Chapter 38

Biological wastewater treatment as an opportunity for energy and resource recovery

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38.1 BIO-BASED TECHNOLOGIES FOR ENERGY AND RESOURCE RECOVERY

As raw materials become increasingly scarce, the current linear system of industrial manufacturing – extracting resources, transforming them into products, and discarding the waste – increasingly appears to be inefficient and unsustainable. This approach is now being succeeded by 'the circular economy', a new manufacturing paradigm which closes production cycles by recovering wastes and reusing them as resources. A prime example is the treatment of wastewater, which aside from reuse as a resource of its own (water), is now being treated to recover the chemicals and energy it contains. Figure 38.1 illustrates the potential pathways by which chemicals, metals, nutrients, thermal energy, biofuels, and the water itself may be recovered from industrial wastewater for reuse (e.g., agricultural reuse).

This new circular approach to the reuse of industrial wastewater has given rise to the development of new technologies, especially biological wastewater treatment methods. These tend to be more sustainable and 'eco-friendly' than either physical or chemical methods, in that they use less energy and produce fewer toxic by-products. On the other hand, biological treatment methods can be limited by the high toxicity of industrial wastewater, which is less biodegradable than domestic wastewater. This chapter presents some new and innovative methods currently being developed and applied to biologically recover energy and materials from industrial wastewater.

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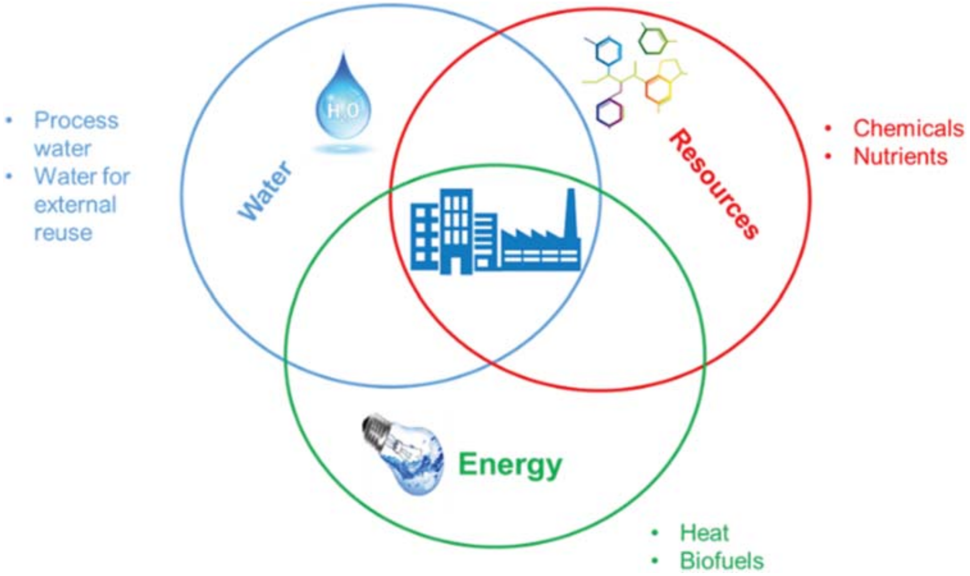

Figure 38.1 Conceptual diagram of recovery of energy and resources from industrial wastewater.

38.2 ENERGY PRODUCTION

38.2.1 Production of methane: anaerobic digestion

The most common way to recover energy from wastewater biologically is by producing methane (CH_4) in biogas as a by-product of anaerobic treatment. Engineered anaerobic systems have been in use for literally hundreds of years. Early designs, applied to organic waste treatment, involved holding waste for relatively long periods of time (on the order of weeks or months) to allow slow-growing anaerobic bacteria to digest organic waste, releasing carbon dioxide and methane in the process. This process is still in use today, for example in nonaerated wastewater treatment and sludge storage lagoons. However, the efficiency of these systems is limited at ambient temperatures, and when feed to the treatment system is diluted.

The design of industrial wastewater treatment is challenging due to the intrinsic characteristics of industrial streams, such as high chemical oxygen demand (COD), extreme pH, and salt content (Massara *et al.*, 2017). Anaerobic systems have been modified to treat various types of industrial wastewater. Enhancements of anaerobic treatment performance are achieved by retaining and concentrating the bacteria in the bioreactor, so that influent comes into contact with a greater amount of biomass, and by increasing the recirculation and settling of the biomass. These high rate anaerobic bioreactors are able to operate at higher efficiencies, because the contact time between the substrate and the biomass (solid retention time or SRT) can be much longer than the residence time of the influent wastewater in the bioreactor (hydraulic retention time or HRT).

