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The use of constructed wetlands for the treatment of industrial wastewater

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Abstract

Constructed wetlands are characterized by specific conditions enabling simultaneous various physical and biochemical processes. This is the result of specific environment for the growth of microorganisms and hydrophytes (aquatic and semiaquatic plants) which are capable of living in aerobic, anaerobic and facultative anaerobic conditions. Their interaction contributes to the intensification of oxidation and reduction responsible for the removal and retention of pollutants. These processes are supported by sorption, sedimentation and assimilation. Thanks to these advantages, treatment wetland systems have been used in communal management for over 50 years. In recent years, thanks to its advantages, low operational costs and high removal efficiency, there is growing interest in the use of constructed wetlands for the treatment or pre-treatment of various types of industrial wastewater. The study analyzes current use of these facilities for the treatment of industrial wastewater in the world. The conditions of use and efficiency of pollutants removal from readily and slowly biodegradable wastewater, with special emphasis on specific and characteristic pollutants of particular industries were presented. The use of subsurface horizontal flow beds for the treatment of industrial wastewater, among others from crude oil processing, paper production, food industry including wineries and distillery, olive oil production and coffee processing was described. In Poland constructed wetlands are used for the treatment of sewage and sludge from milk processing in pilot scale or for dewatering of sewage sludge produced in municipal wastewater treatment plant treating domestic sewage with approximately 40% share of wastewater from dairy and fish industry. In all cases, constructed wetlands provided an appropriate level of treatment and in addition the so-called ecosystem service.

Key words: *constructed wetlands, industrial wastewater, organic matter, specific pollutants, wastewater treatment*

INTRODUCTION

Constructed wetlands (CWs) have traditionally been used to treat municipal wastewaters but during last two decades the application of this technology has significantly expanded to treatment of various industrial effluents. The early constructed wetlands applied to industrial wastewaters included those for wastewaters from petrochemical, abattoir, meat processing, dairy and pulp and paper industries. During the 1990s constructed wetlands were also used to treat effluents from textile and wine industries or water from recirculating fish and shrimp aquacultures. The most recent applications include those for brewery or tannery wastewaters as well as olive mills effluents [VYMAZAL 2014; WU *et al.* 2015].

Wastewater treatment in wetland systems is the result of physical, chemical and biological processes in the soil and water environment with the usage of wetland plants (macrophytes). Unlike conventional biological reactors, wetland systems do not produce secondary sludge. They are also characterized by resistance to uneven and variable flow of sewage. The operational costs of these facilities are very low mainly because of minor energy supply requirements. For the treatment of industrial wastewaters both subsurface and surface flow CWs have been used. Within subsurface flow constructed wetlands both horizontal and vertical flow systems have been designed. Also, the use of various hybrid constructed wetlands for industrial effluent treatment has been reported recently [JAWECKI *et al.* 2017; KADLEC, KNIGHT 1996; KADLEC, WALLACE 2009; SKRZYPIEC *et al.* 2017; STEFANAKIS *et al.* 2014; VYMAZAL 2014].

In this paper the applications of constructed wetlands for treating various industrial effluents are summarized. The purpose of the paper is to review the characteristics of industrial wastewater and possible operational problems occurring in constructed wetlands treating analysed effluents.

CLASSIFICATION OF CONSTRUCTED TREATMENT WETLANDS

Depending on the flow path in the system there are two broad types: free water surface constructed wetlands (FWS CWs), and subsurface flow constructed wetlands (SSF CWs). In FWS CWs, the water slowly flows above a substrate medium, thus creating a free water surface and a water column depth usually of a few centimetres. On the contrary, in SSF CWs the water flows inside a porous substrate. Depending on the direction of the flow path, SSF CWs can be subdivided into horizontal (HSSF) or vertical flow (VSSF) [STEFANAKIS *et al.* 2014]. Types of constructed wetland for wastewater treatment are shown in Figure 1.

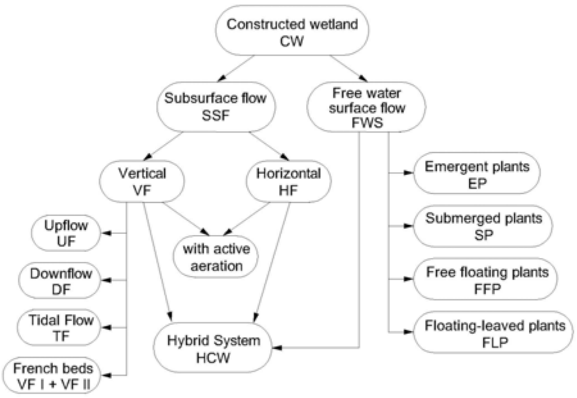

Fig. 1. Classification of constructed wetlands for wastewater treatment; source: STEFANAKIS *et al.* [2014], modified

If an equal treatment performance is targeted, free water surface flow (FWS) CWs need the least energy for operation and maintenance, but largest land area. Otherwise, the intensified wetlands such as aerated wetlands leads to the additional costs for operation and maintenance of the facility, but also certainly occupied a much smaller sized area. Therefore, for treatment of industrial effluents, the decision should only be justified when its lifecycle cost is sufficiently offset by the reduction in the capital cost by the net savings of reduced wetland area size [VYMAZAL 2014; WU *et al.* 2015].

