pulp synthetic wastewater with average COD removal efficiency of 76%.

Because of the little biodegradable of some pulp and paper mill wastewater (with low BOD/COD ratio), AOPs with ultrasonic treatment has been studied as a pre- or post-oxidation combined with biodegradation, showing a final decrease in toxicity and a biodegradability enhancement of paper mill wastewater [44]. The post-bleaching non-biodegradable effluent from cellulose and paper was subjected to a first coagulation-flocculation treatment followed by a UV/TiO₂/H₂O₂ system using mercury lamps, which raised the index of biodegradability from 0.11 to 0.71 [45,46]. Photo-Fenton and TiO₂ were also used to increase biodegradability of paper IWW [13]. Finally, electro-chemical pre-treatment (using iron electrodes) of pulp and paper wastewater raised the biodegradability index from 0.11 to 0.46 [47]. Also, modified magnetic seeds in a super-conducting magnet were used for treating paper factory wastes and removed 76% of COD [30].

The textile industry

The textile industry has many processing categories that are very water intensive for many cleaning and flushing steps. Every textile category wastewater includes additions of a wide variety of dyes and chemicals that arises pollution load (Table 3) [32].

Many treatment technologies, such as physical separation, coagulation, aerobic and anaerobic biological processes adsorption, and advanced oxidation have been used for textile effluent control. A treatability study of IWW of a large fabric textile in Egypt indicated that the traditional low cost settling process could reduce COD, BOD, and TSS with removal efficiency 47, 48 and 56 % respectively [48]. Meanwhile the traditional low cost biological activated sludge process with 6 hrs aeration could reduce the COD and BOD to the regulation limits for disposal in agricultural drains. Studies of water recovery for dyeing concluded that the more selective RO process or NF was required to decolorize for a reusable water product [49,50]. MBRs implementing special dye-degrading microorganisms and addition of adsorbent in MBR have been selected as potential candidates for dye WWT processes [51]. Hence, the conventional methods used in WWT are unsuitable colour inorganic contaminants, advanced treatment methods are applied on textile IWW, including Fenton process, PAC coagulation and ion exchange, and resulted in effluent quality that was suitable for the process water characteristics (Figure 6) [52]. Biological system configurations like biofilm reactors have also been combined with AOPs such as H₂O₂/UV, TiO₂/UV and photo-Fenton to treat

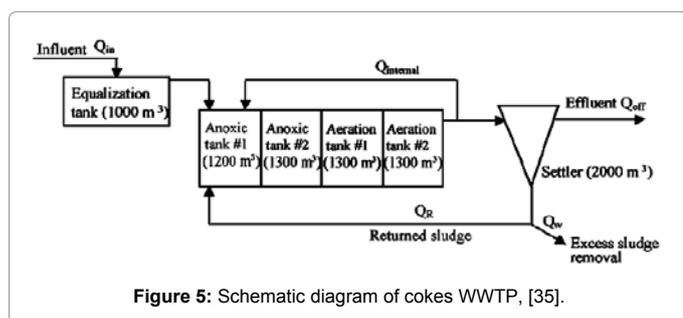


Figure 5: Schematic diagram of cokes WWTP. [35].

Parameters	Categories*						
	1	2	3	4	5	6	7
BOD/COD	0.2	0.29	0.35	0.54	0.35	0.3	0.31
BOD (mg/l)	6000	300	350	650	350	300	250
TSS (mg/l)	8000	130	200	300	300	120	75
COD (mg/l)	30 000	1040	1000	1200	1000	1000	800
Oil and grease (mg/l)	5500	-	-	14	53	0.42	0.27
Total chrome (mg/l)	0.05	4	0.014	0.04	0.05	0.13	0.12
Phenol (mg/l)	1.5	0.5	-	0.04	0.24	0.14	0.09
Sulphide (mg/l)	0.2	0.1	8.0	3.0	0.2	600	600
Colour (ADMI)	2000	1000	-	325	400	8.0	11
PH- value	8.0	7.0	10	10	8.0	20	38
Temperature (°C)	28	62	21	37	39	-	-
Water usage (l/kg)							
Minimum	4	33	111	5	20	8	3
Median	12	-	284	113	83	47	100
Maximum	78	-	657	507	378	163	557

Categories description: 1. raw wool scouring; 2. yarn and fabric manufacturing; 3. wool finishing; 4. woven fabric finishing; 5. knitted fabric finishing; 6. carpet finishing; 7. stock, yarn dyeing and finishing

Table 3: Textile processing categories and effluent characteristics [32].

reactive azo-dyes, achieving 99% removal efficiency [53,54]. Anaerobic biological treatment has also been combined with photocatalysis with immobilised TiO₂ to treat raw solutions of textile dyes [55]. Moreover, electrochemical oxidation has been used and achieved high removal of pollutants from textile IWW [56,57].

