

Life cycle assessment of a sand media filter with an optimised underdrain design

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Abstract

Micro-irrigation is the technology which allows the best water use efficiency. To prevent emitter clogging, which is the main drawback of micro-irrigation systems, filters are mandatory. The filters are the components of the micro-irrigation system with greater pressure (and thus energy) requirements. The increase in energy demand is the main problem related to the adoption of more efficient irrigation techniques. Previous studies have shown that the pressure drop across sand media filters is mainly located at underdrain elements. To minimize this problem a new underdrain was designed (Spanish utility model registry U201530629). The new filter was constructed as a prototype, but to compare it with the commercial, a new design that allows its industrialized production without modifying its hydraulic performances was studied.

The new marketable design allows two different strategies for reducing the environmental impact. The first consists in keeping the original dimensions and reducing the pressure losses across the filter; while the second consists in reducing the filter dimensions (less construction material) but keeping the original pressure losses. To determine the benefits of each strategy, a “cradle to grave” life cycle assessment (LCA) is used. The analysis followed the procedure recommended by the ISO 14044 standard: definition of the goal and scope of the study, life cycle inventory, evaluation and impact interpretation.

The analysis of the LCA results shows that, considering the energy and material consumption and emissions to environment in total life phases, the best strategy is to reduce the size of the filter.

Keywords: drip irrigation, filtration, LCA, CFD, optimal design, environmental improvement, carbon footprint.

1. Introduction

Filtration is a key step for drip irrigation systems. The best option, considering the solid removal efficiency, is to use granular matrix filters. However, this type of filters is associated with an important pressure drop, which is also related to energy consumption and environmental impact.

Several types of sand filter underdrains can be found in the market. The purpose of the underdrain is to discharge as fast as possible the water flow off the filter. When the sand filter behaviour is studied, it shows that most of pressure drop takes place at the drainage area (Arbat et al., 2013; Bové et al., 2015c). However, there are differences between underdrain types, being the nozzle inserted in plate the underdrain with less associated pressure drop (Burt, 2010; Mesquita et al., 2012). To improve the hydraulic behaviour of the filters a new concept of drainage formed by a disc full of granular confined medium, with a more coarse grain than the filtering column, was designed (Bové et al., 2015b).

This new underdrain, which was developed using Computational Fluid Dynamics (CFD) technique, reduces the total pressure drop across the filter by 45%. This design was registered as Spanish Utility Model U201530629 (Bové et al., 2015b). A laboratory scaled filter was constructed and tested in the laboratory from this new design (Bové et al., 2015c).

Results from previous studies (Bové et al., 2015c) showed that the new design allows two strategies to redesign the filter. On one hand, it keeps the effective filtration surface and reduces the pressure drop (as well as it reduces the energetic consumption during the operation life). On the other hand, it reduces the filtration surface (reducing both material and energy needs during the construction phase). So the objective of the present work is to determine the best strategy to reduce the environmental impact at the end of the life cycle of these filters.

2. Materials and Methods

2.1. Description of the alternatives

Three design alternatives were considered in this paper, all of them working with the same flow (3 L s^{-1}). The alternative called 0 was a commercial design with an internal diameter of 500 mm and 12 nozzle inserted in a plate as a drainage element. Considering this geometry, the superficial filtration velocity was 0.015 m s^{-1} for the design flow. Alternative called 1 was the same filter where the nozzle plate was replaced by the new underdrain design keeping the same diameter. In this case, the surface filtration velocity was the same than alternative 0 for the design flow (0.015 m s^{-1}) but the pressure drop was reduced. In the alternative 2, the filter diameter was reduced to 400 mm (less filtration surface), so filtration velocity at the design flow was 0.024 m s^{-1} . In this alternative 2, the pressure drop was similar to that of alternative 0.

The three designs were built by a steel housing with a water inlet and outlet and two lids, one vertical at the top of the filter and the other horizontal at the bottom of the filter. Lids were sealed with nitrile butadiene rubber (NBR) covers. The thick of steel plates was 3 mm and was the same for all three designs.