In the context of land area demands, vertical flow CWs appear as a good compromise between highly intensive treatment systems, usually connected with a high energy input but extreme low area demand like activated sludge technology, and horizontal flow CWs, which can have almost no external energy input demand but also a higher area demand because of the low oxygen input into the system. The main outcome of previous studies on wetland systems is the viability of the application of subsurface flow constructed wetlands to treat the effluents from various industries, e.g. car wash facilities. They have shown resilience to load and hydraulic fluctuations, to chemical pollutants and to variable environmental conditions; being simple to operate and maintain with minimum energy requirements and with an added aesthetical value [STEFANAKIS *et al.* 2014; TORRENS *et al.* 2016a].

CHARACTERISTICS OF INDUSTRIAL WASTEWATER

There are many industrial wastewaters which differ substantially in composition from municipal sewage and also among themselves. In many industrial wastewaters the concentrations of organics, suspended solids, ammonia or some other pollutants are very high and therefore, the use of constructed wetlands nearly always requires some kind of pretreatment. The BOD_5/COD ratio is a parameter which tentatively indicates the biological degradability. If this ratio is greater than 0.5, the wastewater is easily biodegradable, such as wastewaters from dairies, breweries, food industry, abattoirs or starch and yeast production. The BOD_5/COD ratio for these wastewaters usually ranges between 0.6 and 0.7 but could be as high as 0.8. On the other hand, wastewaters with low BOD_5/COD ratio and thus low level of biodegradability are represented, for example, by pulp and paper wastewaters. Tentative comparison of the industrial wastewater strength with municipal sewage could be done through population equivalent (PE = 60 g BOD_5 per person per day). Examples of these estimations are shown in Table 1. However, this approximation is only tentative and for the design of individual treatment systems it is necessary to take into consideration measured parameters for particular wastewater [VYMAZAL 2014].

Constructed wetlands (CWs) have the potential to eliminate organic compounds and nutrients from industrial wastewater, as they efficiently remove suspended solids, biodegradable organic matter and pathogenic microorganisms. Nitrogen removal depends on the system design, process configuration and loading rates [TORRENS *et al.* 2016b].

Table 1. Examples of industrial wastewaters expressed in terms of PE according to BOD_5

Type of wastewater	Amount of product	Population equivalent
Sugar mill	sugar beet (1 t)	45–70
Dairy	milk (1 m^3)	40–230
Paper mill	paper (1 t)	200–900
Brewery	beer (1 m^3)	150–350
Laundry	laundry (1 t)	350–900
Tannery	leather (1 t)	1 000–5 000
Cellulose (sulfite)	cellulose (1 t)	3 000–5 000
Yeast factory	yeast (1 t)	5 000–7 000

Source: VYMAZAL [2014], modified.

Organic matter is decomposed in constructed wetlands by aerobic and anaerobic microbial processes as well as by sedimentation and filtration of particulate organic matter. Because of the heavy organic load, anoxic/anaerobic processes prevail while aerobic processes are restricted to small zones adjacent to roots and rhizomes (radial oxygen loss). Vertical flow constructed wetland (VFCW) promotes higher atmospheric oxygen diffusion inside the matrix and boost organic matter removal [ALMEIDA *et al.* 2016].

The removal of organic compounds is very dependent on several factors namely pH, temperature, dissolved oxygen (DO), feeding mode, hydraulic load (HL) and hydraulic retention time (HRT), depth of bed, plant species and harvesting. Some of them are interrelated to each other. Dissolved oxygen and their transfer to constructed wetland depend on the plants species, type of the flow (vertical flow or horizontal flow, intermittent or continue), HL, HRT and wastewater loading pollutant. HRT affects the duration of wastewater within wetland systems; a longer HRT in constructed wetland may enhance the removal of pollutants due to longer contact period between them and microorganisms. However, if anaerobic conditions dominate in the wetland beds, then significant increase of HRT may not facilitate organic matter removal [ALMEIDA *et al.* 2016; COOPER 2005; KADLEC, WALLACE 2009].

The specific characteristics of various industrial effluents make them difficult for treatment in conventional CWs and often cause a serious of treatment limitations (Tab. 2).

