Approach for an integrated assessment and optimisation of waste water treatment and sediment remediation processes

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Eduardo Arévalo

Contents

Abbreviations

AGI	Algae growth inhibition test with *Pseudokirchneriella subcapitata*
AET	Aquatic ecotoxicity potential
AOX	Adsorbable halogenated organics
BCT	Bacteria contact test with *bacillus cereus* as test organism
BDD	Boron doped diamond anodes
BTP	Best theoretical performance of a process
BUWAL	Swiss Federal Agency of Environment, Forestry and Landscape
COD	Chemical oxygen demand
DBT	Dibutyltin
DSA	Dimensionally stable anodes
DOC	Dissolved organic carbon
EIA	Environmental impact assessment
ERA	Ecological risk assessment
EUSES	European union system for evaluation of substances
FU	Functional unit in life-cycle assessment
GAC	Granular activated carbon
LBT	Luminescence bacteria test with *Vibrio fischeri*
LCA	Life-cycle assessment
LCC	Life-cycle costing
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
LP	Linear programming
HT	Human toxicity
IPP	Integrated product policy of the EU
IPPC	Integrated pollution prevention and control
MO	Multiobjective optimisation
MADA	Multi-attribute decision analysis
MBT	Monobutyltin
NLP	Non-linear programming
OT	Organotin species
REACH	Policy for the registration, evaluation and authorisation of chemicals of the European Union
SED-TOX	Sediment toxicity index
SET	Sediment ecotoxicity potential
SHE	Standard hydrogen electrode
SO	Single objective optimisation
TBT	Tributyltin
Ti/IrO_2	Titanium coated with Iridium dioxide anodes

USES-LCA	Uniform system for evaluation of substances for impact assessment in life-cycle assessment

List of symbols

a	Weighting factor for treatment costs
A	Acidification potential effects, kg SO_2 eq./m^3, kg SO_2 eq./t
A_{Anode}	Anodic area installed in an electrolysis cell, cm^2
A_{lab}, $A_{scale\text{-}up}$	Anodic area installed in the electrolysis cell at laboratory scale and at large scale (10 m^3/h)
BV	Bed volumes to treat before regenerating the activated carbon bed
C_i	Cost of piece of equipment i (e.g. pumps, stirrers, vessels, etc.), €
C_{AOX}	AOX concentration, mg/L, mg/kg
C_{Anode}	Price of the anode material, €/m^2
CAPT	Cumulative average of phase toxicity (SED-TOX methodology)
C_{NaCl}	Cost of NaCl, €/kg
C_{TBT}, C_{DBT}	Concentration of TBT and DBT, ng/L
CI_{El}	Capital investment, €
d	Depreciation period, a
D	Function describing the distance between the normalised Pareto front and the reference point in the distance-to-reference-point theory
DAR	Depletion of abiotic resources effects, MJ fossil energy/m^3, MJ fossil energy/t
E	Electricity consumption, kWh/m^3, kWh/t
EBCT	Empty bed contact time of the activated carbon column, h
EC_{El}	Costs of electricity for the electrolysis, €/m^3, €/t
$EC_{Equipment}$	Costs of electricity to run the equipment of the process, €/m^3, €/t
GW	Global warming effects, kg CO_2 eq./m^3, kg CO_2 eq./t
i	Current density applied in electrochemical treatment, mA/cm^2
$I_{AGI\text{-}G4}$	Inhibition of dilution step G4 for algae growth inhibition test, %
$I_{LBT\text{-}G4}$	Inhibition of dilution step G4 for luminescence bacteria test, %
IC	Investment costs, €/m^3, €/t
IC_{BDD}, $IC_{Ti/IrO2}$	Investment costs for electrochemical treatment using BDD or Ti/IrO_2 anodes, €/m^3
IC_{Floc}	Investment costs for flocculation, €/m^3
IC_{GAC}	Investment costs for granular activated carbon adsorption, €/m^3
TC_{Floc1}, TC_{Floc2}	Treatment costs of flocculation for process chains 1 and 2, €/m^3
IC_{El}	Investment costs for the electrochemical treatment, €/m^3