The commercial drainage was formed by 12 high density polyethylene nozzles with 45 slots per nozzle of 0.45 mm wide that allowed the water passage and retained the filter medium. The new design was formed by a high density polyethylene disc with openings covered by stainless steel mesh. The disc was full of granular confined medium with a coarser grain, which, in addition, caused that flow stream lines were more rectilinear.

Figure 1 shows the differences in the drainage area and diameter of the three studied designs.

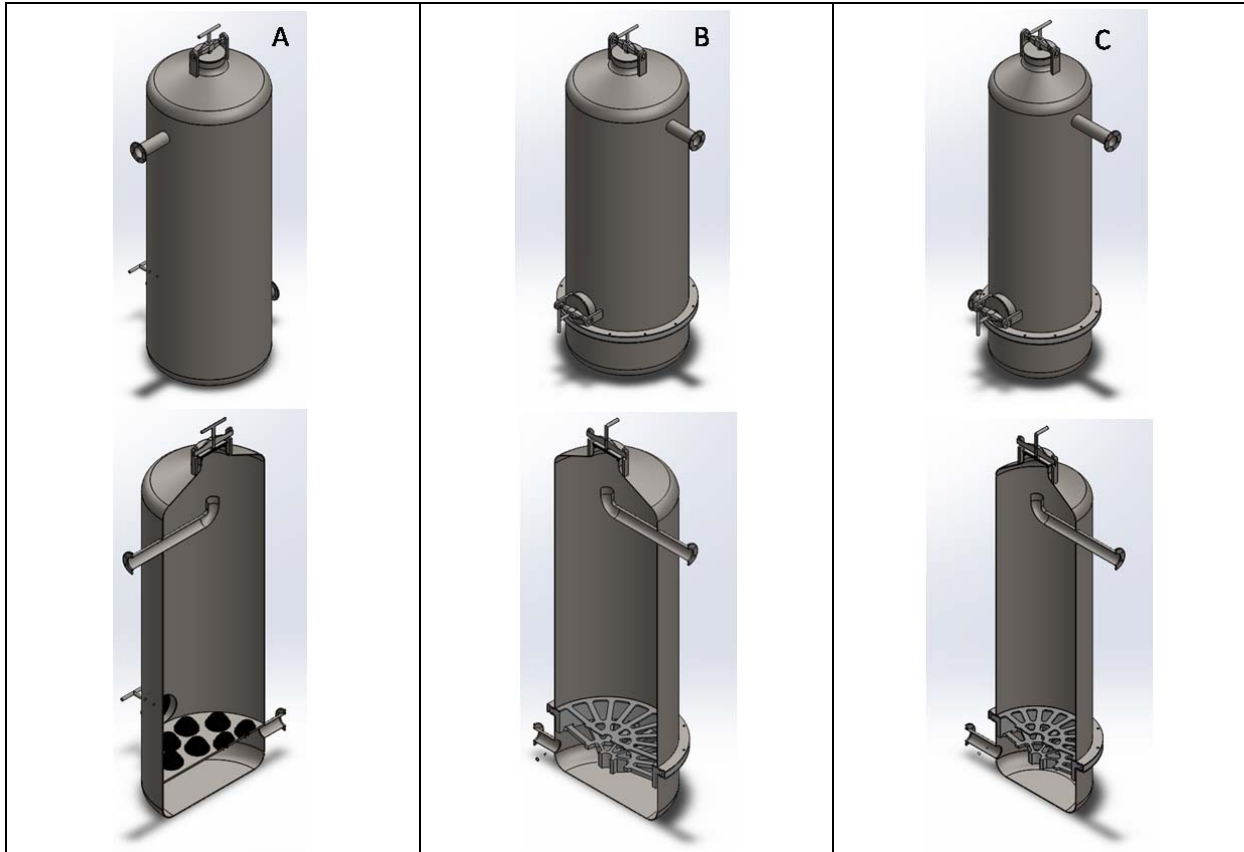


Figure 1. Scheme of A) Alternative 0 , B) Alternative 1 and C) Alternative 2.

