
Volume 150, December 2013
ISSN 0960-8524
ELSEVIER
BIORESOURCE TECHNOLOGY
applied microbiology ▪ bioconversion/biocatalysis ▪ biofuels ▪
biological engineering ▪ biological waste treatment ▪ biomass ▪
bioprocesses ▪ thermo-chemical treatment
Including Special Section:
Special Section on Life-cycle Assessment of Bioproducts
Available online at www.sciencedirect.com
ScienceDirect

Bioresource Technology 150 (2013) 506–512

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Environmental performance of biological nutrient removal processes from a life cycle perspective

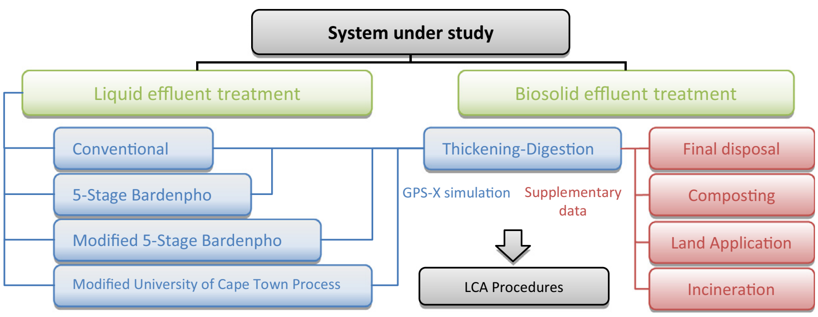
Guillermo A. Ontiveros [a,*], Enrique A. Campanella [a,b]

[a] INTEC, Güemes 3450, Santa Fe 3000, Argentina
[b] FICH – UNL, Ciudad Universitaria, RN N° 168, Km. 472.4, Santa Fe 3000, Argentina

HIGHLIGHTS

- Four wastewater treatment plants were simulated using GPS-X software.
- Each evaluated alternative was composed of liquid and biosolid effluent subsystems.
- Energy usage was the main issue that impacts in Life Cycle Assessment Impact.
- Inclusion of BNRP improves effluent quality.
- The 5-stage Bardenpho produce the most enriched biosolid.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Available online 13 August 2013

Keywords:
Life Cycle Assessment
Biological nutrient removal processes
Wastewater process simulation

ABSTRACT

The goal of the present study is to assess different alternatives for a wastewater treatment plant module with capacity to remove nutrients biologically, taking into account present Argentine regulations for effluent discharge. A computational modeling tool (GPS-X) was employed to simulate the behavior of the different alternatives, and Life Cycle Assessment was applied to quantify the environmental impact. A 2000 m^3/d municipal wastewater flow was used to carry out the simulations, the annual flow was utilized as functional units and the main topics analyzed were energy efficiency, land use, eutrophication reduction and biosolid reuse. Biogas and biosolid generation was evaluated as a good opportunity to generate a cleaner process. This study highlights the fact that nutrient removal processes significantly improve the quality of effluent and biosolids and reduces energy consumption.

1. Introduction

Currently, the number of municipal wastewater treatment plants (MWWTP) designed, constructed and in operation throughout the Argentine territory (Brown et al., 2006) is quite small. This fact calls for a reconsideration of their design so that they work efficiently both from the technical and the environmental point of view, generating different options to allow the reduction of the aforesaid deficit. For this reason, choosing the alternative that achieves discharge specifications in the place where the plant will operate is not enough. The selected alternative has to adapt its performance to reduce certain non-legislated compounds, which produce harmful effects in the environment, such as nutrients made of nitrogen and phosphorus (Smith et al., 1999) or heavy metals or the recently investigated emerging contaminants. This work deals with nutrients only, leaving the other topics to be dealt with in future studies.

A wastewater plant is built to achieve a better quality of treated effluents and is thereby considered a friendly process for the environment. However, since all human activities constitute sources of environmental impact, they should be considered in order to evaluate their performance. Therefore, the overall efficiency of the treatment plant is related to the system under study, the

* Corresponding author. Address: Instituto de Desarrollo Tecnológico para la Industria Química (INTEC), Güemes 3450, Santa Fe S3000GLN, Argentina. Tel.: +54 342 451 1595; fax: +54 342 451 1079.
E-mail address: gontiveros@intec.unl.edu.ar (G.A. Ontiveros).

0960-8524/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2013.08.059

technology involved in each process and the energy consumed during its operation. Additionally, MWWTP might be a generator of different bioproducts (i.e. biogas, biosolids) that creates alternatives to improve plant efficiency; but these products must be handled in a specific way in order to take advantage of their full potential.

