Economic Assessment of Waste Oil-in-Water Emulsion Treatment Processes

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Abstract Preliminary economic analyses of three different processes for treating waste oil-in-water emulsions were performed. The aim was to identify the most suitable technology in terms of economic feasibility. Methods were chosen based on laboratory trials: evaporation, ultrafiltration and electrocoagulation. The annual quantity of waste oil-in-water emulsions was determined at 3 000 t/a, and the value of organic water pollution in terms of chemical oxygen demand (COD) was measured at 30 000 mg/L O2. All three methods would have positive net present values; therefore, the investment would be acceptable. The evaporation process integrated with the final treatment, such as active carbon adsorption, would represent a good compromise solution regarding the fulfilment of environmental requirements and economic efficiency.

Keywords: waste oil-in-water emulsion, ultrafiltration, evaporation, electrocoagulation, economic analysis.

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1 Introduction

The total global market share for cutting fluid management was estimated at 3.5 % to 4 % in 2007 (Sutherland, 2008). Ultimately, emulsions reach the end of their life and must be treated before final discharge. Owing to their oil content, which is limited in waste emulsions, disposal could be a major problem for the environment. The separation of oil and water is much more difficult nowadays than some decades ago, because more and more synthetic additives are used, which prevent simple separation of the two phases in emulsion.

Industrial wastewaters from cutting fluids pose a threat to the environment by affecting the chemical oxygen demand (COD) value, biochemical oxygen demand (BOD), mineral oil content, etc. The pH value has to be equalised to a neutral value (Cheng *et al.*, 2005). The varying content of waste oil-in-water emulsions (WOWE) represents a serious problem. Only when the concentration of oil in the oil-water emulsion is low (oil ≤50 mg/L), can treatment by sand filter be sufficient to meet regulatory requirements for drinking water (Almojjly *et al.*, 2018). Tubular membranes are frequently used for waste oil-in-water emulsion treatment (Nordin & Jönsson, 2010). A cellulose filter paper-polyvinyl alcohol (cellulose-PVA) membrane was fabricated recently for oil-in-water emulsion separation. The efficiency of synthetic emulsion separation was up to 99 % (Xu *et al.*, 2019).

If the oil phase does not contain hazardous material, it could be used as an energy source in incineration plants. Also, some income is guaranteed by the government in order to stimulate incineration and waste volume reduction. Integrated processes composed of selected separation techniques for given ranges of input COD were proposed by applying parametric analyses within the superstructure approach (Novak Pintarič *et al.*, 2016). The model showed that COD values could be reduced below allowable limits for discharging effluent into surface water.

This paper presents economic evaluations of WOWE treatment processes. The three most appropriate treatment methods were chosen: evaporation, ultrafiltration and electrocoagulation. Experiments were made on the laboratory scale to determine the operational efficiency of the selected processes, followed by a scale-up to industrial level and economic evaluations. Based on the experimental results, a techno-economic study was performed. Within this study, simulation and design of a WOWE treatment unit was conducted, thus allowing us to establish whether it would be economically profitable to install such plants, and if it would be technically feasible. The treatment unit was designed and engineered to suit WOWE generated from the eastern region of Slovenia. The results provided data for further optimization.

2 Methods

2.1 The existing treatment technology

The annual amount of treated waste oil-in-water emulsion (WOWE) within this study was 1936 tons. The composition of WOWE varied significantly and could achieve input COD values up to 300 000 mg/L. A company used a technology in which waste oil-in-water emulsions were treated by an emulsion-breaking process, achieving an average COD value in treated wastewater of around 30 000 mg/L O_2. The emulsion-breaking process was done by coagulation, using $Al_2(SO_4)_3$ and flocculent (A-100). The pH value was adjusted by using NaOH. The amount of slurry was determined at 324 t/a. Slurry must be dried and then treated by H_2SO_4 to remove water. The dry slurry amount was determined at 216 t/a. The simplified scheme of WOWE treatment is presented in Figure 1. The costs of emulsion breaking are gathered in Table 1. COD was measured in samples in the laboratory using the ISO 6060 standard method. The COD value of the effluent was still very high and needed to be lowered by additional treatment.