The food and beverage industry

The food and beverage industries are major consumers of water as much as 10-12 tons of water per ton of product - or even more [32,58]. A heavily polluted oil IWW, which had high lightly oil substances, was treated via gravity oil separators, dissolved air floatation, then traditionally biological units in order to reduce the high levels of oil and grease (O&G), BOD, COD, and TSS to the allowable limits to dispose effluent to the public sewerage system [59]. MBRs of microfiltration hollow fibre were used for the treatment of industrial oil contaminated wastewater with high removal efficiency (about 98%) to obtain high clear water for reuse [60]. Amuda and Amoo [61] used ferric chloride and polyelectrolyte (non-ionic polyacrylamide) coagulants for treating of highly colloidal beverage IWW to achieve removals of 91% COD, 99% TP and 97% TSS. Comparison of TiO₂ photocatalysis and photo-Fenton were investigated for enhancement biodegradability of olive mill wastewater, where photo-Fenton was the more efficient of the two [62]. A combination of chemical coagulation-flocculation and AOPs (UV/H₂O₂, UV/O₃ and UV/H₂O₂/O₃) was used for highly efficient removal of organic material, including recalcitrant organic compounds which are low biodegradable compounds, reducing COD by a maximum of 87% [18].

The pharmaceutical industry

Pharmaceuticals and personal-care products are considered environmental emerging contaminants (ECs) of particular concern because of their endocrine-disrupting properties. Their wastewater has many complex and toxic compounds. Estrogenic hormones have been detected not only in WWTP influents and effluents in many countries [63], but also in surface water [64]. Pharmaceuticals and personal-care products of 20 compounds including antibiotics, hormones were occurred in the sewage influent to WWTPs of Ulsan, large industrial city in Korea [65]. Most of these compounds were removed in the WWTPs processes (physicochemical and modified activated sludge with co-existence of anoxic-oxic condition). Meanwhile, Liu et al. [66] used a four-compartment periodic anaerobic baffled reactor for treating Chinese traditional medicine IWW under high alkalinity. The wastewater was rich in macromolecule that was difficult to

be treated and easy to foam in aerobic biodegradation, such as glycosides. The four-compartment anaerobic reactor worked well for biodegradation these substances under the low cost anaerobic condition in construction, operation and maintenance. A combination of coagulation-Fenton (H₂O₂ and Fe₂⁺) process significantly reduced the ecotoxicity of cosmetic industry effluents and markedly increased its biodegradability [67].

The petroleum and chemical industries

Petroleum industry requires large water volumes for the oil and gas refining and processing [68]. The application of biological WWT in the frame of a process integration treatment technology could hopefully close the water cycle allowing the ZED in the petroleum industry [68]. The aerated submerged fixed-film reactor demonstrated 91.8-96.6% removal of soluble COD and exhibited efficient and stable performance in petrochemical WWT with high organic loading rate [69]. Ammonium (NH₄⁺) in the petroleum IWW can be biologically eliminated by means of a double process, nitrification and denitrification, producing molecular nitrogen [68]. Many full-scale anaerobic WWT systems are also used by the chemical and petrochemical industry, as the range of compounds that are found to be biodegraded under anaerobic conditions has increased enormously due to their low cost in construction, operation and maintenance [70,71]. UF membrane was effectively used for treatment of the oily wastewater to achieve high pollution removal to reuse the treated IWW [72]. Moreover, RO could be used for extensively removing pollutants for achieving the ZED [73]. In recent years, AOPs have been evaluated for the treatment of low biodegradable petrochemical IWW and related effluents, such as those coming from oil extraction and achieved high degradation and reduction of pollutants [74,75]. Chemical treatability of water-based IWW via adsorption achieved high COD removal with sodium bentonite and with electro-chemical oxidations because their toxic wastewaters are not easily biodegradable and requiring costly physical or physico-chemical pretreatments [76].