A life cycle analysis is a suitable tool used to evaluate environmental aspects of a production system or service through all the stages of its existence. There are several previous LCA studies which examined different wastewater treatment topics such as plant modifications and operations (Wu et al., 2010; Vidal et al., 2002), wastewater treatment modeling (Foley et al., 2010a; Hoiullon et al., 2005; and Wang et al., 2012), and wastewater sludge treatment process (Hospido et al., 2005; Hong et al., 2009; Peters and Rowley, 2009; Cao and Pawlowski, 2013). This work employed a wastewater modeling tool (GPS-X) and specific LCA software (OpenLCA) to design different alternatives of biological nutrient removal plants. Results were compared against the performance of a conventional plant without nutrients removal. Foley et al. (2010a) and Wang et al. (2012) performed comparisons through the use of computer simulations and LCA tools. The difference with the present work lies mainly in two aspects: the place of application of the study, the Argentine territory, where impact categories will require a different perspective, and the use of a different simulator with a different mechanism in its biological model and other effluent characteristics.

2. Methods

According to the guidelines proposed by USEPA (2006), a series of steps should be in order to carry out a LCA. These phases are briefly described in this section to show the required structure and main elements employed in the present work.

2.1. Goal and scope definition

In this first phase of a life cycle evaluation, the following main topics were defined: goals, scope, functional unit, limit of the system, and data quality. A process of critical review was carried out at the end to establish possible modifications or redefinition of the elements mentioned above. According to Tillman et al. (1994), LCA system boundaries were specified in several dimensions: boundaries between the technological system and nature (wastewater plant physical boundaries); delimitations of the geographical area (Argentine location near a plentiful freshwater body) and time horizon considered (one year of operation).

2.1.1. Goal

According to reports published by the World Bank (1995), environmental pollution in Argentina is larger than what might be expected from a country with a medium to high level of development. Lack of proper collection, treatment and discharge of sewage has resulted in a situation of highly environmental vulnerability, particularly on the margins of large urban areas. For this reason, a comparison between different designs of wastewater treatment plants was performed to setup an optimal scale of operation and environmental performance.

2.1.2. Scope

This work did not perform a detailed analysis of each life cycle stage of the evaluated alternatives; instead, the emphasis was put on the operation phase, since it was considered the most relevant phase (Emmerson et al., 2007; Rodriguez García et al., 2011) where there were more differences presented between each of the designs evaluated. In consequence, the assessment was carried out considering the environmental impact associated with the operational phase of the secondary treatment, the final discharge of treated effluents and the sludge treatment with its subsequent final destination.

2.1.3. Assumptions and restrictions

All scenarios were constructed using the simulation package GPS-X v6.0.2 (Hydromantis, 2010). This simulator has different biological models. In our case, a more complete and new model called "Mantis 2" was utilized, which includes all the processes linked to nitrogen and phosphorus removal, with 52 state variables available. Additional information about GPS-X is summarized in the Supplementary material (SM).

Simulations were carried out only at stationary state without considering changes in the flow or modifications by the weather. Each simulation was performed using the same initial effluent of 2000 m^3/d with moderate characteristics, namely Carbon and Biological Oxygen Demand (COD and BOD_5) of 430 g COD/m^3 and 250 g BOD_5/m^3, respectively, Ammonia 25 g N/m^3, Total Kjeldahl Nitrogen (TKN) 40 g N/m^3, Phosphate 8 g P/m^3 and Total Phosphate 10 g P/m^3. Finally, solid concentrations were of 168 g/m^3 for Volatile Suspended Solids (VSS) and 225 g/m^3 for Total Suspended Solids. Similarly, the basic design parameters employed were taken from the literature (Grady et al., 1999; Tchobanoglous et al., 2003). A range of hydraulic retention times (HRT) of 1–2 h, 2–4 h and 4–12 h were employed to design anaerobic, anoxic and aerobic reactors, respectively. In the same order, sludge retention time (SRT) ranges of 1–2 d, 2–4 d and 4–12 d were used to complete the layout. Other parameters considered were the concentration of mixed liquor suspended solids in the reactors (MLSS), 2500–4000 mg MLSS/L, and the sludge recycle ratios in the range from 0.5 to 1.

Emissions of CO_2 gas from biological reactors were neglected because they are considered as biogenic emissions; moreover, this kind of plant design promotes lower and less variable N_2O generation (Foley et al., 2010b). The estimation methodology proposed by IPCC. (1997) was employed to quantify N_2O emissions. Finally, those emissions arising from the combustion of biogas and biomass incineration were quantified through basic equations of mass balance.