VSSF CWs have been proved to be rather efficient in organic matter (OM) removal as they can achieve removal rates up to 90%, while applied OM surface loads are significantly high. The main reason that these systems achieve high OM removal rates is the retention of suspended solids on the surface of the bed, which can be proved by the respectively high removal efficiencies of total suspended solids (TSS) (from 59% to 99%). Concerning nitrogen, VSSF wetlands present lower removal rates (62–74%). In order to overcome VSSF system drawbacks, recent CWs applications focus on hybrid systems which consist of HSSF and VSSF treatment stages. HSSF and VSSF system combination usually aims at enhancing total nitrogen removal (ammonia removal in VSSF beds and nitrate removal in HSSF beds) and heavy metal removal in the HSSF stage, while OM removal rate is still high in the VSSF stage. Constructed wetlands ability in heavy metals removal is well known and documented [MAINE *et al.* 2009; WOJCIECHOWSKA, GAJEWSKA 2013]. This ability is mainly attributed to the CW vegetation, whose root systems absorb high quantities of heavy metals (plant accumulation). Varying removal rates among heavy metals are indicative of the different levels of their mobility and bioavailability, which affect removal rates rations [BERNINGER *et al.* 2012; STEFANAKIS *et al.* 2014; VYMAZAL 2014; ZUPANCIC *et al.* 2009].

Table 2. Main characteristics of various industrial effluents

Wastewater	Main characteristics
Tannery	high organic loadings, high amount of salts as much as 80 g·dm^{-3} of NaCl
Pulp and paper mill	highly intense colour, chlorophenolic compounds
Oil field and refinery	low biodegradability (0.07–0.19), include oil, various hydrocarbons, metals/metalloids, phenolics, and salts
Textile	harmful residual dyes and highly coloured, often alkaline
Distillery	high organic load
Winery	variable flows and loadings, high content of organic matter and SS, acidic
Seafood processing	high concentrations of organic matter, nitrogen and suspended solids
Coffee processing	acidic, rich in nutrients and organic matter, resultant phenolic compounds
Slaughterhouse	COD is mainly in colloidal form, high content of coarse suspended matter

Source: WU *et al.* [2015], modified.

INDUSTRIAL WASTEWATER TREATMENT

PETROCHEMICAL INDUSTRY

Petroleum refineries convert raw oil and other hydrocarbon-bearing petroleum sources (such as natural gas and oil sands) into a variety of end products and intermediate materials. Wastewater is generated by the topping, cracking, and lube oil manufacturing processes; cooling tower blow-down; water and sludge drainage from tanks; and stormwater drainage and runoff. Typical wastewater pollutants at petroleum refineries include organics, oil and grease, suspended solids, ammonia, phenolics, H_2S and heavy metals. Trace organics include several hydrocarbon classes such as BTEX (benzene, toluene, ethylbenzene, xylenes), GRO (gasoline range organics with 6–9 carbon atoms) and DRO (diesel range organics with 10–40 carbon atoms). Total petroleum hydrocarbons (TPH) is a measure of the sum of paraffinic and aromatic constituents [KADLEC, KNIGHT 1996; KADLEC, WALLACE 2009].

A FWS CW has been used to treat petroleum hydrocarbon-contaminated wastewaters from Amoco's Mandan, North Dakota facility since 1975. The wastewater flowed into a constructed wetland from a conventional oil separator and a 6 ha lagoon. The constructed wetland consisted of 11 ponds with a total area of 16.6 ha. The lagoon-constructed wetland treatment system achieved very good results in terms of removal of BOD (98%), COD (93%), ammonia (84%), sulphides (100%), phenols (99%), oils and grease (99%) at the hydraulic loading rate of 1.2 cm·d^{-1}. In 1979, FWS constructed wetland was built to treat wastewaters from a Tizsa Petrochemical Plant in Hungary. The wetland consisted of series of shallow basins with algae and emergent macrophytes bulrush (*Typha* sp.) and common reed (*Phragmites australis*). The system occupied a total area of 18 ha and the daily flow varied between 2500 and 3000 m^3·d^{-1}. WOOD and HENSMAN [1989] reported the use of 2000 m^2 HSSF system filled with waste and coarse ash and planted with bulrush at the inlet and reed at the outlet for the treatment of petrochemical effluents. A 20 ha FWS CW was built in Beijing Yanshan Petrochemical Company in 1992 to treat secondary treated petrochemical wastewaters. The removal efficiencies of 44% for TSS, 19% for total nitrogen (TN), 68% for total phosphorus (TP) and 50% for BOD_5 were very much affected by very high hydraulic loading rate (HLR) of 47 cm·d^{-1}. However, the wetland system was supplemented with a series of five ponds which made the effluent quality good enough to meet local discharge criteria for agricultural irrigation. HAWKINS *et al*. [1997] reported the use of FWS CW at the Shell Norco refinery in St. Charles Parish, Louisiana, USA. Two parallel wetland cells (30.5 m × 6.1 m) with an alluvial floodplain sediment planted with giant bulrush (*Scirpus californicus*) were used. During a 4.5-month monitoring period the average inflow and outflow concentrations indicated good removal for heavy metals, TSS and organics at 46-h hydraulic retention time [VYMAZAL 2014].

