Articles

Eco-efficiency assessment of domestic wastewater treatment technologies used in Chile

Evaluación de eco-eficiencia de tecnologías de tratamiento de aguas residuales domésticas en Chile

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Abstract

Wastewater treatment plants have been the widest technologies used to mitigate the environmental impacts of domestic wastewater. Currently, Chile has the largest coverage of wastewater sanitation (99.85%) of Latin American, through the use of conventional technologies, mainly active sludge and aerated lagoons and also unconventional technologies such as biofilter, vermi-biofilter, among others. Although all technologies allow fulfilling with discharge standards, there are differences in the flows of matter and energy associated with the kind of technology used, which implies the generation of different environmental impacts. The objective of this research was to evaluate the eco-efficiency of different domestic wastewater treatment technologies used in Chile, based on the requirements of ISO 14045 (2012). For this purpose, 1 kg of removed BOD_5 was used as a functional unit and a value function associated with the volume of treated water (m^3). Fifteen plants of wastewater treatment in Chile were analyzed, using the life cycle assessment methodology to quantify environmental impacts. The main environmental aspect of domestic wastewater treatment for most of the impact categories studied was electricity consumption. The vermi-biofilter was the most eco-efficient technology for climate change and freshwater eutrophication categories. This result reflecting that

unconventional emerging technologies are more eco-efficient than conventional ones.

Keywords: Eco-efficiency, plant of treatment, wastewater domestic, life cycle assessment.

Resumen

Las plantas de tratamiento de aguas residuales han sido el medio más utilizado para mitigar los impactos ambientales de las aguas residuales domésticas. En la actualidad, Chile cuenta con la mayor cobertura de saneamiento de aguas residuales (99.85%) en Latinoamérica, mediante la utilización de tecnologías convencionales, sobre todo lodos activos y lagunas aireadas, y no convencionales como biofiltro, vermi-biofiltro, entre otros. Si bien todas las tecnologías permiten cumplir con las normas de descarga, existen diferencias en los flujos de materia y energía asociados con el tipo de tecnología utilizada, lo que implica la generación de distintos impactos ambientales. El objetivo de esta investigación fue evaluar la eco-eficiencia de diferentes tecnologías de tratamiento de aguas residuales domésticas utilizadas en Chile, con base en los requisitos de la norma ISO 14045 (2012). Para ello se utilizó como unidad funcional 1 kg de DBO$_5$ removida y una función de valor asociada con el volumen de agua tratada (m^3). Se analizaron 15 plantas de tratamiento de aguas residuales en Chile, utilizando la metodología de análisis de ciclo de vida para cuantificar los impactos ambientales. Se determinó que el consumo eléctrico es el principal aspecto ambiental del

tratamiento de aguas residuales domésticas para la mayoría de las categorías de impacto estudiadas. En términos de cambio climático y eutrofización de agua dulce, la tecnología más eco-eficiente fue el vermi-biofiltro, lo cual refleja que las tecnologías emergentes no convencionales son más eco-eficientes que las convencionales.

Palabras clave: Eco-eficiencia, planta de tratamiento, aguas residuales domésticas, análisis de ciclo de vida.

Introduction

The water resource is not only an essential asset for the development of life and the conservation of the environment but also is a unique and strategic natural means for the growth of different productive sectors. For this reason, countries have included within their policies, strategies that ensure access to this vital element in a pollution-free environment,

promoting economic development and the sustainability of the activities that demand this resource.

In Chile, between the different productive sectors, sanitation companies occupy fourth place (6%) of the country's consumptive water rights. The water is used for the production of drinking water, which after it has been used, is collected and treated (Ministerio de Obras Públicas, 2013), about 80% of drinking water produced is converted into domestic wastewater (DS N° 90/00). The treatment of this kind of water is of vital importance to comply with the regulations imposed by governments, to prevents contamination of water bodies.

The coverage of domestic wastewater treatment in Chile is 99.97% in urban areas (zone with sewerage). As a consequence, Chile is the country with the highest sanitation coverage in Latin America, being the active sludge systems the most used wastewater treatment technology (60%). Followed by aerated lagoons and unconventional technologies, such as, biofilters and vermi-biofilters with 19% and 4.3%, respectively (SISS, 2017). Although active sludge technology has been the most widely adopted in the world for the treatment of domestic wastewater (Marti & Batista, 2014), it has a high-energy demand. It is estimated that between 45-75% of the total operating costs are due both of them to the aeration stage for the degradation of organic matter and the consumption of electric energy, varying between 0.3-0.6 kWh per m^3 (1 000 l) of treated water (Roohian & Mehranbod, 2017). Therefore, energy costs can be a limitation for the implementation of active sludge systems especially in developing countries (Muga &

Mihelcic, 2008) or small communities (equivalent population < 2 000 people) (Corominas *et al*., 2013).

Therefore, unconventional technologies have been proposed for the treatment of wastewater, with lower energy requirements and supplies, such as wetlands, biological filters and vermi-biofiltration, among others (Corominas *et al*., 2013; Li, Xing, & Lu, 2013; Tomar & Suthar, 2011; Jiang *et al*., 2016; Lourenço & Nunes, 2017; Samal, Dash, & Bhunia, 2017).

Efficiency in the removal of contaminants present in wastewater varies according to the type of treatment used (Jiang *et al*., 2016), both conventional and unconventional technologies are designed to comply with emission regulations for dumping in receiving bodies of water. The supplies and electrical energy of the wastewater treatment plants can vary significantly depending on the type of treatment used, as well as, varies the environmental aspects associated with their operation (Lorenzo-Toja *et al*., 2016a) giving different kinds of environmental impacts (Corominas *et al*., 2013).

The life cycle assessment (LCA) methodology, internationally standardized by ISO 14040 (2006) and ISO 14044 (2006) has been widely used to quantify the environmental impacts of different domestic wastewater treatment systems ((Emmerson, Morse, Lester, & Edge, 1995; Hospido, Moreira, Fernández-Couto, & Feijoo, 2004; Pasqualino, Meneses, Abella, & Castells, 2009; Rodriguez-Garcia *et al*., 2011). An example of this is evidenced by Kalbar, Karmakar y Asolekar (2012), where a life cycle assessment of different wastewater treatment technologies was performed, obtaining carbon footprint indicators of

31.97 kg CO_2 $_{eq}$ hab^{-1} $year^{-1}$ and 18.20 kg CO_2 $_{eq}$ hab^{-1} $year^{-1}$ for the use of sequential batch reactors (SBR) and active sludge, respectively. Negative indicators were reported in the case of treatment of domestic sewage using wetlands, estimating a carbon footprint of 3.86 kg of CO_2 $_{eq}$ hab^{-1} $year^{-1}$ and variations between 1.38-5.85 kg PO_4^{-3} $_{eq}$ hab^{-1} $year^{-1}$ for the category of freshwater eutrophication. In Chile, the LCA has had a growing development in the evaluation of impacts on waste (Muñoz, Vargas, & Navia, 2015), agriculture (Herrera, Muñoz, & Montalba, 2012) and construction (Cárdenas, Muñoz, Riquelme, & Hidalgo, 2015). However, LCA works in the sanitation sector have been not reported yet.