2.1.4. Functional unit

The definition of functional unit or operational characteristic is the basis of a LCA because it represents the scale of comparison of two or more products or even the improvement of a given product (USEPA, 2006). It is well known that the main function of a sewage treatment plant is the treatment of an effluent (its main objective is to reduce the organic load, nutrients and suspended solids) in order to achieve suitable values before its release in water bodies. A functional unit based on the annual flow of wastewater treated was used (Table 3) and the population equivalent (p.e.) was calculated to facilitate the comparison between the proposed alternatives and previous work in which it was used (Tillman et al., 1998; Ludin et al., 2002; Gallego et al., 2008; Peters and Rowley, 2009; Karman et al., 2011; Wang et al., 2012). Using the design flow of 2000 m^3/d, a BOD concentration of 250 g BOD/m^3, a per capita load of 0.054 kg/hab d (von Sperling and de Lemos Chernicharo, 2006) and an estimated quantity of 9259 p.e. were calculated.

2.1.5. System under study

The incoming effluent was considered as the starting point of the system analyzed. This system included two lines of treatment, one belonging to the liquid effluent incoming to the treatment plant and another line related to the sludge generated in the removal process. In Fig. 1, the system can be observed in a comprehensive manner together with its two subsystems. The figure

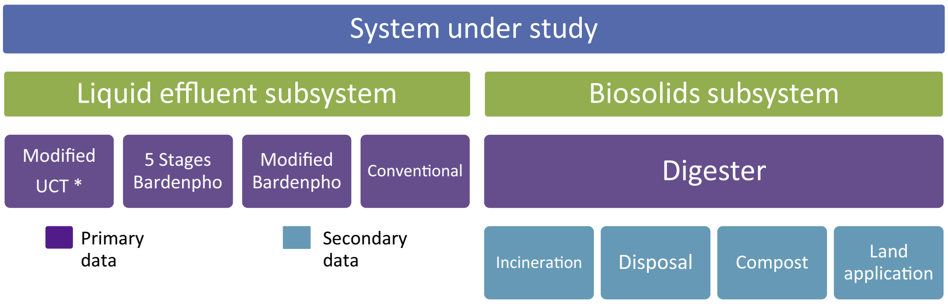


Fig. 1. Complete schema of the studied system divided into two subsystems, liquid and biosolids effluents. Primary data was obtained from software simulation. Secondary data was extracted from literature.*University of Cape Town Process.

shows the difference between data from simulation and data obtained from other sources.

The first subsystem divided into 4 different alternatives (Table 1), where the first option neglected nutrient removal (conventional) and the other three included Biological Nutrient Removal Processes (BNRP), which grew gradually in complexity to reach a higher nutrient removal.

The difference between the alternatives of the second subsystem was given by the final destination that biosolids will receive: incineration and ashes disposal, final disposal in landfill and reuse through composting or land application. The first phase of the second subsystem contemplated the same initial treatment of sludge for all the alternatives (Table 2). Besides the small scale of the analyzed module, the modeling tool allowed us to simulate the second subsystem as a part of a larger sludge treatment plant which would receive material from other modules or small plants. An allocation method was necessary to include only the impacts arising from the evaluated module.

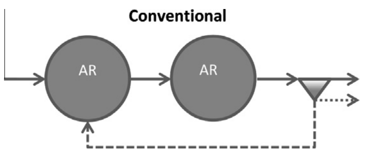
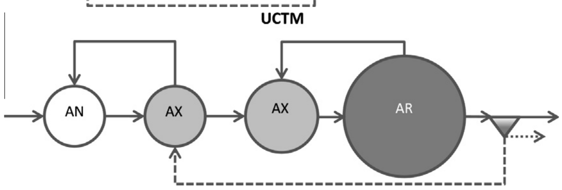
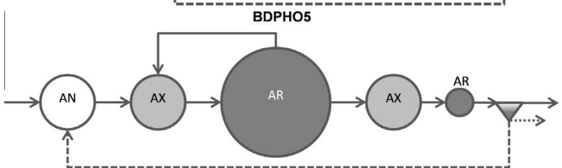
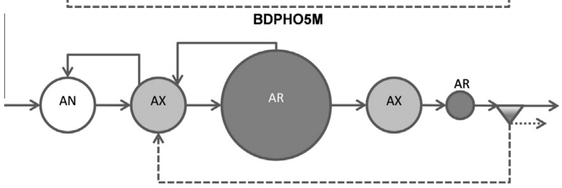
2.1.6. Data quality

The data used for the inventory analysis were divided according to their origin into two types, primary and secondary. Primary data were those obtained through simulations. Each simulated alternative consisted of the first subsystem and the initial treatment of the sludge. Secondary data were taken from prior literature in order to include the effects of sludge final destination. They had to be used because the last stage of the second subsystem could not be simulated with the available software.