M_k	Distance between the normalised Pareto front and the reference point in the distance-to-reference-point methodology
M_{Added_NaCl}	Mass of NaCl added to the sediment suspension, kg/t
MC	Material costs for the pilot plant to treat TBT contaminated sediments, €/t
n	Number of tests of a bioassay battery indicating a toxic response (SED-TOX methodology)
n_i	Quantity of pieces of equipment i required (i.e. pumps, cells, vessels)
$norm\_obj_i$	Normalised value of objective i
norm_LCA	Normalised value of LCA indicators (DAR, GW, A)
$norm\_LCA_{min}$	Normalised minimum LCA indicators ($norm\_LCA_{min} = 1$)
norm_TC	Normalised treatment costs
$norm\_TC_{min}$	Normalised minimum treatment costs ($norm\_TC_{min} = 1$)
OC_{El}	Operation costs, €/m^3, €/t
OC_{Floc1}, OC_{Floc2}	Operation costs of flocculation with process chains 1 and 2, €/m^3
OC_{BDD}, $OC_{Ti/IrO2}$	Operation costs of electrochemical treatment using BDD or Ti/IrO_2 anodes, €/m^3
OC_{GAC}	Operation costs of granular activated carbon adsorption, €/m^3
Q	Volumetric flow, m^3/h
r	Redundancy factor (SED-TOX methodology)
r_i	Coordinate of the reference point for objective i (Best performance point)
TC	Treatment costs, €/m^3, €/t
TC_{BDD}, $TC_{Ti/IrO2}$	Treatment costs of electrochemical treatment using BDD or Ti/IrO_2 anodes, €/m^3
TC_{GAC}	Treatment costs of granular activated carbon adsorption, €/m^3
TIF	Toxicity incremental factor (SED-TOX methodology)
TU	Toxic units (SED-TOX methodology)
U	Working potential of the electrolysis cell, V
$V_{Treated}$	Volume of water treated in the activated carbon filter before regeneration of the adsorber is needed, m^3
V_{Bed}	Volume of the activated carbon bed, m^3
V_w	Batch volume of electrochemical treatment experiments, m^3

Greek symbols

α	Exponent factor defining the form of the function for calculating the distance to the reference point
τ	Residence time, h

Summary

The aim of this work is the design, implementation and evaluation of an approach that integrates economic and environmental criteria for the assessment and optimisation of processes. Even it is clear that the paradigm of sustainable development is the guiding principle to evaluate processes and any human activity, the approach designed covers only two of the columns of the concept of sustainability: economy and environment. The inclusion of social or socio-economic criteria is beyond the scope of this investigation. Among the criteria considered, the focus of this work is set on the environmental aspect.

An environmental assessment approach following the notion of sustainability must attempt to evaluate all potential impacts that a process can cause on the different environmental compartments, not only on a site-specific scale but along the complete network of supply chains to run the process, i.e. *life-cycle*. An approach based on the principles of life-cycle thinking is a necessary step in this direction.

Much efforts have been carried out in the last 15 years to develop life-cycle thinking approaches, e.g. the environmental life-cycle assessment (LCA), which have led to the standardisation of the LCA methodology and its positioning and acceptance as a tool that aims towards a holistic process assessment from a systemwide perspective. However, it has to be acknowledged that no single assessment tool can cover all relevant aspects related to environmental assessment making it necessary to apply a combination of methods.