KADLEC [2003] reported on the efficiency of a pilot scale vertical flow constructed wetlands for removal of hydrocarbon-contaminated groundwater at former Amoco Refinery Site in Casper, Wyoming, USA, where the continuous operation took place between 1912 and 1991. The pilot system was operated from July 2001 to January 2002 and four cells (7 m × 1.7 m each) were operated in an upward vertical flow mode. The cells were filled with layers of sand and gravel and planted with willows (*Salix* spp.), deergrass (*Scirpus* spp.), soft rush (*Juncus* spp.) and common reed. The removal of benzene, BTEX, TPH and MTBE (methyl *tert*-butyl ether) amounted to 65%, 66%, 93% and 18%, respectively. The removal was substantially enhanced by addition of air for benzene (87%) and BTEX (90%). The application of air affected only slightly the removal of TPH (97%) and MTBE (29%). Another vertical flow constructed wetlands filled with gravel and organic compost and planted with tall reed (*Phragmites karka*) was used to treat wastewater from the refinery in Rawalpindi, Pakistan. Both wetlands were intermittently fed with HLR of 10 cm·d^{-1}. The results revealed that the treatment performance during one year period was slightly better for compost wetland as compared to gravel wetland. The respective removal efficiencies were 51% and 49% for COD, 55% and 47% for BOD_5 and 51% and 42% for TSS. The compost-based wetland was also more efficient than the gravel-based wetland for heavy metals removal. The respective efficiencies were 48% and 37% for Fe, 56% and 41% for Cu and 61% and 45% for Zn [VYMAZAL 2014].

PULP AND PAPER INDUSTRY

Pulp and paper industry produces large amounts of wastewater, between 75 and 225 m^3 t^{-1} of product. This type of industry ranks third in the world, after the primary metals and the chemical industries, in terms of freshwater withdrawal. The composition of wastewater from pulp and paper industry depends on the type of process, type of wood material, process technology applied, management practices, internal recirculation of the effluent for recovery, and the amount of water used in the particular process. Concentrations of organics (BOD_5 and COD) and suspended solids are usually high with many volatile organic compounds, fatty acids, lignin and its derivatives, AOX or resins being commonly present. While some of these pollutants are naturally occurring wood extractives, others are xenobiotic compounds that are formed during the process of pulping and paper making (chlorinated lignins, resin acids and phenols, dioxins, and furans) [POKHREL, VIRARAGHAVAN 2004].

A pilot-scale HSSF CW in western Kenya, which was established to remove phenols from pre-treated pulp and paper mill wastewater, was studied under varying hydraulic retention times with batch loading. Results from the 15-month operation indicated that removal efficiencies for phenols were variable but reached 60% at 5-day HRT and 77% at 3-day hydraulic retention time (HRT) on average. The longer retention time might have caused oxygen and nutrient deficiencies, which may have reduced removal performance [WU *et al*. 2015].

METALLURGICAL INDUSTRY

In Taiwan, YANG and HU [2005] used a HSSF mesocosm for treatment of steel mill wastewaters. The wetland was filled with gravel, planted with common reed and bulrush and operated at a HLR of 2.6 cm·d^{-1} and HRT of 7 days. The removal efficiency for COD and TP amounted to 50% and 6%, respectively, and most heavy metals were not below the detection limit in the discharged water. Another example reported the use of lab scale VSSF constructed wetlands (one CW filled with manganese ore, one filled with gravel) for removal of manganese and iron in the reclamation of steel wastewater. The treatment efficiency of the manganese ore wetland outperformed the wetland filled with gravel for all monitored parameters (Fe, Mn, COD, turbidity, NH_4-N and TP). The removal of both Fe and Mn was very effective with effluent concentrations of both elements below 0.05 $mg·dm^{-3}$. A pilot scale HSSF system was also examined, filled with gravel with 0.5 m long manganese ore zone which formed only 4% of the total substrate volume. The system achieved removal of 91% of Fe and 81% of Mn. Huang et al. tested a 91 m^2 HSSF CW to treat wastewaters from a steel enterprise in China. The filtration material was a mixture of gravel and manganese ore (9:1) and the vegetation was composed of common reed, cattail (*Typha* sp.) and windmill grass (*Chloris verticillata*). The inflow concentrations of 26 $mg·dm^{-3}$ COD, 1.73 $mg·dm^{-3}$ N-NH_4, 1.6 $mg·dm^{-3}$ total iron and 0.53 $mg·dm^{-3}$ manganese were reduced to 5.9 $mg·dm^{-3}$, 0.4 $mg·dm^{-3}$, 0.05 $mg·dm^{-3}$ and 0.04 $mg·dm^{-3}$, respectively. The effluent from the constructed wetland was further treated by ultrafiltration and reverse osmosis [HUANG *et al*. 2004; VYMAZAL 2014].

TEXTILE INDUSTRY

Textile industries produce coloured wastewater which is heavily polluted with dyes, textile auxiliaries, and chemicals used in the dyeing and finishing processes. As only 47% of dyes in textile wastewater are biodegradable, colour removal from this wastewater type is the major treatment problem. The most common plant species used to treat textile wastewater is common reed. Common reed is preferred, as this species is indigenous to most regions of the world and shows extreme tolerance to most toxic compounds contained in all wastewater types. Although most plant species tested were affected by the toxic impact of the azo-dyes, common reed was the most tolerant species with great contribution to azo-dye removal [ROUSSY *et al*. 2005; STEFANAKIS *et al*. 2014].