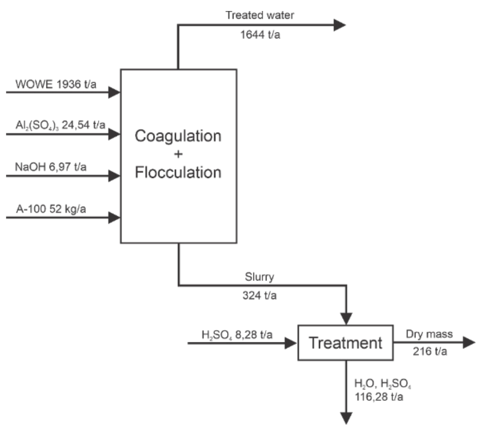

Figure 1: Simplified scheme of WOWE pre-treatment.

Table 1: Annual cost of WOWE emulsion breaking.

	Unit	Cost per unit, €	Amount per year	Annual cost, €/a
WOWE	m^3		1972,74	
Al_2SO_4	kg	0.285	25 500	7267.50
NaOH	kg	0.53	7185	3808.05
A-100	kg	13.40	53.43	715.96
H_2SO_4	kg	0.26	9840	2558.40
Process water	m^3	0.0423	35 033	1481.90
Compressed Air	m^3	0.0157	12 000	188.40
El. power	kWh	0.0369	3381.7	124.78
Power	kW	0.75457	588	443.69
Emissions Trading	kWh	0.07444	3381.7	251.73
Process water fixed	-	208.15	12	2497.80
Water use fee	m^3	0.0732	35 033	2564.42
Rent	€/a	30	1972.74	59 182.20
Waste	kg	0.093	292 094	27 164.74
		Total cost	**€/a**	**108 249.57**

2.2 Economic evaluations

Environmental tax for pollution load was calculated according to Eq. (1) from the Decree on the environmental tax on pollution due to the wastewater discharge (Decree, 2012).

$$c_{\mathrm{tax}} = c_{\mathrm{EO}} \frac{q_{\mathrm{V}} \cdot \gamma_{\mathrm{COD}}}{\gamma_{\mathrm{COD,u}}} \quad (1)$$

where

c_{tax} tax for environmental pollution (€/a)
c_{EO} tax for environmental pollution unit (€)
q_{V} flowrate of wastewater (m^3/a)

γ_{COD}	COD (kg/m^3)
$\gamma_{\mathrm{COD,u}}$	environmental pollution unit (50 kg O_2)

Different criteria were used for evaluating the economic feasibility of certain treatment processes.

Cash flow (C_{A}) is expressed by Eq. (2):

$$C_{\mathrm{A}} = (1 - t)\cdot(R - E) + t\cdot D \qquad (2)$$

Where

C_{A}	cash flow (€/a)
R	revenue (€/a)
E	expenditure (€/a)
D	depreciation (€/a)
t	tax rate.

Depreciation (D) is expressed by Eq. (3):

$$D = \frac{I}{n} \qquad (3)$$

Where

I	investment (€)
n	depreciation period (a).

Payback time(t_{PB}) is defined by Eq. (4)

$$t_{\mathrm{PB}} = \frac{I}{C_{\mathrm{A}}} \qquad (4)$$

Net present value (NPV) is determined by Eq. (5):

$$NPV = -I + f_{\mathrm{PA}} \cdot C_{\mathrm{A}} \qquad (5)$$

Where

NPV net present value (€)
f_{PA} factor of present value (a).

The factor of present value for period (*n*) at discount rate (*p*) is calculated by Eq. 6:

$$f_{PA} = \frac{(1+p)^n}{0{,}1 \cdot (1+p)^n} \quad (6)$$

3 Experimental

Three treatment technologies were tested in order to further decrease the COD value of pre-treated WOWE: evaporation, ultrafiltration and electrocoagulation. These are the most commonly used methods according to the literature (Križan *et al.*, 2013). According to a market survey, it was assumed that the capacity of the treatment process would increase from 1936 t/a to 3000 t/a.

3.1 Evaporation process

An annual quantity of 3 000 t/a and an initial COD value at 30 000 mg/L were assumed. Laboratory experiments determined the WOWE share to distillate at 90 %; therefore, the mass flowrate of distillate was estimated at 2 700 t/a and the flowrate of slurry at 300 t/a. COD in distillate was determined in the laboratory at 1 000 mg/L. Electricity demand was specified by the equipment producer at 60 kWh/m^3. Annual demand was calculated at 180 000 kWh/a. Figure 2 represents a simplified process scheme for WOWE treatment by evaporation (EV). Distillate is further transported to a treatment plant (WWTP). The slurry is transported to an incineration plant and burned.