At the date, the selection of wastewater treatment technologies has considered only aspect related to investment and operating costs (such as, wastewater properties, flow), not taking into account the environmental impacts derived from its operations. Currently, eco-efficiency is recognized as an instrument that seeks to promote fundamental changes in the way in which resources are produced and consumed, is a tool that allows measured progress towards sustainability (ESCAP, 2010).

The eco-efficiency concept was defined for the first time by the World Business Council for Sustainable Development with the aims of producing goods and services using less natural resources and generating lower levels of pollution (Schmidheiny & Businness Council for Sustainable Development, 1992), offering environmental competitiveness from an economic perspective. The eco-efficiency concept was standardized by ISO 14045 (2012) which defined it as a quantitative management tool allowing for the study of the

environmental impacts of a product or service throughout its life cycle, giving a value in parallel. Therefore, eco-efficiency has three goals: a) increase the value of the service or goods; b) optimize the use of resources, and c) reduce the environmental impact (Robaina-Alves, Moutinho, & Macedo, 2015).

ISO 14045 (2012) leaves a wide range of methodological assumptions for the selection of the value (Lorenzo-Toja, Vázquez-Rowe & José, 2016b). The value can vary according to the interested parties and can be expressed for example, as functional value, in terms of quality, monetary, or others less tangible (Ribarova & Stanchev, 2016), where the different criteria adopted can lead to different results according to the unit of value chose. Within the framework of this concept, Lorenzo-Toja *et al*. (2014), carried out an eco-efficiency assessment of 133 domestic wastewater treatment plants in Spain, with different sizes concerning the amount of water being treated, showing that larger plants tend to be more eco-efficient. Also, Lorenzo-Toja *et al*. (2016b) compared the eco-efficiency of 22 treatment plants by ISO 14045 (2012), using a monetary cost value function to treat 1 m^3 through life cycle cost analysis (LCCA) of the stage operation in the wastewater treatment plant. The aim of this work was creating a classification scheme as an eco-efficiency eco-label proposal for each plant depending on its performance, which depended on various factors, such as, plant configuration, size or even government regulations.

From a value point of view, the functionality of a product or process commonly tends to be measured in terms of its monetary value,

which automatically induces professionals to combine LCA with LCCA. However, some services are regulated by tariffs, as is the case of sanitation companies in Chile, generating a disincentive to be more eco-efficient in monetary terms and having to resort to another type of value, such as treated a volume of wastewater. In this context, the present work seeks to show that non-conventional domestic wastewater treatment technologies are more eco-efficient compared to conventional technologies used in Chile. To promote domestic wastewater treatments with less intensity in the use of natural resources, which in addition to complying with the treatment of domestic wastewater must be within current regulations, resulting in a decrease in environmental impacts for these systems.

Materials and methods

Definition of goal and scope of the study

The aim of this study was to evaluate the eco-efficiency of different domestic wastewater treatment technologies used in Chile based on the international standard ISO 14045 (2012). For that purpose, four wastewater technologies grouped in conventional treatments (active sludge systems and aerated lagoons) and unconventional treatments (biofilters and vermi-biofilters) were studied.

The quantification of environmental impacts for different wastewater treatment technologies was carried out using the life cycle assessment methodology, established in ISO 14040 (2006) and ISO 14044 (2006). The main function of domestic wastewater treatment plants was considered to be the decrease in organic matter expressed as biological oxygen demand (BOD_5) where a functional unit of 1 kg of BOD_5 removed was selected.

The total number of domestic wastewater treatment plants (DWWTPs) studied was 15 (Table 1), with different sizes of the installation concerning the treated flow or population served and technologies used in sludge stabilization. Of the total of plants, 8 correspond to active sludge with prolonged aeration, of which, 4 perform sludge stabilization by anaerobic digestion with biogas generation (used to heat the sludge), 2 DWWTPs by lime and 2 DWWPTs only with landfill sanitary disposal.

Table 1. Domestic wastewater treatment plants in study.

Region	Technology	N°	Treated flow (m³/month)	Estimated population (hab)*
Araucanía Region	Aerated lagoons	DWWTP 1	37337.0	10989
Bio Bio Region		DWWTP 2	21453.1	6314
Coquimbo Region		DWWTP 3	383197.6	112784
Valparaíso Region		DWWTP 4	9214.4	2712
Araucanía Region		DWWTP 5	256029.8	75356
Coquimbo Region	Active sludge	DWWTP 6	3696.8	1088
Aysén Region		DWWTP 7	2116.1	622
Metropolitana Region		DWWTP 8	7467.8	2198
Los Ríos Region		DWWTP 9	10682.3	3144
Valparaíso		DWWTP	331208.8	97483

Region		10		
Los Lagos Region		DWWTP 11	861714.5	253624
Metropolitana Region		DWWTP 12	23745708.8	6988965
Metropolitana Region		DWWTP 13	16462744.0	4845403
Metropolitana Region	Biofilter	DWWTP 14	1113972.2	327870
Coquimbo Region	Vermi-biofilter	DWWTP 15	2251.9	662

*Estimated population based on a water endowment of 137 L/hab/d with 80% recovery (SISS, 2017).

In the case of aerated lagoon technology, 5 DWWTPs were studied. Of these, only one performs stabilization of its sludge, through the anaerobic digestion process with biogas collection.

For the treatment of domestic wastewater through unconventional systems, a biofilter plant and a vermi-biofilter plant were evaluated. The biofilter technology consisted mainly of a fixed bed with polyvinylchloride material, on which the microorganisms adhere forming a film. In this case, sludge stabilization is performed by anaerobic digestion with biogas generation and heat production in the boiler.

Finally, the vermi-biofilter plant performs the degradation of organic matter through the use of Californian red worms (*Eisenia Foetida*), generating humus, which is arranged in green areas of the sanitary installation.