ALCOHOL FERMENTATION INDUSTRY

The alcohol fermentation industry is divided into three main categories: brewing, distilling and wine manufacture. In this paper treatment of winery wastewater is analysed. This particularly complex wastewater is often characterized by fluctuations in terms of quality and quantity during the whole year, that are depending on several factors like as the adopted industrial process chain and its seasonality or the kind of produced wine. But in average for 1 dm^3 of wine about 1.6–2.0 dm^3 of wastewater are generated and the ratio between the organic load and the produced wine is 5–10 kg $COD·m^{-3}$ [ANASTASIOU *et al*. 2009; FERNANDEZ *et al*. 2007].

Winery wastewaters contain high concentrations of readily biodegradable soluble organic matter such as sugars (glucose and fructose), alcohols (ethanol and glycerol), acids (tartaric, lactic, and acetic) and recalcitrant high molecular weight compounds such as polyphenols, tannins and lignins. These are not easily removed by physical or chemical treatment alone and tannins in particular can inhibit microbial digestion [VYMAZAL 2014].

Direct feeding of winery wastewater with high concentration organic compounds into CWs often shows limits in the tolerance of wetlands and have a serious negative effect, such as clogging which reduces oxygen infiltration into the growth media and typically causes rapid failure of the wetland system. Substrates are clogged because of a combination of accumulation of solids and subsequent biomass growth. Clogged substrates are a problem for both vertical and subsurface flow wetlands [GRISMER *et al*. 2003; MOSSE *et al*. 2011].

Reported experiments show that most of full scale CWs for treating winery wastewater are of subsurface HSSF type, probably because of its passive operation. Constructed wetlands are also directly used in treating raw winery wastewater, which is mostly generated from small or moderate-sized wineries, particularly in rural areas [WU *et al*. 2015].

In Table 3 results from a hybrid CW treating winery wastewater are presented.

Table 3. Treatment efficiency of a HF-VF hybrid constructed wetland for treatment of winery wastewater in Spain

Parameter	TSS	COD	BOD_5	TKN	N-NH_3	PO_4^{3-}
Inflow, $mg·dm^{-3}$	129	1.558	942	52.9	28	2.3
VSSFout, $mg·dm^{-3}$	65	711	418	26.0	19.4	2.4
HSSFout, $mg·dm^{-3}$	17	448	279	25.2	12.5	1.9
Efficiency, %	87	71	70	52	55	17

Source: VYMAZAL [2014], modified.

FOOD PROCESSING INDUSTRY

Slaughterhouses (abattoirs) produce large volumes of wastewater which usually contains high concentrations of biodegradable organics in soluble fraction as well as in insoluble fraction in the form of colloidal and suspended matter such as fats, proteins and cellulose. It contains high concentrations of oil and grease up to 1000 $mg·dm^{-3}$. In addition, abattoir wastewaters carry high levels of pathogenic microorganisms that may constitute a risk for humans and animals [GANNOUN *et al*. 2009].

HSSF constructed wetland was built in 1994 in Mexico, to treat anaerobically digested abattoir effluent. The constructed wetland (1144 m^2) was filled with gravel and planted with common reed and bulrush in alternate strips. In Table 4, treatment performance of the HSSF part is presented.

Reduction of faecal and total coliforms amounted to 5.5 and 5.0 log units, respectively. Organic load was very high with the average values of 82 $g·m^{-2}·d^{-1}$ for COD and 33 $g·m^{-2}·d^{-1}$ for BOD_5.

Table 4. Removal efficiency of the abbatoir wastewater treatment system in Mexico; concentrations in mg·dm^{-3}

Parameter	Inflow	Inflow CW	Outflow CW	Removal[1)]
COD	3 633	1 440	375	90 (74)
BOD_5	1 593	585	137	91 (77)
TSS	1 531	421	236	75 (44)
N_{org}	26.6	10.1	5.3	80 (48)

[1)] Removal efficiency (in %) of horizontal subsurface flow constructed wetland in parentheses.
Source: VYMAZAL [2014], modified.

MILK AND CHEESE INDUSTRY – DAIRY WASTEWATER

The dairy industry generates strong wastewaters characterized by high concentrations of organics (BOD_5, COD) and wide range of pH values between 3.5 and 11.0 caused by the use of alkaline and acid cleaners and sanitizers. The wastewater production is frequently seasonal and since the dairy industry produces various products (milk, butter, yoghurt, ice cream, and cheese) the composition of the effluent varies according to the type of product and technology used [DEMIREL *et al*. 2005].