Additional improvements have been made by further modifying the equipment and operating strategies. For example, by increasing the concentration of biomass with a filtration unit consisting of a permeable membrane, the anaerobic membrane bioreactor (AnMBR) is able to obtain much higher gas production rates than conventional anaerobic digesters relying on gravity settling. Moreover, the almost complete retention of the biomass allows the production of high quality effluents suitable for reuse. The up-flow anaerobic sludge blanket reactor (UASB) introduces wastewater through the bottom of the tank, allowing

Table 38.1 Methane (CH_4) production rates in different anaerobic treatment systems.

Anaerobic System/Industrial Wastewater	Chemical Oxygen Demand (g/L)	Organic Loading Rate (kg_{COD}/m^3 d)	CH_4 in the Biogas (%)	CH_4 Production Rate, $^a(L_{CH4}/d)$, $^b(L_{CH4}/g_{COD\ removed})$	Scale	Ref.*
Anaerobic membrane bioreactor						
Distillery	22.6	2.06	55	1.54^a	Lab	(1)
Brewery	80–90	28.5	65–80	280^b	Pilot	(1)
Pharmaceutical	4.3	0.025	60	$0.5–0.6^b$	Pilot	(2)
Bamboo	17.2	6		$10.3–13.2^b$	Lab	(2)
Expanded granular sludge bed						
Coal gasification	2.3–2.5	0.63	–	0.27^a	Pilot	(1)
Inverse fluidized bed reactor						
Dairy	1	0.5	–	0.24^a	Lab	(1)
Pulp and paper	1–8	20	–	$0.247–0.283^b$	Lab	(1)
Up-flow anaerobic sludge blanket						
Palm oil mill	95	0.0175	50	7^a	Lab	(3)
Sunflower oil	15.3	1.6–7.8	85	47.6^a	Pilot	(3)

*(1) Massara *et al.* (2017); (2) Musa *et al.* (2018); (3) Ahmad and Ghufran (2019).

it to flow through a thick layer of sludge suspended towards the top, thus maximizing the contact substrate-biomass. The UASB bioreactor also acts as a settling unit; depending on the flux conditions, it can promote biomass granulation. Effective contact between substrate and biomass is also achieved in expanded granular sludge bed (EGSB) reactors with the influent wastewater flowing through the sludge layer at a fast rate, causing it to expand. In the inverse fluidized bed reactor (IFBR), cells are immobilized on low-density particles, to achieve effective biomass retention and high SRTs. Particles are fluidized downwards, that is, the wastewater flows towards the bottom of the tank. Each of these modifications offers advantages that might be adapted to any given industrial setting. Data for biogas production reported in several recent review papers is summarized in Table 38.1 below, which shows energy production rates (in terms of methane production rate) as high as 280 L_{CH4}/g COD removed (for brewery wastewater).

38.2.2 Production of electricity: microbial fuel cells

Another important innovation is the development of the microbial fuel cells (MFCs), which have now produced electricity directly through biological treatment of organic wastewater at both research and pilot scales (Mo & Zhang, 2013). The substitution of a biological catalytic redox reaction for one of the poles in a classic abiotic electrochemical cell allows current to be generated (Santoro *et al.*, 2017). Although MFCs have been widely studied over the last 15 years, applications of these systems are only at a pilot scale for wastewater treatment so far (Mo & Zhang, 2013). Technology limitations of MFCs currently being investigated include high energy loss during the generation, low organic utilization rates, and high capital costs (around 800 times of an anaerobic system). As shown in Table 38.2 below,

Table 38.2 Microbial fuel cells for the treatment of wastewater from various industrial sources.