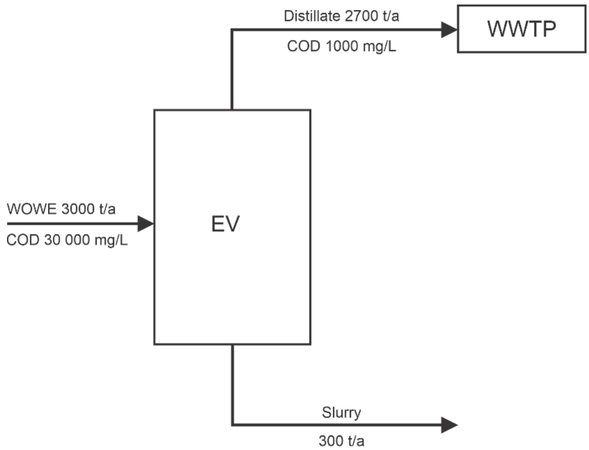

Figure 2: Simplified evaporation process for WOWE treatment.

3.1.1 Capital cost of the evaporation process

The capital cost of an evaporator was obtained from three different suppliers and assessed to an average value of 200 000 €. A 30 m^3 reservoir is needed for three-day storage of WOWE. The capital cost of the installed tank was estimated at 23 760 €. It was calculated that 5.7 t/week of slurry would be produced. The tank volume of slurry storage was estimated at 6 m^3 and capital cost at 10 450 €.

Total investment was calculated at 234 210 €.

3.1.2 Revenue and operating cost

If the price of WOWE was 100 €/a, the revenue (*R*), assuming a capacity of 3000 m^3/a, would be 300 000 €/a.

Operating costs were as follows:

- electricity at a price of 0.07 €/kWh (Price, 2019)
  180 000 kWh/a · 0.07 €/kWh = 12 600 €/a
- salary for one person: 40 000 €/a
- tax for water emissions was calculated by Eq. (1):
  c_{tax} = 1 404 €/a

Total cost, i.e. expenditures (*E*), was calculated at 54 004 €/a.

3.1.3 Economic criteria

Eq's. 2 to 6 were used for calculation of depreciation *D*, cash flow C_A, payback time t_{PB} and net present value *NPV*.

$$D = \frac{234\ 210}{10} = 23\ 421\ €/\text{a}$$

The cash flow assuming an 18 % tax rate could be calculated as follows:

C_A = 205 933 €/a
t_{PB} = 1.14 a
f_{PA} = 6.1438
NPV = 1 031 001 €

An *NPV* greater than zero and a payback time of about one year indicate an acceptable investment project for the evaporation process.

3.2 Ultrafiltration process

Fig. 3 presents a simplified scheme of the ultrafiltration process (UF). WOWE flows into the UF cell; a permeate then flows into WWTP, and the concentrate is a waste product that can be incinerated.

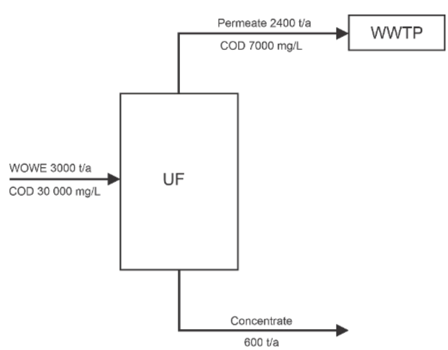

Figure 1: Simplified process flow for WOWE treatment by ultrafiltration.

Annual WOWE was the same as with the first treatment (evaporation); 80 % of the initial WOWE is permeate 2 400 t/a and 20 % concentrate 600 t/a. The COD value in the permeate was determined at 7 000 mg/L. It was assumed that specific electricity consumption would be 18 kWh/m^3. Annual electrical energy demand is 54 000 kWh/a.

3.2.1 Capital cost of the ultrafiltration process

The capital cost of an ultrafiltration unit was obtained from the supplier: 7 000 €.

The tank for WOWE was the same as for the evaporation process: 23 100 €.

Double the volume was needed for concentrate storage than in the evaporation process, which means 12 m^3 and a capital cost of 14 895 €.

Total investment was calculated at 44 995 €.

3.2.2 Revenue and operating cost

Revenue was the same as in the evaporation process: 300 000 €/a.