Dairy wastewater usually has high BOD_5 (500–2600 mg·dm^{-3}) and COD concentrations (2000–7000 mg·dm^{-3}) and contains fats (90–500 mg·dm^{-3} fats, oil and grease), nutrients (30–100 mg·dm^{-3} TN and 20–100 mg·dm^{-3} TP), suspended solids (200–1000 mg·dm^{-3}), and lactose, as well as detergents and sanitizing agents. In thus wastewater, the cheese whey is the most common effluent. In most experiments of dairy wastewater treatment with CWs, the pretreatment stage mainly aims at the removal of SS, which is essential before the dairy wastewater enters the CW bed, to avoid clogging of the porous media and reduce the organic load. Common pretreatment methods include simple settling basins. The plant species used in various dairy wastewater treatment experiments were flowering rush (*Butomus umbellatus*), pumpkin (*Cucurbita maxima*), common reed (*Phragmites australis*), woodland ragwort (*Senecio sylvaticus*), common bulrush (*Typha latifolia*), and common nettle (*Urtica dioica*) [STEFANAKIS *et al*. 2014].

The use of VSSF CWs in dairy wastewater treatment is limited, since in most cases it has been observed that the wetland systems were poor in P removal. In fact, these wetland beds are only reported in diary wastewater treatment as a part of hybrid CW systems also comprising HSSF beds. Hybrid systems have been used with rather high removal efficiencies (83–96% for COD; 65–92% for nitrogen; 52–99% for TP; 83–99% for TSS). These removal efficiencies were achieved even though pollutant surface loads were higher than those usually applied to CW systems. It is stated that vegetation enhanced N and P removal efficiencies. This could be attributed to the aeration zone created in the plant rhizosphere, which promoted aerobic degradation processes, increase nitrification and subsequent gaseous losses of N through denitrification. Reported the existence of a diverse bacterial community (especially, *Nitrosospira* sp.) responsible for ammonia oxidation and possibly for nitrification processes. Combined CW systems have been found to achieve higher removal efficiencies of organic matter than VSSF systems alone. Differences in nutrient and solid concentrations across the wetland system could be attributed to a number of removal mechanisms. HSSF systems, however, appear to be more efficient in dairy wastewater treatment [STEFANAKIS *et al*. 2014; VYMAZAL 2014; WU *et al*. 2015].

FISH AND SEAFOOD PROCESSING

The seafood industry generally generates a large quantity of wastewater that contains high concentrations of organic matter, nitrogen, and suspended solids (SS). The main components of fish processing wastewater are fat, oil and grease and proteins. Also, the pH values vary from 3.8 to 10 depending on the technology and fish species processed. In Southern Thailand the dynamics of nitrogen and SS removal in a full-scale FWS CW for post-treatment of seafood processing wastewater was evaluated. The average removal efficiency of BOD_5, SS, TKN, ammonium nitrogen, and organic nitrogen is about 84%, 94%, 49%, 52%, and 82%, respectively. Effluent BOD_5, SS, and nitrogen can meet the Thailand Industrial Effluent Standard at levels lower than 20, 50, and 100 mg·dm^{-3}, respectively [WU *et al*. 2015; YIRONG, PUETPAIBOON 2004].

In 1994 the use of HSSF systems for seafood processor wastewater in Alabama, USA was reported. Two wetlands were 1 m wide, 4 m long and filled with a 0.3 m layer of crushed limestone (2.5–5 cm diameter). One wetland was planted with common reed and the other with smooth cordgrass (*Spartina alterniflora*). At HLR varying from 1.28 to 4.27 cm·d^{-1}, the inflow concentrations of BOD_5 and ammonia of 125 mg·dm^{-3} and 95 mg·dm^{-3} were reduced to respective outflow concentrations of 7–11 mg·dm^{-3} and 5–54 mg·dm^{-3}. The HLR had much greater influence on removal of ammonia than BOD_5 [VYMAZAL 2014].

LAUNDRY

The quality of wastewater depends on the origin with the highest values occurring from dirty items containing oils, heavy metals or other dangerous substances. Higher concentrations of pollutants are found in hospital laundry wastewater which contains flood remains, blood and urine. Laundry wastewaters from household items is the less polluted. The laundry wastewaters always contain high concentrations of both anionic (MBAS) and non-ionic (BIAS) surfactants. Linear alkylbenzene sulfonates (LAS) are the most widely used synthetic anionic surfactants. They account for 28% of the total production of synthetic surfactants in Western Europe, Japan and the United States and due to its high-volume use in laundry and cleaning products, LAS is a ubiquitous water contaminant [HUANG *et al*. 2004; VYMAZAL 2014].

The removal of LAS in a pilot scale HSSF CW in Barcelona was studied. The highest rates of LAS oxidation were observed in shallow beds where a more oxidized environment occurred. They also observed that biodegradation of LAS and sulfophenyl carboxylate biointermediates occurred under sulfate-reducing and mixed conditions, i.e., sulfate reducing and denitrification. C13 LAS homologues were generally removed to a higher extent than the shorter alkyl chain counter-parts. The removal has also been found to be temperature and HLR dependent. The use of HSSF constructed wetland planted with a mixture of bulrush (*Typha orientalis*) and marsh clubrush (*Bolboschoenus fluviatilis*) for the treatment of commercial laundry wastewater was reported at The Channon, Australia. At the HRT of 6.1 days the removal of BOD_5, TSS, TN and TP amounted to 61%, 83%, 62% and 32%, respectively [DAVISON *et al*. 2005; HUANG *et al*. 2004].