The system boundaries of each technology studied are presented in Figure 1, where the scope considered was from the reception of the wastewater in a DWWTPs, to the discharge into a receiving water body.
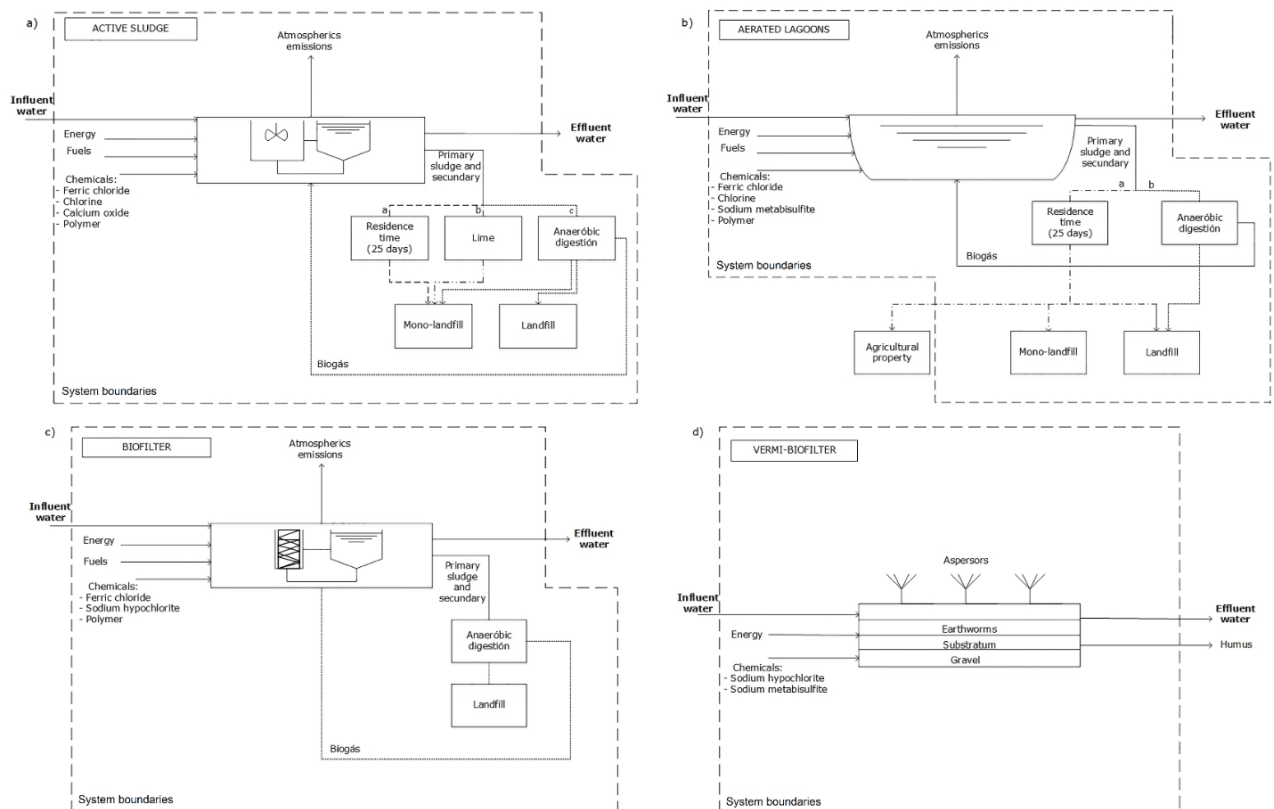
Figure 1. Diagram of water treatment processes for each type of technology studied: a) Active sludge; b) Aerated lagoons; c) Biofilter, and d) Vermi-biofilter.

Life cycle inventory

For the construction of the life cycle inventory, Superintendency of Sanitary Services (SISS), a public service institution in charge of the control and fiscalization of the DWWTPs, provided the data. The data provided by the SISS were the operation parameters (flows, chemicals, electrical energy, and sludge production) and self-control parameters (BOD_5, phosphorus, Kjeldahl total nitrogen, total suspended solids, and residual chlorine). The data used corresponds to the year 2015.

For electricity energy, 14 plants were modeled considering the energy matrix of the Central Interconnected System (CIS) of 2016, which was constituted by 32% coal, 20.6% hydroelectric bypass, 14.9% by reservoir, 19.4% natural gas, 5% biomass, 3.6% wind, 1.5% oil and 3% solar. In the case of the Aysén treatment plant (DWWTP 7), the electrical energy from the Aysén matrix was considered, consisting of 37.9% of hydroelectric power, 57.6% diesel, and 4.5% wind for the

same year. The construction of the electricity matrices was modeled in the SimaPro software using international databases (Ecoinvent).

Ecoinvent database was modified for the landfill to bring this type of solid waste disposal closer to the reality of Chile. It was considered that the effluents and sludges generated from the leachate treatment plant belonging to the sanitary landfill are recycled in their totality in the same landfill. For the biogas generation of the landfill, it was calculated using the values used in the study by Suh and Rousseaux (2002), with a gas collection efficiency of 30%. Finally, the methane generated from torch burning was quantified using the IPCC model (2006)

Impact assessment

The SimaPro Software version 8.0.4.30 was used to quantify the environmental impacts. The evaluation method used was ReCiPe MidPoint (H), and the impact categories selected were: climate change (kg CO_2 $_{eq}$), human toxicity (kg 1.4-DB $_{eq}$), freshwater ecotoxicity (kg 1.4- DB $_{eq}$) and eutrophication of freshwater (kg P $_{eq}$).

Definition of eco-efficiency

The value function selected was the volume of wastewater treated (m^3) by each treatment technology, thus representing another important function of a wastewater plant. As previously mentioned, it was not considered a monetary value as a unit of value because in Chile the tariff regulation for concessionaires in charge of wastewater treatment (according to D.F.L. No. 70/88 which regulates the calculation rates) establish a marginal income plus a royalty of 3-3.5% per risk, evidencing a disincentive for the investments to the Sanitary sector to obtain lower environmental impacts.

The eco-efficiency indicator was obtained by the relationship established in ISO 14045 (2012) as observed in Eq. 1. For the eco-efficiency indicator, the categories corresponding to climate change (kg CO_{2eq}) and freshwater eutrophication (kg P_{eq}) were selected. These indicators were mainly selected due to the great interest of the scientific environment to study LCA and eco-efficiency works (Lorenzo-Toja *et al*., 2016b; Lorenzo-Toja *et al*., 2014; Lundin & Morrison, 2016):

$$eco - efficiency\ indicator = \frac{value\ function}{environmental\ impact} \qquad (1)$$

Sensitivity analysis

A sensitivity analysis was performed in a DWWTP with vermi-biofilter technology used as an example of a wastewater plant. To study the effect of the composition of the energetic matrix in the variation of environmental impacts and their eco-efficiency because electric energy is considered as an environmental hotspot associated with climate change. The projection consisted of a 60% increase in non-conventional renewable energy (NCRE) by 2035, and 70% by 2050, based on the international commitment to reduce greenhouse gas emissions, to reduce the percentage of coal-based power generation sources that are the main contributor to climate change.

The sources of electrical energy that projected the increase in NCRE were wind and solar energy (mainly due to the increase in projects of this nature in Chile, inequitable percentage, while the source of energy generation from coal has diminished) (Ministerio de Obras Públicas, 2013).