In order to illustrate the need of combining several assessment tools and the limitations of part of current methods available in LCA, e.g. impact assessment methods for toxic emissions, two end-of-pipe processes dealing with the elimination of toxic compounds from waste waters and sediments have been studied. The elements composing the integrated approach for assessing and optimising treatment processes are:

a) Economic analysis to determine treatment costs

b) Environmental assessment based on a combination of a LCA-based approach complemented with eco-toxicological investigations to assess the quality of the treated materials and potential toxic impacts when they are discharged in the aquatic environment

Although it is clear that on the first instance end-of-pipe technologies do not represent an option that fully fits into the concept of sustainability, they are considered as a last resource to prevent pollution or higher risks to the environment. Two end-of-pipe processes are studied in this investigation for the following reasons:

a) Treatment and remediation processes illustrate best the methodological challenges of attempting an approach based on life-cycle thinking for processes traditionally assessed from a *site-specific* perspective.

b) The analysis of treatment processes evidences the need to combine existing tools for process assessment of technologies dealing with toxic emissions and to identify their synergies, e.g. the combination of an *effect-oriented* approach (based on bioassays) with an *inventory-oriented* approach such as life-cycle assessment.

The first process studied was a laboratory scale process to treat dockyard waters contaminated with copper, zinc and tributyltin (TBT). The elimination of the heavy metals was done by means of flocculation with ferric salts, while TBT was decomposed by means of electrolysis.

The main task consisted in developing the electrochemical treatment process to eliminate TBT because conventional water treatment processes are not suitable to reach a final TBT concentration of 100 ng/L Sn. Two anode materials for the electrolysis were tested: boron-doped diamond anodes (the support material was niobium and the doping level of boron was 2000 ppm) and titanium coated with iridium dioxide (Ti/IrO_2). The former is a novel material with exceptional properties for hydroxyl radical generation, whilst the latter is a commercially available material.

The results of the assessment showed that it was possible to destroy organotins down to the target concentration with both anode materials exhibiting similar degradation rates. Nevertheless it was necessary to add a granular activated carbon (GAC) adsorption unit to eliminate AOX formed during the electrolysis and residual oxidants and reduce the high toxicity levels indicated by the bioassays. The life-cycle assessment of this process revealed that the most environmentally "costly" operation unit was electrochemical treatment (compared to flocculation and GAC) and therefore was subjected to optimisation.

A multiobjective optimisation (MO) approach was needed to optimise the operation of the electrochemical reactor in terms of treatment costs and life-cycle impacts (depletion of abiotic resources, global warming and acidification effects). The MO problem was solved using the ε-constraint method to obtain the non-inferior solutions for the criteria considered. Operating with Ti/IrO_2 resulted advantageous mostly due to the lower anode material costs. To select the "best" operation conditions out of the non-inferior curve, the point closer to a reference point representing the best theoretical performance that the electrolysis could achieve was selected (the best operating conditions obtained were: employing Ti/IrO_2 anodes at a current density of 9.5 mA/cm^2, which resulted in treatment costs of 1.18 €/m^3, required 72.8 MJ of fossil energy per m^3 and emission of 6.0 kg CO_2 equivalents and 0.034 kg SO_2 equivalents per m^3).

The second process was a pilot scaled process to remediate TBT contaminated sediments by means of electrolysis. The sediment throughput of the plant was 0.2 t/h. The process was able to decrease TBT down to the target 100 μg/kg in the range of 4.4 to 6.6 mA/cm^2 with treatment costs between 20 to 23 €/t. Similarly to the waste water treatment process, the LCA methodology applied resulted unsuitable to assess the behaviour of toxicity of the sediment during treatment. TBT and PAH decreased but heavy metals and PCB were not affected by treatment. Although the concentrations of these pollutants of concern decreased or remained constant, the effect-oriented approach (ecotoxicological test investigation) indicated high toxicity of the sediment. By-products (e.g. AOX) and residual oxidants were the cause of these effects.

These examples showed the synergies between inventory- and effect-oriented approaches for assessment of processes dealing with toxic emissions. In addition, the compatibility of LCA with site-specific assessment tools to improve the quality of environmental assessments was demonstrated, as well as its compatibility with multi-criteria tools for optimisation and integration of environmental and economic criteria in a sustainability-oriented approach.