CONCLUSIONS

Based on the carried out survey it could be concluded.

Constructed wetland became more and more popular alternative for conventional technologies in wastewater treatment from industry. Due to special wastewaters examined in this paper share common characteristics (i.e. high heavy metal concentrations, high organic matter and nitrogen loads, etc.) and therefore, constructed wetland systems treating industrial effluents face almost the same problems and limitations. Thus common suggestions can be expressed concerning constructed wetland design and operation for the treatment of the mentioned special wastewater types. The most important issues which should always be discussed include suggestions about pretreatment stage, vegetation, porous media, and constructed wetland operation strategy. There is a need for further investigation and searching for new potential and solutions in constructed wetland application.

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REFERENCES

ALMEIDA A., CATARINO A., RIBEIRO C., CARVALHO F., PRAZERES A. 2016. VFCW applied to treatment of cheese whey wastewater pretreated by basic precipitation: Influence of bed depth. 15th IWA International Conference on Wetland Systems for Water Pollution Control, Gdańsk, Poland p. 28–38.

ANASTASIOU N., MONOU M., MANTZAVINOS D., KASSINOS D. 2009. Monitoring of the quality of winery influents/effluents and polishing of partially treated winery flows by homogenous Fe(II) photooxidation. Desalination. Vol. 248. Iss. 2 p. 836–842.

BERNINGER K., KOSKIAHO J., TATTARI S. 2012. Constructed wetlands in Finish agricultural environments: balancing between effective water protection, multifunctionallity and socio-economy. Journal of Water and Land Development. No. 17 p. 19–29.

COOPER P. 2005. The performance of vertical flow constructed wetland system with special reference to the significance of oxygen transfer and hydraulic loading rates. Water Science and Technology. Vol. 51. Iss. 9 p. 81–90.

DAVISON L., HEADLEY T., PRATT K. 2005. Aspects of design, structure, performance and operation of reed beds – eight years experience in northeastern New South Wales, Australia. Water Science and Technology. Vol. 51. Iss. 10 p. 129–138.

DEMIREL B., YENIGUM O., ONAY T.T. 2005. Anaerobic treatment of dairy wastewater: A review. Process Biochemistry. Vol. 40. Iss. 8 p. 2583–2595.

FERNANDEZ B., SEIJO I., RUIZ-FILIPPI G., ROCA E., TARENZI L., LEMA J. 2007. Characterization, management and treatment of wastewater from white wine production. Water Science and Technology. Vol. 56. Iss. 2 p. 121–128.

GANNOUN H., BOUALLAGUI H., OKBI A., SAYADI S., HAMDI M. 2009. Mesophilic and thermophilic anaerobic digestion of biologically pretreated abattoir wastewaters in an upflow anaerobic filter. Journal of Hazardous Materials. Vol. 170. Iss. 1 p. 263–271.

GRISMER M.E., CARR M.A., SHEPHERD H.L. 2003. Evaluation of constructed wetland treatment performance for winery wastewater. Water Environment Research. Vol. 75. Iss. 5 p. 412–421.

HAWKINS W.B., RODGERS J.H., JR., DUNN A.W., DORN P.B., CANO M.L. 1997. Design and construction for aqueous transfers and transformations of selected metals. Ecotoxicol. Environ. Saf. No. 36 p. 238–248.

HUANG Y., LATTORE A., BARCELÓ D., GARCÍA J., AGUIRRE P., MUJERIEGO R., BAYONA J.M. 2004. Factors affecting linear alkylbenzene sulfonates removal in subsurface flow constructed wetlands. Environmental Science and Technology. Vol. 38. Iss. 9 p. 2657–2663.

JAWECKI B., PAWĘSKA K., SOBOTA M. 2017. Operating household wastewater treatment plants in the light of binding quality standards for wastewater discharged to water bodies or to soil. Journal of Water and Land Development. No. 32 p. 31–39.

KADLEC R.H. 2003. Effects of pollutant speciation in treatment wetland design. Ecological Engineering. Vol. 20. Iss. 1. p. 1–16.

KADLEC R.H., KNIGHT R.L. 1996. Treatment wetlands. Boca Raton. CRC Press. ISBN 0-87371-9304 pp. 893.

KADLEC R.H., WALLACE S. 2009. Treatment wetlands. 2nd ed. Boca Raton, New York. CRC Press. Taylor & Francis Group. ISBN 9781566705264 p. 267–290.

LEFEBRE O., MOLETTA R. 2006. Treatment of organic pollution in industrial saline wastewater: A literature review. Water Research. Vol. 40. Iss. 20 p. 3671–3682. DOI: 10.1016/j.watres.2006.08.027.

MAINE M.A., SUÑE N., HADAD H., SÁNCHEZ G., BONETTO C. 2009. Influence of vegetation on the removal of heavy metals and nutrients in a constructed wetland. Journal of Environmental Management. Vol. 90. Iss. 1. p. 355–363. DOI: 10.1016/j.jenvman.2007.10.004.