Results and discussions

Life cycle inventory

The results of the life cycle inventory for the removal of 1 kg of BOD_5 by the different technologies are shown in Table 2, evidence that the treatment plants that used aerated lagoons have the highest electrical energy consumption with a range 1.1-5 kWh/kg BOD_5, followed by active sludge. These results agree with the study by Muga and Mihelcic (2008), which indicates that aeration in the stabilization ponds can exceed the electrical consumption of the active sludge for certain sizes. The aerated lagoon technology also presented the highest consumption of sodium hypochlorite for the disinfection stage, beside ferric chloride and petroleum inputs.

Table 2. Life cycle inventory to remove 1 kg de BOD_5.

Tecnology	N°	Electric power (kWh)	Fuels (kg)	Sodium hypochlorite (kg)	chlorine (kg)	Ferric Chloride (kg)	Polymer (kg)
	DWWTP 1	2.3	0.01	0.3	0.1	-	-
	DWWTP 2	2.7	0.004	-	0.04	1.1	0.01
Aerated lagoons	DWWTP 3	2.1	0.003	-	0.1	-	-
	DWWTP 4	5.0	0.002	0.9	-	-	-
	DWWTP 5	1.1	0.0001	0.8	-	-	-
	µ	2.6	0.004	0.7	0.08	1.1	0.01
	DWWTP 6	2.1	0.02	0.01	-	-	-
	DWWTP 7	1.3	-	0.08	-	-	-
	DWWTP 8	5.5	0.01	0.7	-	-	0.02
	DWWTP 9	3.5	0.03	0.05	-	-	0.002
Active sludges	DWWTP 10	3.0	0.04	-	0.04	0.04	0.01
	DWWTP 11	1.4	0.004	-	-	-	0.01
	DWWTP 12	1.1	0.0001	-	0.02	0.1	0.01
	DWWTP 13	1.5	0.001	-	0.03	0.02	0.01
	µ	2.3	0.02	0.2	0.03	0.1	0.01
Biofilter	DWWTP 14	1.2	0	0.001	0.03	0.03	-

Vermi-biofilter	DWWTP 15	1.7	-	0.1	-	-	-

For the disinfection stage, sodium hypochlorite was the most widely used chemical in terms of mass for treatment in the different technologies studied, while polymer consumption was similar for aerated lagoons and active sludge.

Life cycle assessment

The results of the life cycle assessment revealed that the aerated lagoons have the greatest environmental impacts for all impact categories studied on the removal of 1 kg BOD_5, as shown in Figure 2, in agreement with the largest energy consumption (2.6 kWh/kg BOD_5 on average) and chemical supplies for the disinfection stage and the use of ferric chloride (Table 2). Also, the same Figure 2 shows that biofilter technology has lower environmental impacts in all impact categories evaluated.
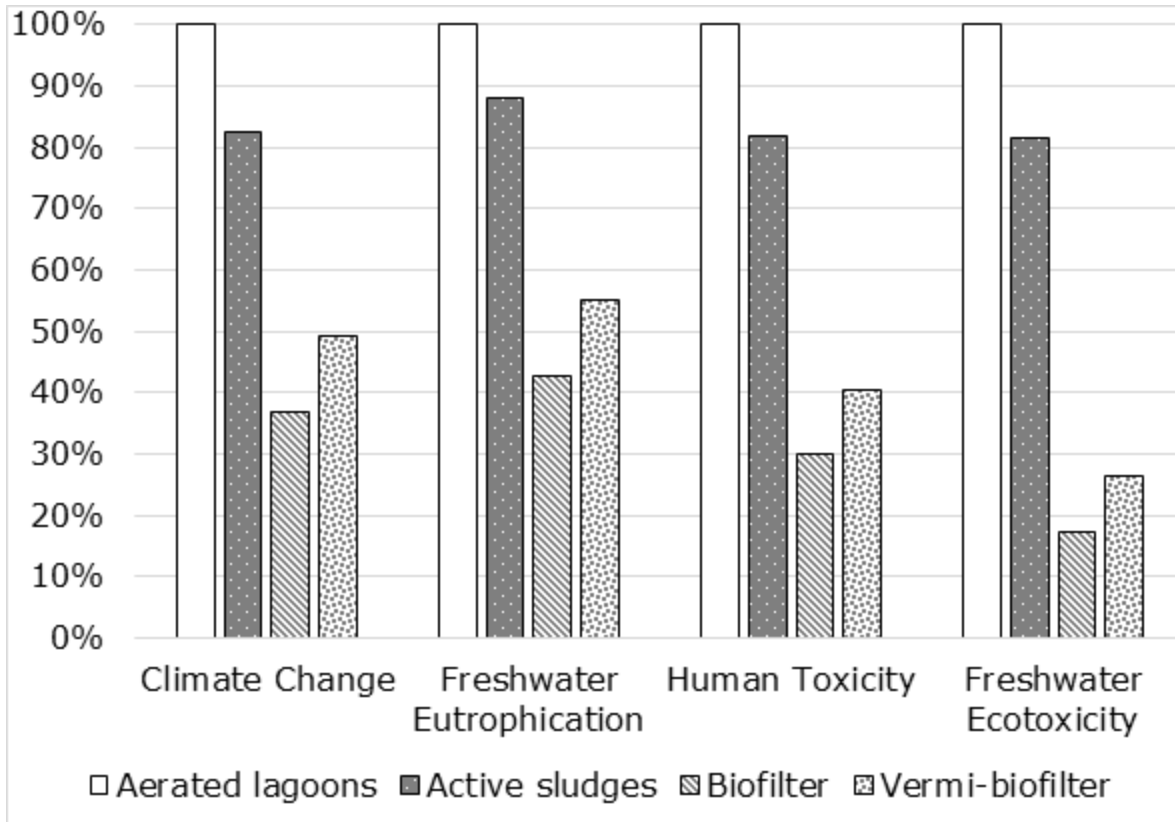
Figure 2. Comparison of average environmental impacts by the kind of technology used for the removal of 1 kg BOD_5.