2.2. Inventory analysis

Through various simulations (primary data) and supplementary calculations (secondary data) the inventory analysis was developed; main flows corresponding to each alternative were studied (Table 3). For the liquid subsystem, the parameters considered were flow, amount of organic matter (COD), nitrogen in its various forms, phosphorus and energy usage quantification. For this latter

Table 1
Description of each alternative evaluated for the liquid effluent subsystem.

Alternative	Description	Diagram
Conventional treatment	Consisting of two anaerobic reactors placed in series and a clarifier is used to separate the sludge generated	
Modified University of Cape Town process (UCTM)	The schema consists of 4 reactors distributed as follows: an anaerobic reactor followed by two anoxic ones and an aerobic one at the end. The activated sludge is also separated by a clarifier	
Bardenpho of 5 stage (BDPHO5)	Contrasting with the previous schema, this one has 5 reactors placed as follows: anaerobic, anoxic, aerobic, anoxic and aerobic. A secondary decanter is used to separate the sludge of the treated effluent	
Modified Bardenpho of 5 stage (BDPHO5M)	Schematically, it is equal to the former with a slight difference in the internal recycles. It aims to reduce biological competition in the first reactor, avoiding the nitrates recycle and improving the growth of polyphosphate accumulating organisms (PAOs)	

The alphabetic code used represents AR for aerobic reactor, AN for anaerobic reactor, and AX for anoxic reactor.

Table 2
Description and main parameters utilized to design the initial phase of the second subsystem.

Unit	Units	Parameters [a]
Thickener	Gravity thickening is the simplest and most commonly used method for sludge thickening in wastewater treatment plants. Circular concrete tanks are the most common configuration for gravity thickeners	Thickening time 15 h Dry solids loading 25–80 kg/m^2 d
Digester	Anaerobic digestion is one of the oldest and most widely used processes for wastewater sludge stabilization. Due to energy recovery capability, a mesophilic anaerobic digester was chosen	Solids loading rate 1.6–3.2 kg SSV/ m^3 Solids retention time 15–20 d
Dehydrator	The last device included within the simulation was a conventional sand drying bed, which is the oldest and most commonly used type of drying bed used in small plants	Dry Solids Loading 80 kg/m^2 yr

[a] Parameters extracted from the literature (Turovskiy and Mathai, 2006).

Table 3
Main flow parameters obtained in the simulations of the liquid effluent subsystem.[a]

Description	Unit	Influent	Conventional	Modified UCT	5-Stage Bardenpho	Modified 5-Stage Bardenpho
Effluent parameters						
Flow	m^3	730,000	729,453	729,453	729,672	729,635
COD	kg	313,900	25,716	25,581	24,706	24,678
BOD_5	kg	182,238	3,194	4556	3172	3434
Ammonia-N	kg	18,250	100	829	614	943
Nitrite-N	kg	0	26	249	816	1148
Nitrate-N	kg	0	21,650	6587	3206	3432
TKN	kg	29,200	1831	2518	2259	2597
Phosphate-P	kg	5840	5573	1949	3747	3641
Total reactor volumes						
Aerobic	m^3		1000	1100	900	900
Anaerobic	m^3		–	250	250	250
Anoxic	m^3		–	1100	1200	1200
Additional data						
Energy	kWh	–	52,163	46,761	42,613	45,625
Sludge	kg	–	86,140	106,945	95,995	97,455
CO_2	kg		36,003	34,673	32,778	32,840

[a] 1 Year of operation was considered to carry out the analysis and LCA elaboration.

Table 4
Main data[a] utilized to quantify the four alternatives for the solid effluent subsystem.

	Parameter	Unit	Conventional	Modified UCT	5-Stage Bardenpho	Modified 5-Stage Bardenpho
Incineration	Energy	kWh	15,320	19,020	17,073	17,333
	Ash	kg	7274	9031	8106	8230
	Transport	kg diesel	27,931	34,677	31,126	31,600
Final disposal	Energy	kWh	0	0	0	0
	Disposed sludge	kg	86,140	106,945	95,995	97,455
	Transport	kg diesel	330,760	410,647	368,602	374,208
Compost	Energy	kWh	0	0	0	0
	Compost	kg	77,526	96,251	86,396	87,710
	Transport	kg diesel	297,684	369,583	331,741	336,787
Land application	Energy	kWh	0	0	0	0
	Biosolids	kg	86,140	106,945	95,995	97,455
	Transport	kg diesel	330,760	410,647	368,602	374,208

[a] The calculation of each alternative was based on 1 year of operation.

topic, the energy consumption of various devices was included, specifically reactors aeration/mix equipment, pumps that transport effluent and sludge, and part of sludge treatment (thickener and digester). It is important to highlight that the energy source was adapted to the local energy matrix available; the calculation of fuel oil, diesel and natural gas consumptions were based on information provided by the Energy Secretary (2010) and the resulting flows were included into the LCA. For more information about life cycle inventory and percentage breakdown of Argentina's energy fuel types, please see the information included in the SM.