Anode/Cathode	Industrial Wastewater	COD (g/L)	Working Volume (L)	P_{dmax}, ^{a}(mW/m^2), ^{b}(mW/cm^3)	Ref.*
Single-chambered fuel cells					
Graphite felt	Coal tar	2.01	0.6	4.5^a	(1)
Graphite fiber-brush/carbon cloth	Coking	3.20	0.3	538^a	(1)
Graphite fiber-brush anode	Paper recycling	1.46	0.3	501^a	(2)
Toray carbon/carbon cloth	Swine	8.32	0.03	$182–261^a$	(2)
Single-chambered fuel cells with air cathode					
Proofed carbon cloths	Brewery	2.24	0.03	205^a	(2)
Graphite plates	Pharmaceutical	7.98	0.43	205.6^a	(1)
Single-chambered fuel cells with granular activated carbon (GAC)					
GAC bed	Textile	2.20	2.5	0.008^b	(1)
Two-chambered fuel cells					
Graphite plates	Dairy	53.22	2	621^a	(1)
Carbon graphite	Palm oil mill	2.68	0.1	451.3^a	(1)
Two-chambered fuel cells with granular graphite					
Carbon rod/graphite flake	Refinery	0.25	0.4	330.4^b	(1)

*(1) Pandey *et al.* (2016); (2) Pant *et al.* (2010).

maximum power density of different types of MFCs varies widely between of 4.5 and 621 mW/cm^2 depending on their configuration. A threshold value for feasible industrial application of MFCs for energy recovery from organic matter, suggested by Pham *et al.* (2009), is 1.0 kW/m^3 evaluated for reactor volumes $>$1 L.

38.3 RESOURCE RECOVERY

38.3.1 Membrane treatment methods

Membranes are incorporated into the industrial wastewater treatment process, to provide a 'double optimization', resulting not only in effective removal of toxic pollutants but also in recovery of reusable resources such as heavy metals, salts, and valuable chemicals. As shown in Table 38.3 below, a broad range of recovery strategies has been developed, based on products to be recovered. It should be noted that results for technologies currently under development reflect treatment of synthetic wastewater at lab scale. However, in a recent study (Lu *et al.*, 2019), a pilot membrane bioreactor (working volume 200 L) was successfully used to treat actual brewery wastewater. Biomass consisted of photosynthetic bacteria able to convert substrates into bioproducts used in the agriculture, cosmetic, and health industries, including proteins, amino acids, carotenoids, and coenzyme Q. These valuable resources are directly recovered from the bacteria, avoiding additional operation of sludge treatment and disposal.

Table 38.3 Resource recovery from various industrial wastewaters.

Industrial Wastewater	Resource Recovered	Technology	Reuse	Recovery (%)	Ref.*
Meat processing	Nutrients	Anaerobic membrane bioreactor	N,P	N: 90, P: 74	(1)
Biorefinery	Chemicals	Electrolytic membrane bioreactor	Acetate	96	(2)
Brewery	Chemicals	Photosynthetic membrane bioreactor	Bio-products	0.25–42	(3)
Tannery	Metals	Two-phase partitioning bioreactor	Cr(VI)	100	(4)
Metallurgical process	Metals	Microbial fuel cell, microbial electrolytic cell	Co	100	(5)
Olive processing	Salts	Sequencing batch reactor with ultra- and nano-filtration	Brine	98	(6)
Hypersaline	Salts	Two-phase partitioning bioreactor	Brine	100	(7)

*(1) Jensen (2015); (2) Andersen *et al.* (2014); (3) Lu *et al.* (2019); (4) Mosca Angelucci *et al.* (2017); (5) Huang *et al.* (2014); (6) Ferrer-Polonio *et al.* (2017); (7) Tomei *et al.* (2018).

38.3.2 Microbial electrolysis cells

Microbial electrolysis cells (MECs) require an external source of electricity to produce valuable chemicals (Mo & Zhang, 2013). MEC technology uses microorganisms as a catalyst and the oxidation reaction occurs at the anode with the production of CO_2, electrons, and protons. The electrons then travel through an external circuit to the cathode and combine with the free protons in solution to produce H_2, while CO_2 and protons react to form methane and H_2O. The flux of electrons is ensured by the external power supply (Zou *et al.*, 2017).

Applications of this technology normally produce H_2, CH_4, or other chemicals such as formic acid and hydrogen peroxide (Hua *et al.*, 2019). However, MEC technology is still in its infancy and must overcome serious challenges before practical large-scale applications can be achieved, including reactor configuration optimization, optimization of degradation conditions, and screening dominant strains with good electricity production (Hua *et al.*, 2019).

38.3.3 Case study: two-phase partitioning bioreactors (TPPBs)

One particular challenge of recovering resources from industrial wastewater with bio-based technologies is the toxicity related to these streams: indeed the bacteria able to remove biodegradable pollutants are often sensitive to toxic and/or high concentration of chemicals. In order to overcome this limitation, a unique technology has been developed that concentrates the toxic substrates in a non-aqueous phase (termed partitioning phase, a solvent or solid) and gradually delivers them to the bacteria in the aqueous phase at a tolerable concentration. Release is driven by the bacterial metabolic demand.