Climate change

The climate change category is one of the best known and commonly used as an environmental impact indicator, although the discharge of effluent into the environment does not have an important effect on this category. The energy intensity in the treatment process makes it important to include it for evaluation (Lorenzo-Toja *et al*., 2016b). In this context, electric power proved to be the main contributor in all technologies evaluated as shown in Figure 3.
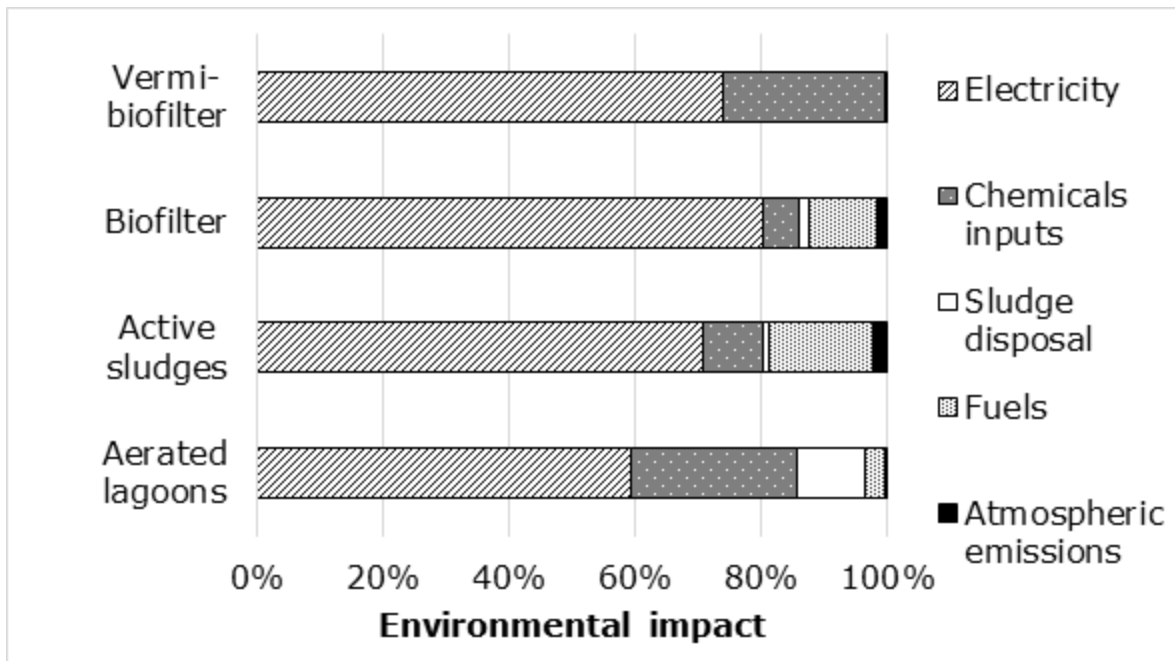
Figure 3. Contribution of the kind of technology for the removal of 1 kg BOD$_5$ for the climate change category

Ranges between 1.24-3.49 kg CO_{2eq} /kg BOD_5 were obtained for aerated lagoon plants, with an average of 2.38 kg CO_{2eq} /kg BOD_5, where the consumption of electric energy contributed 59% of the impacts. A 27% of the contribution to the environments impacts were due to the use of chemicals inputs, where the disinfection stage had the higher contribution (15.4%) due to the use of sodium hypochlorite (15%) and chlorine gas (0.4%), followed by inputs chemicals such as ferric chloride (9.8%), sodium metabisulfite (1.1%) and polymer (0.7%). Finally, the disposal of sludge contributed 11% of the impacts, mainly due to methane emissions in the landfill and monorefilled landfill disposal.

It was found that DWWTP 2 and 4 obtained the worst performances in energy terms (2.7 and 5 kWh / kg of BOD_5 respectively), with both having in common the lack of use of supplies and electrical energy for sludge stabilization, so the energy demand is attributed exclusively to the treatment of the waterline showing energy inefficiencies in its process, compared to the other aerated lagoon plants, such as DWWTP 5, which has a consumption of 1.1 kWh/kg of BOD_5 without sludge purge.

Ranges of 0.67-3.98 kg CO_{2eq} / kg BOD_5 with an average of 1.96 kg $CO_{2\ eq}$/kg BOD_5 were found by active sludge technology. Being the electricity the main contributor with consumptions that vary from 0.8 - 5.5 kWh / kg BOD_5 and thus causing 71% of the impacts. Followed by diesel fuel used in the generation of electrical energy, and the use of chemical inputs, with a contribution of 16% and 10%, respectively. In

the case of the use of inputs products, the disinfection stage contributed 6%, where the sodium hypochlorite was responsible for 99% of these impacts, having an average consumption of 0.2 kg/kg BOD_5. The atmospheric emissions related to the burning of diesel fuel and biogas generated in anaerobic digestion plants contributed only 2.3%, proving to be negligible compared to the other contributions.

The plants with the most impact on removing 1 kg BOD_5 in the climate change category were DWWTPs 8, 9 and 10, in agreement with the higher energy and fuel consumption required for their process. These DWWTPs having in common that they do not use anaerobic digestion with biogas recovery and requiring other power supply for their energetic demands.

In the case of the biofilter and vermi-biofilter DWWTPs electrical power also proved to be primarily responsible for impacts with 80% and 74% respectively, followed by biofilter fuel (11%), and the use of chemicals for vermi-biofilter (25%). In the last one, the use of sodium hypochlorite contributed about 20% of these impacts.