The remaining part of the sludge treatment that could not be simulated was analyzed separately through the use of secondary data. For each of the four alternatives analyzed, different parameters were required, mainly the amount of energy necessary to carry out the treatment, the percentages of sludge/biosolids reduction and fuel consumption for transportation. For the incineration process, an energy consumption of 1.14 KWh/kg sludge was estimated as well as 90% of mass reduction (Turovskiy and Mathai, 2006). The remaining alternatives did not entail energy consumption. A reference distance of 40 km and 0.263 kg diesel/tn as fuel consumption were used to calculate energy consumption for sludge transportation (Suh and Rousseaux, 2001). Table 4 shows the most relevant inputs and outputs of processes which give a final destination to treated sludge in each alternative evaluated.

2.3. Impact analysis

According to Renou et al. (2008) the selection of Impact Analysis influences the results of the wastewater treatment plant LCA.

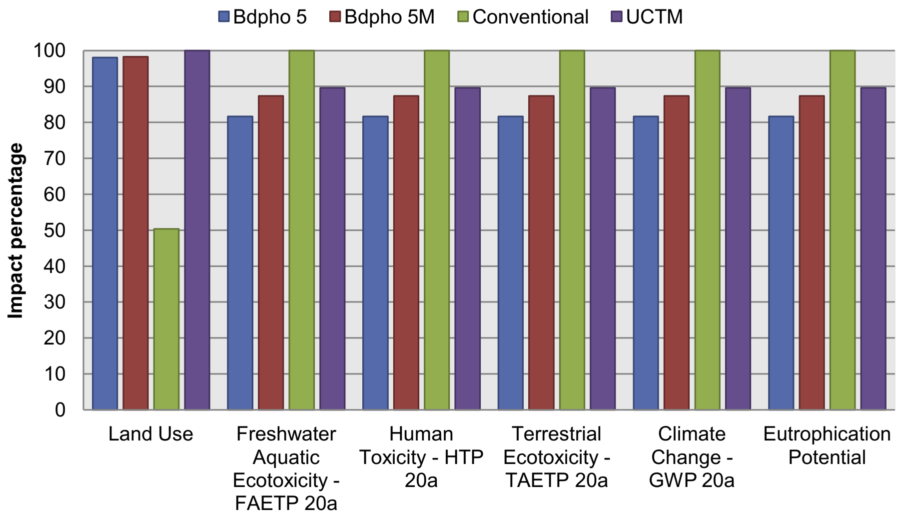


Fig. 2. Comparison made between alternatives of the liquid subsystem: conventional treatment (CONVENTIONAL), Modified University of Cape Town process (UCTM), 5 stages Bardenpho (BDPHO5) and modified 5 stages Bardenpho (BDPHO5M).

The selection of a suitable methodology is crucial to achieve the goals proposed. In the present work, CML 2001 (Guinée et al., 2002) was the method used for impact quantification because of its extensive impact categories and accurate results shown in previous studies (Suh and Rousseaux, 2001; Consonni et al., 2005; Ortiz et al., 2010; Freitas de Alvarenga et al., 2012). The diagrams for each analyzed alternative were built with the OpenLCA software; data produced before in the inventory analysis phase were utilized to obtain impact values and specific indexes were chosen to satisfy a criteria of representativeness of selected environmental issues. For example, the category of global warming was linked to energy consumption, toxicity was linked to hazardous compounds handling, eutrophication was related with nutrient emissions and land used was related to infrastructure demand. Then, the categories used were: land use, freshwater aquatic ecotoxicity potential (FAETP 20a); human toxicity potential (HTP 20a); terrestrial ecotoxicity (TETP 20a), climate change (GWP 20a) and eutrophication potential. Suffix 20a represents potentials for a time horizon of 20 years; the potential is calculated over this specific time interval. The selection of this time horizon responds to the number of years that have been planned, along which the plant will retain the same operating conditions; furthermore, small differences were found for potential impact calculation with different time horizon if heavy metals were neglected in marine environment or soil compartments (Huijbregts et al., 2001).