To determine the pressure drop in the studied designs, SolidWorks FlowSimulation was used. This is a CFD software package integrated in the design program SolidWorks SP5.0 (SolidWorks, 2014). This software generates a Cartesian finite elements mesh that catches all the singularities of the filter's geometry (SolidWorks, 2014). Meshes were formed by 600,000 cells; turbulent intensity and length model was used with 2% for intensity value and 0.00692 m for the turbulence length (SolidWorks, 2012). The porous medium was modelled from experimental results obtained in previous works (Bové et al., 2015a). With this, a curve that represents the pressure drop as function of flow was obtained for each filter design. This pressure drop was used to determine the energy consumption along the functional life of filters.

2.2. Annual equivalent flow and dissipated energy along the functional life of the filter

To develop a study case, the filters were considered to be used in an irrigation system of an apple orchard located at in Baix Empordà (Catalonia, Spain). Data of the orchard and crop are shown in Table 1.

Energy consumption by the filter is related to the water flow energy dissipated in the filter and it was calculated as:

$$E = Q \cdot \Delta p \cdot t \quad (1)$$

where E is energy dissipated across the filter (MJ); Q is flow across the filter ($\text{m}^3 \text{s}^{-1}$); Δp is pressure drop across the filter (MPa); and t is time of use (s).

Table 1. Data used in the study case.

Parameter	Value	Observations
Surface	10,200 m ²	Is a typical fruit farm surface of the zone (IDESCAT, 2015), it is divided in 2 irrigation sectors both of 5,100 m ² which are related to filter dimensions.
Climatic data	Various	Historical data series of precipitation and evapotranspiration in agroclimatic station of La Tallada d'Empordà (Ruralcat, 2016) considering that 80% of the total rainfall was effective.
Location coefficient (K _l)	0.316	Calculated according to Aljibury et al. (1974)
Crop coefficient (K _c)	Various	K _c takes different values according to the vegetative plant status (Girona, 2013)
Distribution efficiency	0.85	Mean value considered by the Catalan Water Agency (ACA, 2016)
Drip emitter discharge	2x4 L h ⁻¹ tree ⁻¹	Two 4 L·h ⁻¹ emitters for tree is the most commonly used irrigation configuration in the region

Time of use is the product of multiplying the irrigation hours for the functional life of the filter, which was fixed in 15 years.

2.3. Filters life cycle assessment, objectives definition and scope

The LCA methodology was applied in the three alternatives following the directives and phases defined by ISO 14044 (2006) for comparing their environmental impact.

The functional unit was the unit where system inlets and outlets were referred to. In this case “use a sand filter in a micro-irrigation system with a flow of 3 L s⁻¹, for fifteen years in an apple commercial orchard at Baix Empordà (Spain)”.

The life cycle phases were simplified as follows: Fabrication > Transportation > Utilization > Transportation > Waste/recycling. These phases define the life cycle from the cradle to the grave. Fabrication included all the process necessary to obtain a filter ready to use. In this part of life cycle the obtaining of materials, fabrication process, assembly and all auxiliary operations were considered. The utilization took into account the energy consumption during the functional life of the filter. Waste/recycling was the part of the life cycle that considered the recuperation of materials and energy and/or soil deposition of the filter parts at the end of life. For every phase the transportation of the materials from the raw material to the fabrication parts centres, from the fabrication part centres to the assembly centres, from the assembly centres to the place of use and from the place of use to the recycling/waste centre were considered. Following this procedure, the life cycle of the filters can be summarized as shown in figure 2.

The elements without a significant importance were excluded from the use phase of the study, i.e. water and energy used in the filter backwashing.