Operating costs were as follows:

- electricity: 54 000 kWh/a · 0.07 €/kWh = 3 780 €/a
- salaries: 40 000 €/a
- membrane replacement: the cost of 24 800 $/a was found in the literature (Cheryan and Rajagopalan, 1998) for 19 059 m^3/a. Therefore, for 3 000 m^3/a, it was calculated at 2 866 €/a.
- tax for water emissions was calculated by Eq. (1)
  $c_{\text{tax}} = 26 \cdot \frac{2.4 \cdot 7000}{50} = 8\,736$ €/a

Total cost was calculated at 55 382 €/a.

3.2.3 Economic criteria

D = 4 500 €/a
C_A = 201 397 €/a
t_{PB} = 0.22 a
$NSV = -I + f_{PA} \cdot C_A = -44\,995 + 6.1438 \cdot 201\,397 = 1\,192\,348$ €

The ultrafiltration process had an *NSV* greater than zero and a payback time shorter than 1 year, which indicated the investment project for ultrafiltration was acceptable.

3.3 Electrocoagulation process

Figure 4 shows the simplified process of electrocoagulation (EC). Annual WOWE was the same as previously determined. It was established experimentally that 80 % would separate as purified water and 20 % as a slurry. The COD value in purified water was determined at 12 000 mg/L. Electricity demand was estimated at 2 kWh/m^3 for a capacity of 3 000 m^3/a (Rodriguez *et al*, 2007), yielding an annual demand of 6 000 kWh/a.

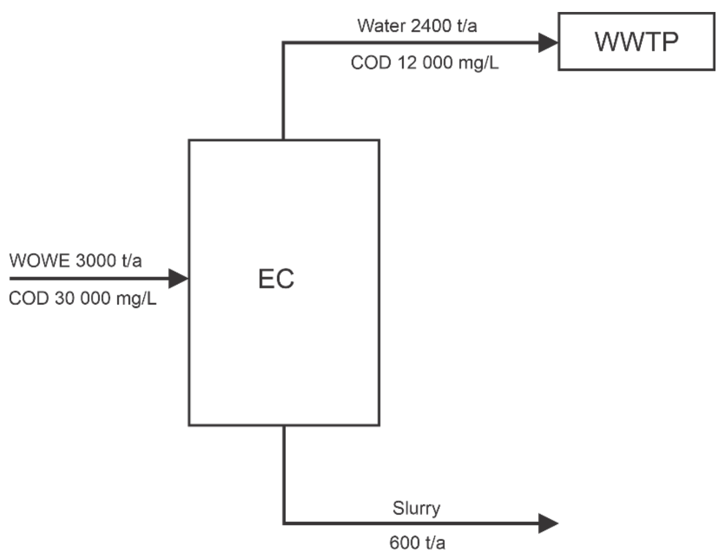

Figure 4: Simplified process flow for WOWE treatment by electrocoagulation.

3.3.1 Capital cost of the electrocoagulation process

Capital cost was determined by using a six-tenth factor rule and a reference price of 4 621 778 $ for equipment with a capacity of 500 gal/min (Hamilton, 2009), which amounted to 141 845 € for the capacity of 3000 m^3/a.

Reservoirs for WOWE were assumed the same as for the ultrafiltration process, i.e. 30 m^3, and 23 100 € +14 895 € = 37 995 €.

Total investment was estimated at 179 840 €.

3.3.2 Revenue and operating costs

Income is the same as in the other two processes: 300 000 €/a.

Costs:

- electricity: 6 000 kWh/a · 0.07 €/kWh = 420 €/a
- salaries: 40 000 €/a
- electrode replacement: aluminium demand is 0.1 kg/m^3; the price for aluminium tile was 4 €/kg (Rodriguez *et al.*, 2007), which in our case amounted to 1 200 €/a.
- tax for water emissions was calculated by Eq. (1)

$$C_{\text{tax}} = 26 \cdot \frac{2.4 \cdot 12\ 000}{50} = 14\ 976\ €/\text{a}$$

Total cost was calculated at 56 596 €/a.

3.3.3 Economic criteria

D = 17 984 €/a
C_{A} = 202 828 €/a
t_{PB} = 0,89 a
NPV = 1 066 295 €/a

Results are gathered in Table 2. All three technologies are economically acceptable at a discount rate of 10 %.