The leather industry

Tannery wastewater contains high concentrations of organic matter and chemicals, such as COD, BOD, chromium, chlorides, sulfides, Ca, Mg, bactericides, emulsifiers, ammonia, detergents and toxic substances [77-79]. Pre-treatment of an actual Egyptian tannery wastewater revealed that electrolytic system at different current had poor removal of contaminants, while, physico-chemical system removed of 98.8% chromium, 31% COD, 25.8% BOD and 51.2% TSS

[80]. Calheiros et al [81] studied the diversity of bacterial communities from two series of two-stage CW systems (which have low cost in construction, operation and maintenance in low-priced available land) and showed high removal of organics from tannery wastewater. Also, anaerobic treatment of two stage UASB reactors connecting in series at 12 h HRTs have been effectively used for controlling the pretreated tannery wastewater to be disposed to the municipality sewers [82,83]. Due to the characteristics of raw tannery effluents of high toxic organic matters, specific AOPs/biological systems for the treatment of this wastewater is focused on using the AOP as a post-treatment step after biological treatment [13].

Miscellaneous Industries wastewater

This section presents a brief summary of treatment of some other highly polluted industrial effluents.

Metal plating wastewaters concentrations could only be reduced through chemical precipitation to about 5 mg/L. Filtration effectively removes most of the metal particles to about 1-2 mg/L. Furthermore, ion exchange can polish the effluent to 20 ppb [3].

Heavy metals (HMs) toxicity can result in damage of mental and nervous, blood composition, lungs, kidneys, liver and much other damage to life community. HMs in industrial effluents have been treated and cost effectively removed through CW systems (in low-priced available land) with removal efficiencies of 50%, 91.9%, 74.1%, 40.9%, 89%, and 48.3% for Pb, Cd, Fe, Ni, Cr, and Cu, respectively [84]. Also, free water surface CWs were utilized to improve the water quality in Egyptian agricultural drain and was able to remove its HMs as; Fe: 51%, Cu: 36%, Zn: 47% and Pb: 52% [85]. Furthermore, the modified industrial wastes from fly ash, blast furnace slag and sludge, black liquor lignin, red mud, and waste slurry showed high adsorption and removal of HMs from wastewater [86].

Highly saline wastewater is likely produced in many industrial sectors. Proper adaptation of the biomass and the use of halophilic organisms in anaerobic or aerobic biological processes have proved to be feasible treatment and recycling of carbonaceous, nitrogenous and phosphorous pollution at high salt concentrations (Figure 7) [87].

Landfill leachate can be traditionally treated using either: (a) biodegradation: aerobic and anaerobic processes or (b) chemical and physical methods: chemical oxidation, adsorption, chemical precipitation, coagulation/flocculation, sedimentation/flotation and air stripping [88]. A significant decrease in overall leachate treatment cost could be achieved by combining AOPs with a biological process [13].

Degradation kinetic models

With increasingly stringent regulations of effluent quality, process monitoring and control have become important to enhance process performance by detecting disturbances leading to abnormal process operation in an early stage and to cope with influent variations that

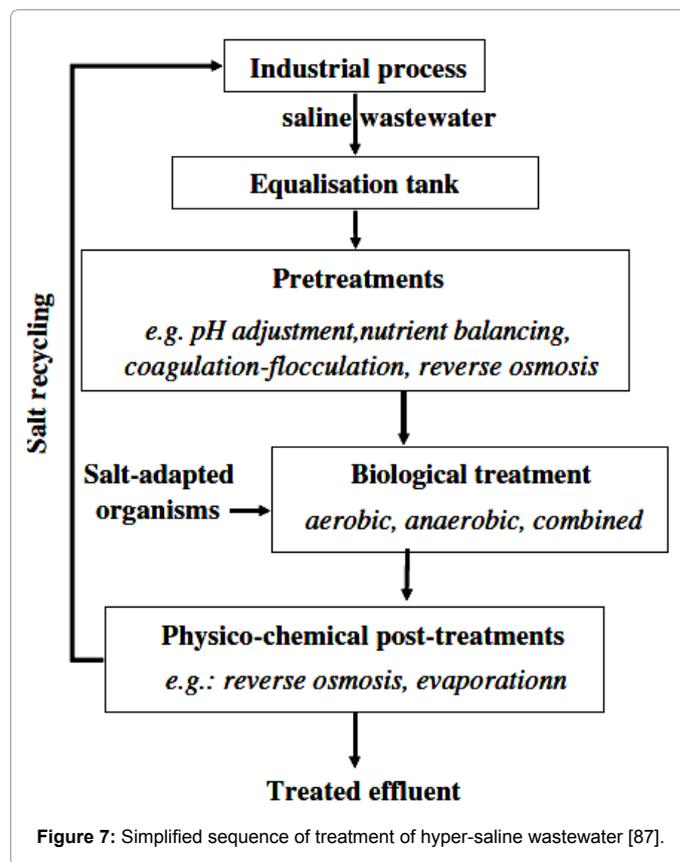


Figure 7: Simplified sequence of treatment of hyper-saline wastewater [87].