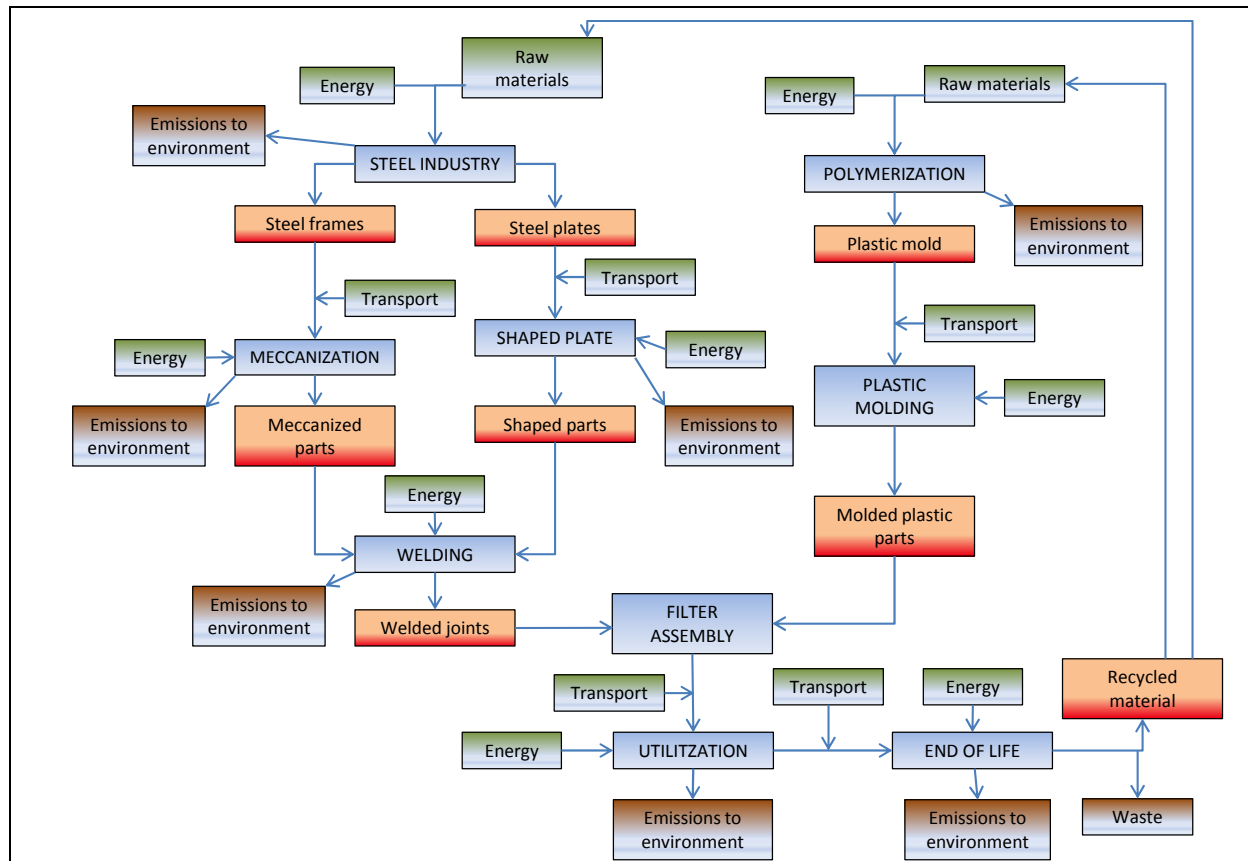


Figure 2. Filter life cycle flow diagram.

2.4. Life cycle inventory

For the assessment of inventory, both system mass and energy balances were carried out for the inlet (consumption) and outlet (emissions).

Global warming potential (expressed as kg of equivalent CO_2), atmospheric acidification potential (expressed as kg of equivalent SO_2) and freshwater eutrophication (expressed as kg of equivalent PO_4) were the emissions to environment considered in this study. Energy consumption in the process was expressed in MJ. All these parameters can be extracted for each section of life cycle.

The value of the aforementioned parameters in the fabrication and waste/recycling phases was determined from the physical and geometrical characteristics of each filter component using the Institute of Environmental Sciences of Leiden University method (CML) (Guinée et al., 2002) and the GaBi database associated to this method, which integrates raw material production, transformation processes, transport and waste/recycling. Both the CML model and GaBi data base are integrated in the SolidWorks software.

Inputs for the fabrication model were: material from recycling as a percentage of the raw material, fabrication, functional life and travelled distance and mode of transport to the utilization place. The inputs for the waste/recycling process were: percentage of waste and percentage to recycling. Table 2 summarizes model inlets for the materials.

For the global transportation at the end of life cycle 1,000 km by truck were considered. The principal market for the enterprise that commercializes the filters is Spain and, in a less extension, Northern Africa, therefore a great part of the sales were made at relatively short distances. For this reason, 1,000 km were considered a good mean. However, this value was the same for all the alternatives and the relative importance of transportation was not a critical parameter.