3. Results and discussion

As might be expected when the scheme grew in complexity the results for nutrient removal were enhanced. In comparison with the conventional alternative, 60% nitrogen and 51% phosphorus removal was produced by the UCTM alternative, 85% and 24%, respectively, by the five-stage Bardenpho option and, finally, 85% and 26%, respectively, by modified five-stage Bardenpho.

Fig. 2 shows a chart that summarizes the comparisons made between the alternatives of the liquid subsystem. The ordinate indicates the impact percentage of each alternative and the abscissa displays each category. It can be observed that OpenLCA gives an impact percentage of 100% to the alternatives that have the highest impact in each category.

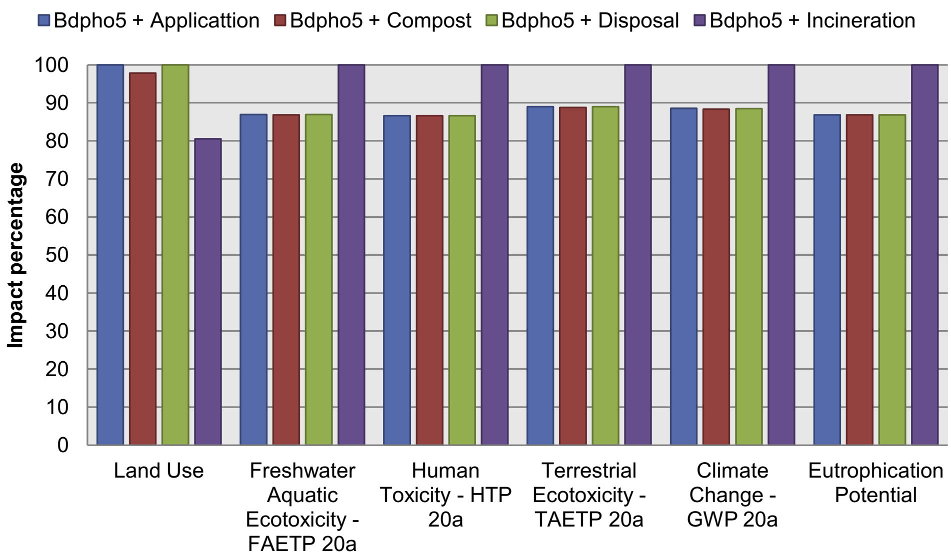


Fig. 3. Comparison made between the alternatives of the biosolids subsystem applied to Bardenpho of 5 stages (BDPHO5).

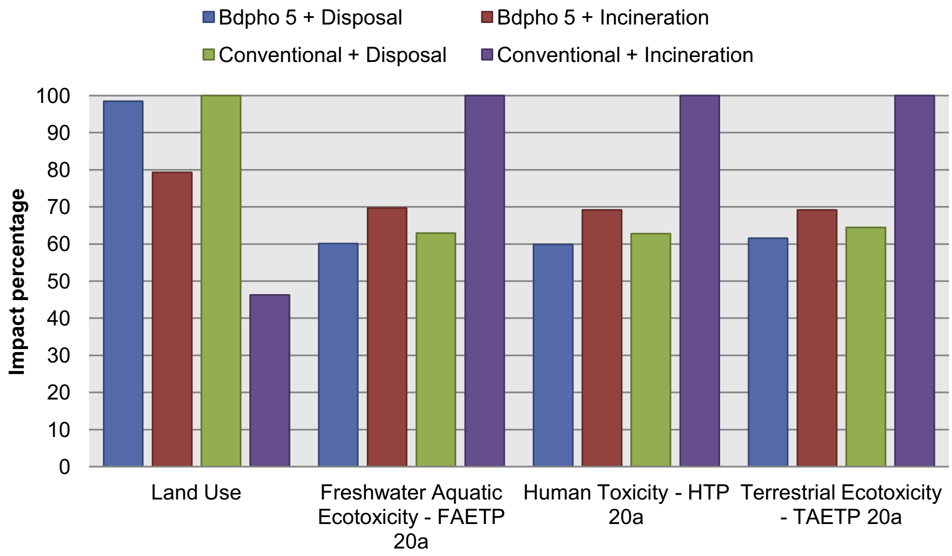


Fig. 4. Comparison made between whole alternatives which have lower and higher land use: 5-stage Bardenpho + sludge disposal (BDPHO5 + Disposal); 5-stage Bardenpho + sludge incineration (BDPHO5 + Incineration); Conventional + sludge disposal (Conventional + Disposal) and Conventional + sludge incineration (Conventional + Incineration).

It can be observed that the Conventional alternative presented the highest impact in all categories except for Land Use, while the remaining alternatives showed an opposite behavior, having lower values in categories of toxicity like global warming and eutrophication but showing almost a double impact in land use in contrast with the first alternative.