The comparison showed that evaporation has the highest capital cost and electricity demand. This technology was also the most efficient in COD reduction; however, its payback time was the longest and NPV the lowest. The less expensive technology was ultrafiltration, which showed the highest NPV and the shortest payback time. In general, cash flows of all three options were similar at 200 000 €/a and the net present values at around 1 000 000.

Table 2: Results of economic evaluation for three technologies.

	EV	UF	EC
WOWE flow rate (m^3/a)	3 000	3 000	3 000
COD (mg/L)	1 000	7 000	12 000
Electricity consumption (kWh/m^3)	60	18	2
Electricity cost (€/a)	12 600	3 780	420
Total cost (€/a)	54 004	55 382	56 596
Capital cost (€)	234 210	44 995	179 840
Cash flow (€/a)	205 933	201 397	202 828
Payback time (a)	1.14	0.22	0.89
NPV (€)	1 031 001	1 192 348	1 066 295

3.4 Integration of all three technologies with active carbon adsorption

Within laboratory experiments, it was determined that the evaporation process could reduce COD to 1000 mg/L, ultrafiltration to 7000 mg/L and electrocoagulation to 12 000 mg/L. None of these three output concentrations was suitable to discharge treated water into surface water. Therefore, experiments were conducted to further reduce the effluents' COD values by using adsorption on active carbon. It was established that:

- the addition of active carbon in the amount of 2 kg/m^3 reduced the COD value of the effluent from the evaporation process from 1000 mg/L to 120 mg/L, which was suitable for discharging into a river.
- the addition of active carbon in the amount of 40 kg/m^3 reduced the COD value of the effluent from the ultrafiltration process from 7000 mg/L to 3060 mg/L, and final treatment in WWTP was still needed; however, this meant a lower water emission tax.
- The COD of electrocoagulation effluent was reduced from 12 000 mg/L to 5246 mg/L by using 40 kg/m^3 of active carbon. Final treatment in WWTP was still needed at a lower cost.

The investment costs of all three technologies were increased by 10 000 € for a filtration vessel with active carbon. The expenditures were increased for purchasing active carbon at a price of 1.5 €/kg and removing used active carbon at a price of 0.36 €/kg. In the case of ultrafiltration and electrocoagulation, the water emission tax was also calculated because final COD values were above 120 mg/L.

Table 3 present the results of integrated technologies with final treatment using active carbon. The operating costs of ultrafiltration and electrocoagulation integrated with adsorption are high because of their high consumption of active carbon. Net present values are therefore lower than in Table 2; however, the difference is the smallest in the case of evaporation. Evaporation showed the highest NPV, despite large capital cost, but the operating cost was lower and cash flow higher.

Table 3: Results of economic evaluation for three technologies plus active carbon.

	EV+AC	UF+AC	EC+AC
WOWE flow rate (m^3/a)	3 000	3 000	3 000
COD (mg/L)	120	3 060	5 246
Electricity consumption (kWh/m^3)	60	18	2
Electricity cost (€/a)	12 600	3 780	420
Total cost (€/a)	62 644	229 025	226 727
Capital cost (€)	244 210	54 995	189 840
Cash flow (€/a)	199 028	59 190	63 501
Payback time (a)	1.23	0.93	2.99
NPV (€)	978 578	308 656	200 297

4 Conclusion

This paper presented evaluations of the economic viability of three technologies for treating waste oil-in-water emulsions: evaporation, ultrafiltration and electrocoagulation. The annual amount of WOWE was estimated at 3 000 t/a and initial COD value 30 000 mg/L.

The lowest COD value of the effluent (1000 mg/L) was achieved by the evaporation process; however, its capital cost was the highest, and NPV the lowest, yet still positive. The NPVs for the ultrafiltration and electrocoagulation processes were slightly higher; however, the effluents' COD values were relatively high: 7 000 mg/L and 12 000 mg/L, respectively. The payback period for the evaporation process was slightly above one year, electrocoagulation slightly below, and ultrafiltration only 0.22 years.

When the effluents from these methods were treated by adsorption on activated carbon, only evaporation achieved a final COD value suitable for discharging treated water into a river. NPV decreased by around 5 %, while NPV for combinations of ultrafiltration and electrocoagulation with active carbon decreased by 75 % and 81 %, respectively. Evaporation technology integrated with final adsorption treatment with active carbon represents a good compromise solution between the efficiency of COD reduction and economic viability.

Acknowledgments

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