These two-phase partitioning bioreactors (TPPBs) have been successfully applied for the treatment of aqueous contaminants (Tomei *et al.*, 2011) and for soil bioremediation (Tomei *et al.*, 2015) with

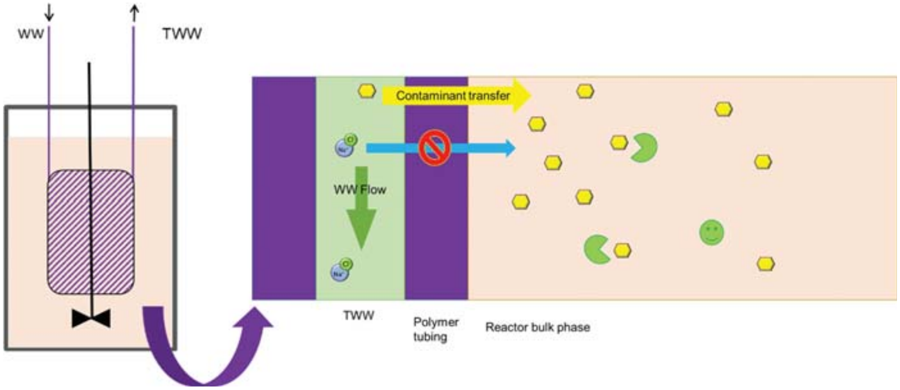

Figure 38.2 Schematic representation and principle of operation of a tubing-TPPB (WW = wastewater; TWW = Treated wastewater).

thermoplastic granular polymers acting as the partitioning phase. These polymeric beads can be tailored to maximize the uptake of specific contaminants to enhance their biodegradation.

38.3.3.1 Tubing TPPBs: Principle of operation

A recent modification to TPPBs has been the development of tubing TPPBs operated as extractive membrane bioreactors (Livingston *et al*., 1998), by substituting the silicon rubber tubing of their original configuration with polymeric tubing. This technology combines the advantages of extractive membrane systems with the best features of conventional TPPBs because the polymeric composition and affinity can be specifically tailored for the organic contaminant to be removed, thus extending the system applicability to a wider spectrum of compounds. By pumping the influent wastewater through the tube-shaped semipermeable polymer, hazardous organic compounds susceptible to biodegradation can be separated from inorganic (or other ionic) compounds that would interfere with biological treatment, while valuable inorganic materials can be recovered from the effluent. The principle of operation is illustrated in Figure 38.2, below, which shows how biodegradable toxic organic pollutants in the untreated industrial wastewater diffuses through the tubing walls to the biomass on the bioreactor side, where biodegradation occurs. In this case phenols, represented as yellow-filled symbols, flow through the tubing walls while the recoverable constituents in ionic form (such as metals and salts) are left behind in the liquid flowing inside the tubing. The tubing TPPB works in a continuous mode, providing complete separation between the wastewater flowing inside the tubing and the bulk solution containing the biomass, thus protecting the cell-containing aqueous phase from the toxic components present in the industrial stream. Since the biological environment is not affected by the toxic characteristics of the wastewater, tubing TPPB systems are able to treat a variety of ‘hostile’ industrial wastewater, including high salinity, extreme pH, as well as certain toxic inorganic and organic contaminants.

38.3.3.2 Tubing-TPPB: Applications

Tubing-TPPB systems have been successfully used to treat wastewater from several industrial sources, including phenolic wastewater (Tomei *et al*., 2016) and fracking fluids (Mullins and Daugulis, 2019). They have also been used for tannery (Mosca Angelucci *et al*., 2017) and hypersaline wastewater (Tomei *et al*., 2017, 2018) where tubing bioreactors successfully recovered materials from organic contaminants that were separated from inorganic components. These results are summarized in