Freshwater eutrophication

The greatest impacts for the freshwater eutrophication category were obtained in aerated lagoons, varying from 8.14×10^{-4} to 2.15×10^{-3} kg P eq/kg BOD_5, with an average of 1.30×10^{-3} kg P eq/kg BOD_5. For active sludge wastewater treatment plants, a range between 8.20×10^{-5} and 2.36×10^{-3} kg P eq/kg BOD_5 was obtained, with an average of 1.15×10^{-3} kg P eq/kg BOD_5. Impacts of 5.56×10^{-4} kg P eq/kg BOD_5 and 7.18×10^{-4} kg P eq/kg BOD_5 were obtained in the biofilter and vermi-biofilter technologies, respectively, suggesting that biofilter technology has the best environmental performance. Electrical consumption turned out to be the process with the greatest contribution to this category, this being between 70-80% (Figure 4); except for DWWTP 7, mainly due to the change in the energy matrix used in the plant (Aysén matrix). In the case of DWWTP 7, sodium hypochlorite was the main contributor to the freshwater eutrophication category.
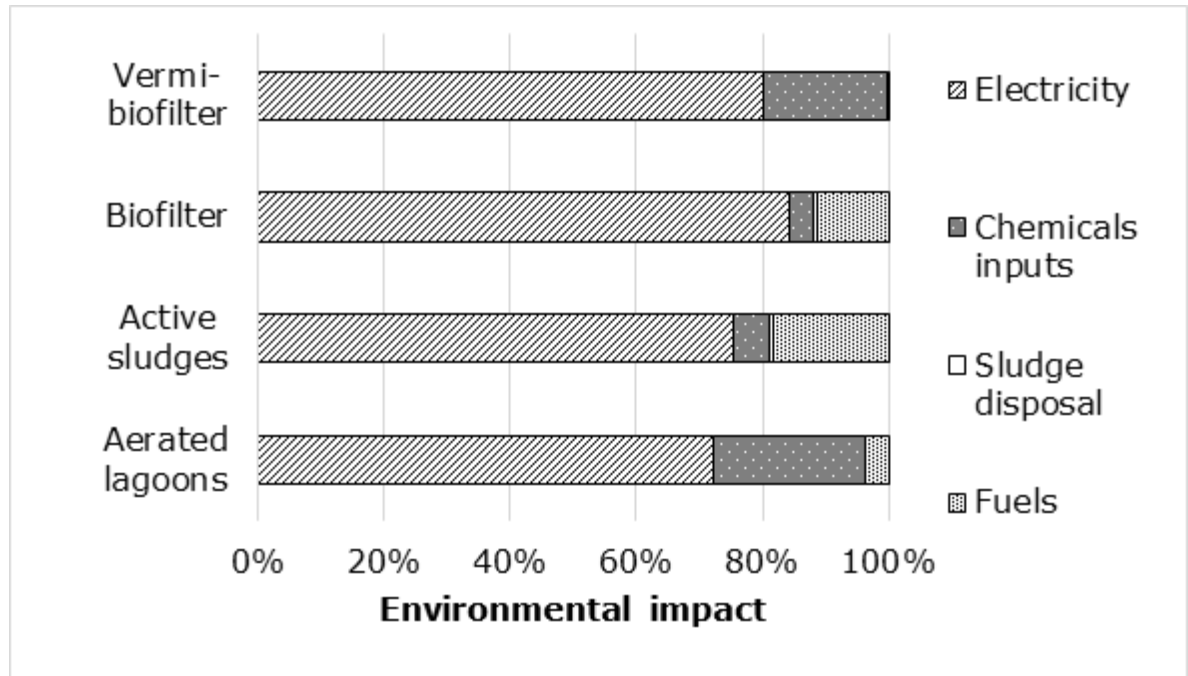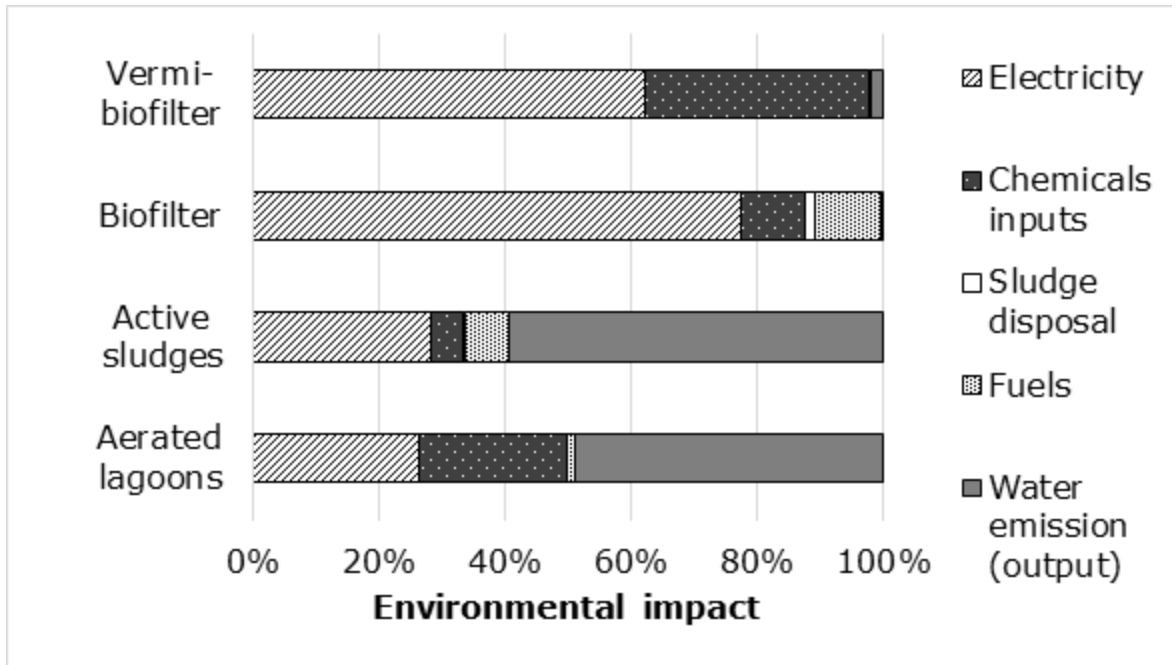
Figure 4. Contribution by kind of technology for the removal of 1 kg BOD$_5$ for the category of freshwater eutrophication.

The second contributor to the freshwater eutrophication category was the use of chemicals inputs, with a contribution of 24% and 20% for aerated lagoons and vermi-biofilter technologies, respectively. Sodium hypochlorite was one that contributed the most to these impacts with 13% for aerated lagoons and 16% for vermi-biofilter, followed by ferric chloride (10%) and sodium metabisulfite (4%). On the other hand, for active sludge and biofilter, the second contributor was diesel fuel.

Freshwater Ecotoxicity

In the freshwater ecotoxicity category the impacts varied from 0.03 to 0.12 kg 1.4-DCB $_{eq}$/kg BOD$_5$, with an average of 0.07 kg 1.4-DCB $_{eq}$/kg BOD$_5$ for aerated lagoons, having this technology the greatest impacts. For active sludge values between 0.01 - 0.12 kg 1.4-DCB $_{eq}$ / kg BOD$_5$ were obtained, with an average of 0.06 kg 1.4-DB eq / kg BOD5. Impact of 0.01 kg 1.4-DCB $_{eq}$/kg BOD$_5$ and 0.02 kg 11.4-DCB $_{eq}$/kg BOD$_5$ were obtained by biofilter and vermi-biofilter technologies, respectively, suggesting that biofilter technology had the best environmental performance. The electricity was the main contributor to the freshwater ecotoxicology category for the case of vermi-biofilter and biofilter technologies, with 62.4% and 77.6% of the contribution, respectively (Figure 5), being the emission of copper the main aspect within this category (30 - 36%). On the other side, water emissions (discharge) from the dumping of treated waters contributing 48.8% and 59.2% for the technologies of aerated lagoons and active sludge, respectively, thus being the residual chlorine the main contributed (between 48 - 55%).

Figure 5. Contribution of kind of technology for the removal of 1 kg BOD$_5$ in the freshwater ecotoxicity category.

For vermi-biofilter technology the second contributor to the freshwater ecotoxicity category corresponds to the use of chemicals inputs represent a 32%, while for aerated lagoons the contribution of chemical products was a 30%. For biofilter technology, chemists accounted for 10.2%, mainly due to the use of ferric chloride (8.2%), and fuel use (10.6%). On the other hand, the use of electrical energy contributed 26.4% and 28.1% for the technologies of aerated lagoons and active sludge respectively.

DWWTP 11 shows the lowest values for this category with 0.01 kg 1.4-DCB $_{eq}$/kg BOD$_5$, attributed to the use of ozone for the disinfection

stage, where, residual chlorine emissions were not generated. Finally, the technologies that presented the highest consumption of electrical energy (lagoons and sludge with 2.6 and 2.3 kWh / kg of BOD_5 respectively), did not show a significant impact in this category, mainly due to the greater contribution of emissions to water, specifically for residual chlorine, since this substance has a high characterization factor equivalent to 19 kg 1.4-DCB $_{eq}$/kg Cl.