MOSSE K., PATTI A., CHRISTEN E., CAVAGNARO T. 2011. Review: winery wastewater quality and treatment options in Australia. Australian Journal of Grape and Wine Research. Vol. 17. Iss. 2 p. 111–122. DOI: 10.1111/j.1755-0238.2011.00132.x.

POKHREL D., VIRARAGHAVAN T. 2004. Treatment of pulp and paper mill wastewater – A review. Science of the Total Environment. Vol. 333. Iss. 1–3 p. 37–58. DOI: 10.1016/j.scitotenv.2004.05.017

ROUSSY J., CHASTELLAN P., VAN VOOREN M., GUIBAL E. 2005. Treatment of ink-containing wastewater by coagulation/flocculation using biopolymers. Water SA. Vol. 31. No. 3 p. 369–376.

SKRZYPIEC K., BEJNAROWICZ A., GAJEWSKA M. 2017. Rozwiązania gospodarki ściekowej na obszarach niezurbanizowanych. Małe oczyszczalnie ścieków zgodne z zasadami zrównoważonego rozwoju [Wastewater treatment and management solutions for non-urban areas. Small wastewater treatment plants in accordance with the principles of sustainable development]. Rynek Instalacyjny. Nr 4 p. 85–89.

STEFANAKIS A., AKRATOS C., TSIHRINTZIS V. 2014. Vertical flow constructed wetlands: eco-engineering systems for wastewater and sludge treatment. Amsterdam, Netherlands. Elsevier Science. ISBN 978-0-12-404612-2 pp. 392.

TORRENS A., BAYONA C., SALGOT M., FOLCH M. 2016b. Performance, design and operation of hybrid subsurface flow constructed wetland for swine slurry treatment. 15th IWA International Conference on Wetland Systems for Water Pollution Control, Gdańsk, Poland p. 1044–1045.

TORRENS A., FOLCH M., SALGOT M., TENA S., BUSSE J., RIERA E., AULINAS M. 2016a. Innovative carwash wastewater treatment and reuse through subsurface flow constructed wetlands. 15th IWA International Conference on Wetland Systems for Water Pollution Control, Gdańsk, Poland p. 1042–1043.

VYMAZAL J. 2014. Constructed wetlands for treatment of industrial wastewaters: A review. Ecological Engineering. No 73 pp.724–751.

WOJCIECHOWSKA E., GAJEWSKA M. 2013. Partitioning of heavy metals in sub-surface flow treatment wetlands receiving high-strength wastewater. Water Science and Technology. Vol. 68. Iss. 2 p. 486–493.

WU S., WALLACE S., BRIX H., KUSCHK P., KIPKEMOI KIRUI W., MASI F., DONG R. 2015. Treatment of industrial effluents in constructed wetlands: challenges, operational strategies and overall performance. Environmental Pollution. Vol. 201 p. 107–120.

YANG L., HU CC. 2005. Treatments of oil-refinery and steel-mill wastewaters by mesocosm constructed wetland systems. Water Science and Technology. Vol. 51. Iss. 9 p. 157–164.

YIRONG C., PUETPAIBOON U. 2004. Performance of constructed wetland treating wastewater from seafood industry. Water Science and Technology. Vol. 49. Iss. 5–6 p. 289–294.

ZUPANCIC JUSTIN M., VRHOVŠEK D., STUHLBACHER A., BULC T.G. 2009. Treatment of wastewater in hybrid constructed wetland from the production of vinegar and packaging detergents. Desalination. Vol. 246. Iss. 1–3 p. 100–109.

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Zastosowanie obiektów hydrofitowych do oczyszczania ścieków przemysłowych

STRESZCZENIE

W ostatnich latach rośnie zainteresowanie użyciem systemów hydrofitowych do oczyszczania lub wstępnego oczyszczania różnego rodzaju ścieków przemysłowych. W pracy zanalizowano aktualne wykorzystanie tych obiektów do oczyszczania ścieków przemysłowych na świecie. Przedstawiono warunki wykorzystania i skuteczności usuwania zanieczyszczeń łatwo i wolno biodegradowalnych, ze szczególnym naciskiem na zanieczyszczenia specyficzne poszczególnych gałęzi przemysłu. Opisano zastosowanie złóż z poziomym przepływem do oczyszczania ścieków między innymi z przeróbki ropy naftowej, produkcji papieru i przemysłu spożywczego. W Polsce obiekty hydrofitowe są wykorzystywane do oczyszczania ścieków i osadów z przetwórstwa mleka w skali pilotażowej lub do odwadniania osadów ściekowych wytwarzanych w oczyszczalni ścieków komunalnych z udziałem ścieków z przemysłu mleczarskiego i rybnego w wysokości 40%. We wszystkich przypadkach oczyszczalnie hydrofitowe zapewniły odpowiedni poziom usuwania zanieczyszczeń oraz tak zwany ecosystem service.

Słowa kluczowe: *materia organiczna, oczyszczalnie hydrofitowe, oczyszczanie ścieków, ścieki przemysłowe, zanieczyszczenia specyficzne*