The results obtained indicate that energy consumption was greater for the conventional alternative and was mainly due to aeration equipment. On the one hand, the inclusion of anoxic and/or anaerobic processes reduced the consumption of electricity but on the other hand, the overuse of internal recycles acted in a negative way increasing energy needs. Additionally, infrastructure requirement and operational complexity grew with improved nutrient removal due to the presence of internal recycles, and of anaerobic and anoxic reactors.

When the Eutrophication category was considered, the analysis could be divided into two subcategories corresponding to phosphorus and nitrogen releases. It is evident that nutrients removal processes promoted a reduction in both subcategories, and, if the alternative had a lower energy consumption it also helped to reduce the nitrogen oxides (NOx) released into the environment.

Fig. 3 shows the comparison between sludge treatments applied to the most environmentally friendly alternative of the liquid subsystem, 5-stage Bardenpho. Slight differences were found between compost, land application and disposal in categories linked to toxicity, eutrophication and energy consumption. The Land use category indicated a lower impact if the incineration process was involved, but in the remaining categories the impacts were higher due to the energy consumption. The energy required for the incineration process had significant negative effects in all categories, while other processes such as disposal, land application and composting produced minor effects because of their null energy requirement, even if the amount of sludge handled was slightly greater than those managed in the incineration.

The last topic analyzed was the Land Use category. Fig. 4 shows a comparison made between the alternative which made the greatest use of the land (Bardenpho 5 + sludge disposal option) and those that had a lower usage (Conventional + sludge incineration option) and other two options with equivalent characteristics. The comparison revealed that incineration reduced land occupation in about 50% if it was applied to the Conventional option and 80% if the Bardenpho 5 option was chosen. Nevertheless, incineration impacted negatively on the remaining categories, making the disposal alternative a better option.

A more detailed comparison of the environmental impacts can be found in the Life Cycle Impact Assessment (LCIA) section of the SM.

4. Conclusion

The inclusion of BNRP improves significantly effluent quality and reduces energy consumption due to the inclusion of anaerobic and anoxic processes. The 5-stage Bardenpho alternative appears as the environmentally friendliest option. However, its complex operation represents an important challenge to obtain better discharged effluents and enriched biosolids for useful land application or composting. Final disposal, with leachate and gas control, is the alternative that would generate the smallest impact on the environment. Finally, some issues such as heavy metals sorption and emerging pollutants fate should be included in future work in order to reject possible negative effects of biosolids reuse.

Acknowledgements

The authors are grateful to Universidad Nacional del Litoral (UNL), and the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) for their financial support. Special thanks are given to Elsa Grimaldi for the English language editing.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2013.08.059.

References

Brown, A. et al., 2006. La situación ambiental argentina en 2005, first ed. Fundación Vida Silvestre Argentina, Buenos Aires.

Cao, Y., Pawlowski, A., 2013. Life cycle assessment of two emerging sewage sludge-to-energy systems: evaluating energy and greenhouse gas emissions implications. Bioresour. Technol. 127, 81–91.

Consonni, S., Giugliano, M., Grosso, M., 2005. Alternative strategies for energy recovery from municipal solid waste: Part B: emission and cost estimates. Waste Manage. (Oxford) 25 (2), 137–148.

Energy Secretary, 2010. Información del Mercado, Secretaría de Energía de la Nación. <http://energia3.mecon.gov.ar/contenidos/archivos/Reorganizacion/informacion_del_mercado/publicaciones/mercado_electrico/estadisticosector-electrico/2010/parte1y2/genpotcombpanuario10.zip>.

Emmerson, R.H., Morse, G.K., Lester, J.N., Edge, D.R., 2007. The life-cycle analysis of small-scale sewage treatment processes. Water Environ. J. 9, 317–325.

Foley, J., de Haas, D., Hartley, K., Lant, P., 2010a. Comprehensive life cycle inventories of alternative wastewater treatment systems. Water Res. 44, 1654–1666.

Foley, J., de Haas, D., Yuan, Z.G., Lant, P., 2010b. Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. Water Res. 44, 831–844.

Freitas de Alvarenga, R.A., da Silva Jr., V.P., Soares, S.R., 2012. Comparison of the ecological footprint and a life cycle impact assessment method for a case study on Brazilian broiler feed production. J. Clean. Prod. 28, 25–32.

Gallego, A., Hospido, A., Moreira, M.T., Feijoo, G., 2008. Environmental performance of wastewater treatment plants for small populations. Resour. Conserv. Recy. 52, 931–940.