Human toxicity

For aerated lagoons, the impacts averaged 1.40 kg 1.4-DCB $_{eq}$/kg BOD_5, while for active sludge, 1.15 kg 1.4-DCB $_{eq}$/kg BOD_5 was obtained. In the case of biofilter and vermi-biofilter, these technologies show the best environmental performance impact results with 0.42 kg 11.4-DCB $_{eq}$/kg BOD_5 and 0.57 kg 1.4-DCB $_{eq}$/kg BOD_5 respectively. In the same way, electrical energy was the process with the greatest contribution for the human toxicity category (Figure 6), with a contribution of 44% and 74% for aerated lagoons and biofilter, respectively. This result is mainly due to the use of manganese, which comes from electrical power generation by the use of coal within the composition of the energy matrix. Followed then by use of chemicals inputs (about 30%), mainly

for sodium hypochlorite, providing 15.5% for air lagoons and 27% for biofilter in the disinfection stage, followed by ferric chloride with 13% in aerated lagoons and biofilter fuel (10 %). For active sludge, water emissions (discharge) had a contribution of 29%, mainly due to the chlorine emitted by the effluent, where the latter has a characterization factor equivalent to 170 kg 1.4-DCB $_{eq}$/kg Cl for this category.
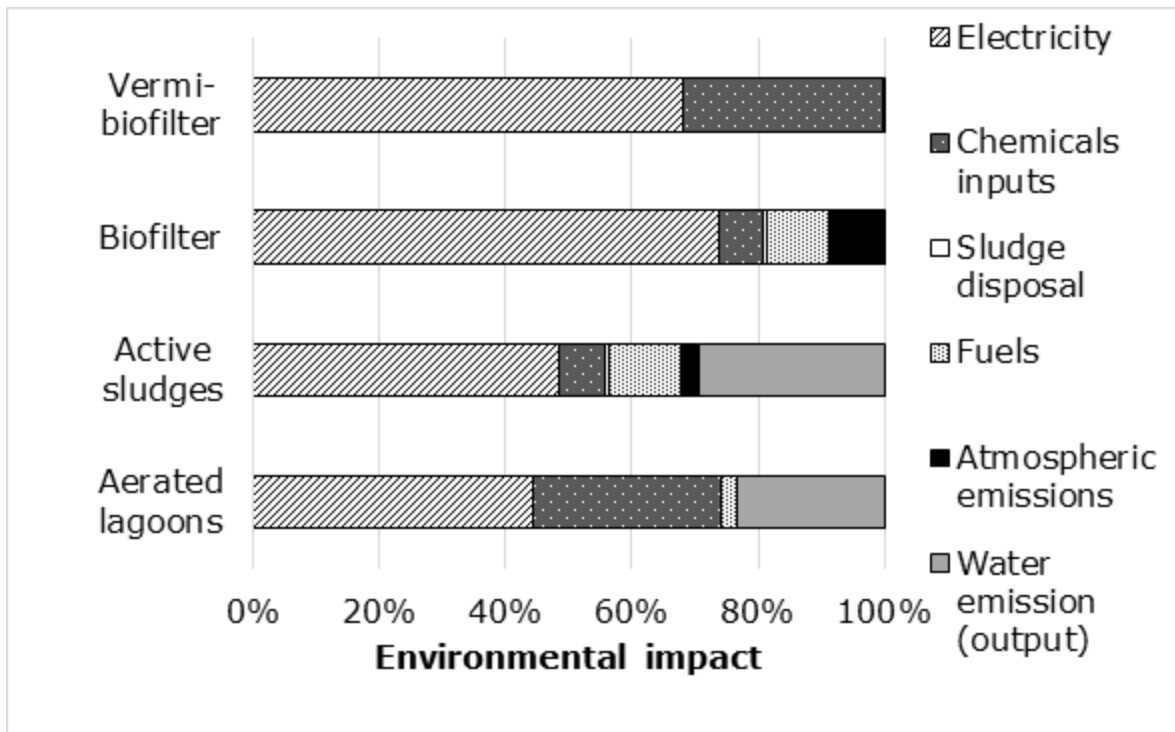
Figure 6. Contribution by type of technology for the removal of 1 kg BOD$_5$ for the category of human toxicity.

Eco-efficiency assessment

Vermi-biofilter proved to be the most eco-efficient technology with a higher indicator corresponding to 6.7 m^3 / kg $CO_{2\ eq}$, followed by biofilter with 5.1 m^3 / kg $CO_{2\ eq}$. On the other hand, the vermi-biofilter technology was the most eco-efficient treatment technology with indicators of 10 984.1 m^3/kg P_{eq}, followed by active sludge with 10 518.5 m^3/kg P_{eq}, in the freshwater eutrophication category, as shown in Table 3.

Table 3. Eco-efficiency indicators and X factor averages by kind of technology.

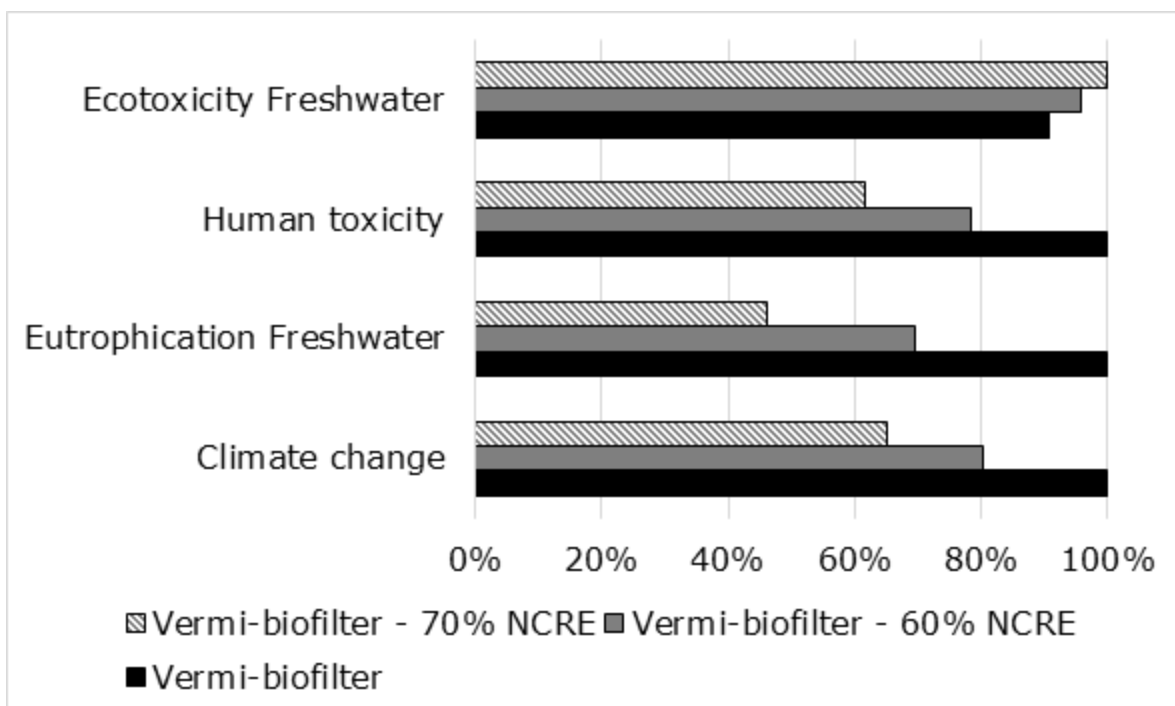|	Eco-efficiency indicator 1	Factor X	Eco-efficiency indicator 2	Factor X
	m^3/ kg $CO_{2\ eq}$		m^3/kg P_{eq}	
Aerated lagoons	3.4	2.0	5876.0	1.9
Active sludge	3.8	1.7	10518.5	1.0
Biofilter	5.1	1.3	8076.6	1.4
Vermi-biofilter	6.7	-	10984.1	-