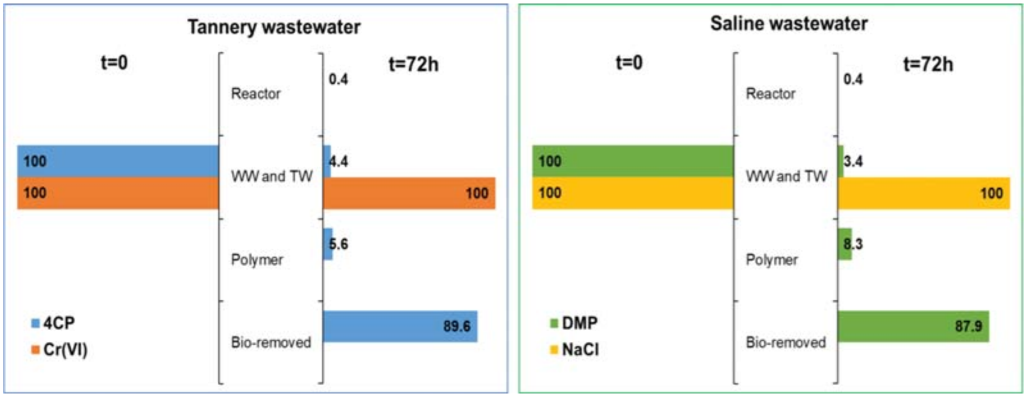

Figure 38.3 Percentage distribution of investigated compounds among phases in the tubing-TPPB.

Figure 38.3, which shows the percentage of 4CP (4-chlorophenol) removed from chromic tannery wastewater, and DMP (2, 4-dimethylphenol) removed from a hypersaline wastewater and the distribution of the contaminants resulting from the mass balance. In both cases, removal efficiencies of target organics were greater than 99%, and biodegradation efficiencies ranged between 88% and 90%. All the CrVI or NaCl was retained either in the wastewater or in the tubing, which absorbed less than 6% and 9% (of the fed amounts) of chrome and salt, respectively for tannery and saline wastewater.

One important advantage of the tubing TPPB process is that inorganics can be recovered without additional pre-treatment. This feature makes tubing-TPPB systems competitive with other resource recovery-aimed technologies as they can be implemented at relatively low cost, simply by adding tubing TPPB modules to existing suspended biomass reactors. A future development will involve the application of anaerobic bacteria to recover energy as well as resources.

The present level of application of TPPBs is at lab-scale and current research is focused on scaling up the technology.

Figure 38.4 Energy and resource recovery concept in industry.

38.4 CONCLUSIONS

To become more sustainable, industrial water management strategies should address the environmental, economic, and social aspects of water use throughout the planning and design process. This is most effectively done by following the 'hierarchy of reuse' illustrated in Figure 38.4 below.

Research activity and scaling testing are needed to achieve the implementation of more sustainable solutions, with the combination of feasibility and economic studies and stakeholder participation in planning and design. A sustainable water management integrated with energy and resource recovery should: (1) consider water and resource supply and demand, (2) enable an efficient recovery of resources by analyzing and maximizing the purity grade, and (3) take account of country regulations.

Review of the available technologies for recovery and reuse in wastewater treatment showed that some of them were extensively investigated and their feasibility demonstrated and this is the case of anaerobic treatment of concentrated streams for energy recovery or technologies for metals and nutrient recovery.

Further work in the development of new technologies like tubing TPPB is required and will be of particular interest to industries in search of pharmaceutical and nutraceutical resources as well as those required to treat toxic or other marginally biodegradable wastewater. By implementing industrial wastewater treatment processes that provide both energy and resource recovery, companies can not only reduce their water demand and recover useful chemicals, they can also more readily meet local and national regulations.

REFERENCES

Ahmad A. and Ghufran R. (2019). Review on industrial wastewater energy sources and carbon emission reduction: towards a clean production. *International Journal of Sustainable Engineering*, **12**(1), 47–57.

Andersen S. J., Hennebel T., Gildemyn S., Coma M., Desloover J., Berton J., Tsukamoto J., Stevens C. and Rabaey K. (2014). Electrolytic membrane extraction enables production of fine chemicals from biorefinery sidestreams. *Environmental Science & Technology*, **48**, 7135–7142.

Ferrer-Polonio E., Carbonell-Alcaina C., Mendoza-Roca J. A., Iborra-Clar A., Alvarez-Blanco S., Bes-Pia A. and Pastor-Alcaniz L. (2017). Brine recovery from hypersaline wastewaters from table olive processing by combination of biological treatment and membrane technologies. *Journal of Cleaner Production*, **142**, 1377–1386.

Hua T., Li S., Li F., Zhou Q. and Ondon B. S. (2019). Microbial electrolysis cell as an emerging versatile technology: a review on its potential application, advance and challenge. *Journal of Chemical Technology & Biotechnology*, **94**, 1697–1711.

Huang L., Yao B., Wu D. and Quan X. (2014). Complete cobalt recovery from lithium cobalt oxide in self-driven microbial fuel cell-microbial electrolysis cell systems. *Journal of Power Sources*, **259**, 54–64.