Grady Jr., L., Daigger, G., Lim, H., 1999. Biological Wastewater Treatment, second ed. CRC Press, London.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A., De Oers, L., Sleeswijk, A., Suh, S., Udo de Haes, H.A., Bruijn, H., Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to ISO Standards. Kluwer Academic Publishers, Leiden.

Hong, J., Hong, J., Otaki, M., Jolliet, O., 2009. Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. Waste Manage. (Oxford) 29, 696–703.

Hospido, A., Moreira, T., Martín, M., Rigola, M., Feijoo, G., 2005. Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: anaerobic digestion versus thermal processes. Int. J. Life Cycle Ass. 10, 336–345.

Houillon, G., Jolliet, O., 2005. Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis. J. Clean. Prod. 13, 287–299.

Huijbregts, M.A., Guinée, J.B., Reijnders, L., 2001. Priority assessment of toxic substances in life cycle assessment. III: Export of potential impact over time and space. Chemosphere 44 (1), 59–65.

Hydromantis, 2010. GPS-X Technical Reference Manual. Hamilton, Ontario, Canada.

Intergovernmental Panel on Climate Change (IPCC), Houghton, J.T., Meira Filho, L.G., Lim, B., Tréanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J., Callander, B.A., 1997. Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories. IPCC, Paris.

Karrman, E., Jonsson, H., 2011. Including oxidization of ammonia in the eutrophication impact category. Int. J. Life Cycle Ass. 6, 29–33.

Lundin, M., Morrison, G., 2002. A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems. Urban Water J. 4, 145–152.

Ortiz, O., Pasqualino, J.C., Castells, F., 2010. Environmental performance of construction waste: comparing three scenarios from a case study in catalonia. Spain. Waste Manage. 30, 646–654.

Peters, G.M., Rowley, H.V., 2009. Environmental comparison of biosolids management systems using life cycle assessment. Environ. Sci. Technol. 43, 2674–2679.

Renou, S., Thomas, J.S., Aoustin, E., Pons, M.N., 2008. Influence of impact assessment methods in wastewater treatment LCA. J. Clean. Prod. 16, 1098–1105.

Rodriguez-Garcia, G., Molinos-Senante, M., Hospido, A., Hernández-Sancho, F., Moreira, M.T., Feijoo, G., 2011. Environmental and economic profile of six typologies of wastewater treatment plant. Water Res. 45, 5997–6010.

Smith, V.H., Tilman, G.D., Nekola, J.C., 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environ. Pollut. 100, 179–196.

Suh, J.H., Rousseaux, P., 2001. An LCA of alternative wastewater sludge treatment scenarios. Resour. Conserv. Recy. 35, 191–200.

Tchobanoglous, G., Burton, F.L., Stensel, H.D., 2003. Wastewater Engineering, fourth ed. McGraw-Hill, New York.

Tillman, A.M., Ekvall, T., Baumanna, H., Rydberg, T., 1994. Choice of system boundaries in life cycle assessment. J. Clean. Prod. 2, 21–29.

Tillman, A.M., Svingby, M., Lundström, H., 1998. Life cycle assessment of municipal waste water systems. Int. J. Life Cycle Ass. 3, 145–157.

Turovskiy, I.S., Mathai, P.K., 2006. Wastewater Sludge Processing. John Wiley & Sons Ltd., New Jersey.

US Environmental Protection Agency (USEPA), 2006. Life Cycle Assessment: Principles and Practice. National Risk Management Research Laboratory, Cincinnati, Ohio.

Vidal, N., Poch, M., Martí, E., Rodríguez-Roda, I., 2002. Evaluation of the environmental implications to include structural changes in a wastewater treatment plant. J. Chem. Technol. Biotechnol. 77, 1206–1211.

Von Sperling, M., de Lemos Chernicharo, C.A., 2006. Biological Wastewater Treatment in Warm Climate Regions. IWA Publishing, London, UK.

Wang, X., Liu, J., Ren, N.Q., Duan, Z., 2012. Environmental profile of typical anaerobic/anoxic/oxic wastewater treatment systems meeting increasingly stringent treatment standards from a life cycle perspective. Bioresour. Technol. 126, 31–40.

World Bank, 1995. Latin America and the Caribbean, Country Dept. I. Environment and Urban Development Division. Managing environmental pollution: Issues and options, vol. 1 of 2, World Bank, Washington.

Wu, J.G., Meng, X.Y., Liu, X.M., Liu, X.W., Zheng, Z.X., Xu, D.Q., Sheng, G.P., Yu, H.Q., 2010. Life cycle assessment of a wastewater treatment plant focused on material and energy flows. Environ. Manage. 46, 610–617.