When the eco-efficiency of the plants is analyzed in the climate change category, the DWWTP 3, 5, 7, 11, 12 and 13 have the best indicators for lagoons and active sludge technologies, in agreement with the size of the plants, as was pointed by (Lorenzo-Toja *et al*., 2014), with exception of the DWWTP 7 which corresponds to a small plant (662.8 inhabitants). The change in the electrical matrix is an important point for the determination of its impacts, and therefore its eco-efficiency. In the same way in the category of freshwater eutrophication, the DWWTP 7 obtains the best eco-efficiency indicator attributable to the energy matrix type mentioned above.

According to factor X (Table 3) in the climate change category, the vermi-biofilter is almost twice the time eco-efficient than aerated lagoons and active sludge plants. Finally, for the freshwater eutrophication category, vermi-biofilter plants turned out to be twice eco-efficient than for aerated lagoons, followed by biofilter, and to a lesser measure with active sludge.

Sensitivity analysis

The results of the environmental impact for the sensitivity analysis (Figure 7), show a decrease in environmental impacts by increasing the unconventional renewable electrical energy in the energy matrix. In the climate change and human toxicity categories a decrease close to 20% and 35% were obtained for vermi-biofilter with 60%-NCRE and vermi-biofilter with 70%-NCRE, respectively. On the other hand, the opposite is true for the category of freshwater ecotoxicity, however, the differences in environmental impact did not exceed 9%, mainly attributed to the 11% increase in photovoltaic and wind energy generation, which 43.2% of the impact contributed to 60%-NCRE, and 60.5% to 70 -NCRE.

Figure 7. Environmental impacts for vermi-biofilter for different compositions in the energy matrix.

Finally, for the eco-efficiency indicator, the vermi-biofilter plant with the highest percentage of NCRE (70%-NCRE) for both categories studied was more eco-efficient. In the category of climate change, the conventional matrix plant decreased its eco-efficiency by 35% and 19% for the matrix with 60%-NCRE, for the freshwater eutrophication category, the decrease in eco-efficiency for the plant with Conventional energy matrix was 54% and for the plant with 60%-NCRE it was 34% with respect to the plant with the highest NCRE (Figure 8).
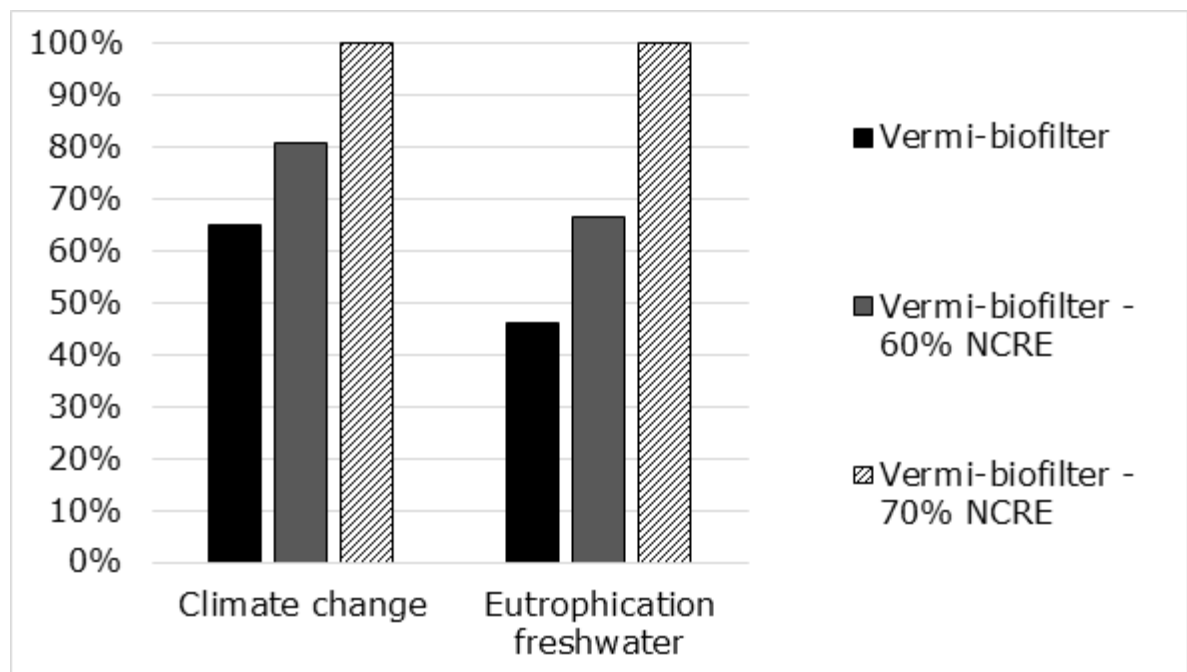
Figure 8. Eco-efficiency indicators with energy matrix projection.

Finally, with this assessment, it can be demonstrated that eco-efficiency can vary without modifying the flows (required inputs), in terms of efficiency, if not, that the indicator can be altered by simply changing the composition of the electrical matrix, that is, without a change in its design, because the electricity corresponds to an environmental hotspot for the treatment systems.

Conclusions

It was determined that for indicators climate change and freshwater eutrophication the most eco-efficient treatment technology corresponds to vermi-biofilter compared to technologies such as aerated lagoons and active sludge, suggesting that in Chile emerging technologies are more eco-efficient than conventional.

Electric power is an environmental hotspot within the treatment plants, with the composition of the country's energy matrix being decisive, concerning the environmental impact and its eco-efficiency.

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