are typical of WWTP [35]. Inferential sensors, as software sensors, can be developed to estimate difficult and delay measurable variables from other easily measurable process variables and historical operation data [89]. To reduce development costs, computer models have been introduced to simulate and optimize the IWWTP system, thus making significant improvements in the efficiency of new technologies [90]. Yuan et al. [91] examines two operational strategies, decentralized model and an innovative integrated model, and showed that the integrated model has significantly improved IWWTP performance and effectively reduced illegal discharge of IWW. In recent years, nonlinear kernel-based algorithms as kernel partial least squares (KPLS) have been proposed to map each point in an original data space into a feature space via nonlinear mapping and then to develop a linear PLS model in the mapped space. Therefore, KPLS can efficiently compute latent variables in the feature space by means of integral operators and nonlinear kernel functions with good application in IWWT [35].

The most common proposal is kinetic models (sometimes including mass and/or thermal balances) demonstrating the dependence of degradation or mineralization rate constants on the operating parameters; H_2O_2 concentration, initial organic content, light intensity, catalyst concentration, etc. [92-94]. Bianco et al. [25] performed extensive experimental study of chemical Fenton oxidation for understanding and modeling the optimal operative conditions in real IWWT. The simulated model resulted in an accurate description of the COD removal in different initial conditions with a $R^2=0.85$. Simunovic et al. [95] also developed a mechanistic model for describing the behavior of photo-Fenton process treating the simulated IWW containing oxalates and formates. The developed was characterized as interpretable, transparent, flexible and accurate.

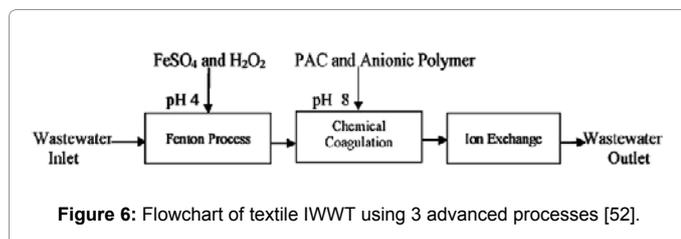


Figure 6: Flowchart of textile IWWT using 3 advanced processes [52].

Conclusions

Over the past two decades, environmental regulations have become more stringent, requiring an improved quality of industrial wastewater (IWW) effluent. The large number of studies reviewed here is indicative of the extensive and intense research that has been carried out in the field of IWW treatment (IWWT). These studies cover a wide range of industrial pollutants, a wide range of treatment technologies, and model solutions with individual substances to real effluents containing a mixture of various persistent substances. The selection of the most suitable treatment for IWW depends mainly on its characteristics and on many other parameters such as pollution control, availability and testing of the technology, the overall performance and experience technologies, plant simplicity, environmental impact, as well as economics parameter including the capital investment and operational costs. Although a systematic procedure consisted on using model substances before studying the real wastewater, and evaluating toxicity and biodegradability during and after the degradation process, more pilot-plant scale experiments with real IWW must be performed on a larger scale. The new integrated technology requires assessing the complete wastewater treatment in order to be reused in the industry itself.

In recent years, considerable attention has been directed towards IWWT in integrated anaerobic-aerobic bioreactors which combine the aerobic and anaerobic process in a single bioreactor with developing of its configurations to optimize its application. Many authors have also developed combined AOP and biological systems for the treatment of a diversity of IWW. New adsorbents, coagulants, photo catalysis and membrane filtration are frequently studied and widely applied for the treatment of the contaminated IWW. Combinations and intergradations of more than a technology were able to treat a wide range of high strength and toxic industrial. As such, the intergradations of treatment technologies can shift the paradigm of wastewater management from 'treatment and disposal' to 'beneficial utilization' as well as 'profitable endeavor'.

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