Jensen P. (2015). Integrated Agri-Industrial Wastewater Treatment and Nutrient Recovery, Year 3. Project Report, 2013/5018. Australian Meat Processor Corporation.

Livingston A. G., Arcangeli J. P., Boam A. T., Zhang S., Marangon M. and Freitas dos Santos L. M. (1998). Extractive membrane bioreactors for detoxification of chemical industry wastes: process development. *Journal of Membrane Science*, **151**, 29–44.

Lu H., Peng M., Zhang G., Li B. and Li Y. (2019). Brewery wastewater treatment and resource recovery through long term continuous-mode operation in pilot photosynthetic bacteria membrane bioreactor. *Science of the Total Environment*, **646**, 196–205.

Massara T. M., Komesli O. T., Sozudigru O., Komesli S. and Katsou E. (2017). A mini review of the techno-environmental sustainability of biological processes for the treatment of high organic content industrial wastewater streams. *Waste and Biomass Valorization*, **8**, 1665–1678.

Mo W. and Zhang Q. (2013). Energy nutrients water nexus: Integrated resource recovery in municipal wastewater treatment plants. *Journal of Environmental Management*, **127**, 255–267.

Mosca Angelucci D., Stazi V., Daugulis A. J. and Tomei M. C. (2017). Treatment of synthetic tannery wastewater in a continuous two-phase partitioning bioreactor: biodegradation of the organic fraction and chromium separation. *Journal of Cleaner Production*, **152**, 321–329.

Mullins N. R. and Daugulis A. J. (2019). The biological treatment of synthetic fracking fluid in an extractive membrane bioreactor: selective transport and biodegradation of hydrophobic and hydrophilic contaminants. *Journal of Hazardous Materials*, **371**, 734–742.

Musa M. A., Idrus S., Man H. C. and Nik Daud N. N. (2018). Wastewater treatment and biogas recovery using anaerobic membrane bioreactors (AnMBRs): strategies and achievements. *Energies*, **11**(7), 1675.

Pandey P., Shinde V. N., Deopurker R. L., Kale S. P., Patil S. A. and Pant D. (2016). Recent advances in the use of different substrates in microbial fuel cells toward wastewater treatment and simultaneous energy recovery. *Applied Energy*, **168**, 706–722.

Pant D., Van Bogaert G., Diels L. and Vanbroekhoven K. (2010). A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production. *Bioresource Technology*, **101**, 1533–1543.

Pham T. H., Aelterman P. and Verstraete W. (2009). Bioanode performance in bioelectrochemical systems: recent improvements and prospects. *Trends Biotechnology*, **27**(3), 168–178.

Santoro C., Arbizzani C., Erable B. and Ieropoulos I. (2017). Microbial fuel cells: from fundamentals to applications. A review. *Journal of Power Sources*, **356**, 225–244.

Tomei M. C., Rita S., Mosca Angelucci D., Annesini M. C. and Daugulis A. J. (2011). Treatment of substituted phenol mixtures in single phase and two-phase solid-liquid partitioning bioreactors. *Journal of Hazardous Materials*, **191**, 190–195.

Tomei M. C., Mosca Angelucci D., Ademollo N. and Daugulis A. J. (2015). Rapid andeffective decontamination of chlorophenol-contaminated soils by sorption ontocommercial polymers and process modelling. *Journal of Environmental Management*, **150**, 81–91.

Tomei M. C., Mosca Angelucci D. and Daugulis A. J. (2016). Towards a continuous two-phase partitioning bioreactor for xenobiotic removal. *Journal of Hazardous Materials*, **317**, 403–415.

Tomei M. C., Mosca Angelucci D., Stazi V. and Daugulis A. J. (2017). On the applicability of a hybrid bioreactor operated with polymeric tubing for the biological treatment of saline wastewater. *Sciences of the Total Environment*, **599–600**, 1056–1063.

Tomei M. C., Stazi V. and Mosca Angelucci D. (2018). Biological treatment of hypersaline wastewater in a continuous two-phase partitioning bioreactor: analysis of the response to step, ramp and impulse loadings and applicability evaluation. *Journal of Cleaner Production*, **191**, 67–77.

Zou S., Qin M., Moreau Y. and He Z. (2017). Nutrient-energy-water recovery from synthetic sidestream centrate using a microbial electrolysis cell – forward osmosis hybrid system. *Journal of Cleaner Production*, **154**, 16–25.