Emissions during the functional phase were calculated from the energy consumption and equivalence factors between MJ and emissions were considered, $0.11 \text{ kg equivalent CO}_2 \text{ MJ}^{-1}$, $3.90 \cdot 10^{-4} \text{ kg equivalent SO}_2 \text{ MJ}^{-1}$ and $3.53 \cdot 10^{-11} \text{ kg equivalent PO}_4 \text{ MJ}^{-1}$ (EC, 2016).

The final destination of the materials at the end of functional life was estimated from the Eurostat data (EC, 2016), which showed that that approximately 50% of the materials were recycled.

Table 2. Model inlets for the materials.

	Material		
	Steel	Polyethylene	NBR
Recycled material content	15.0%	0.0%	0.0%
Fabrication process	Shape / meccanization	Moulding	Moulding
Waste	10.0%	2.0%	5.0%
Transportation	1,000 km (truck)	1,000 km (truck)	1,000 km (truck)
End of life	99.93% recycling 0.07% waste	92.97% recycling 7.07% waste	92.97% recycling 7.07% waste

3. Results and Discussion

3.1. CFD modelling results

Pressure drop produced by the three different filter configurations at different flowrates were obtained from CFD software computations. A silica sand column, 300 mm height, with particle sizes ranging from 0.63 to 0.75 mm was considered in the three alternatives (Figure 3).

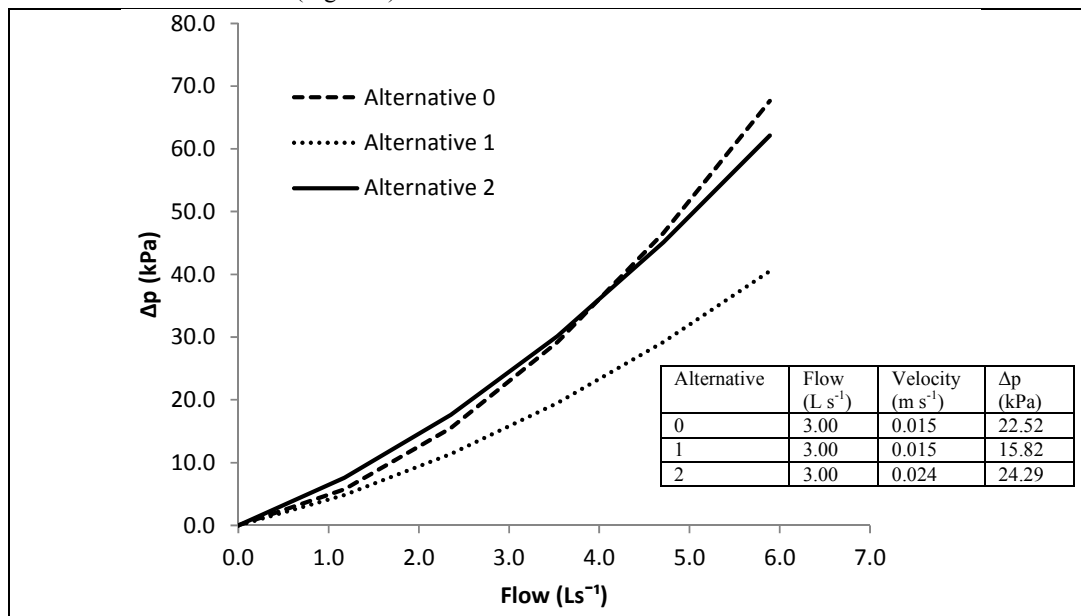


Figure 3. Pressure drop produced by the different filter configurations at different flowrates. A silica sand column, 300 mm height, with particle sizes ranging from 0.63 to 0.75 mm was considered in the three alternatives.

Pressure drop along the filter is shown in Figure 4. Alternatives 0 and 2 produced similar values of total pressure drop. However, these alternatives showed different behaviour at the filter medium and underdrain element. On the other hand, alternative 1 implied a pressure drop reduction close to 30% compared with the other two configurations.

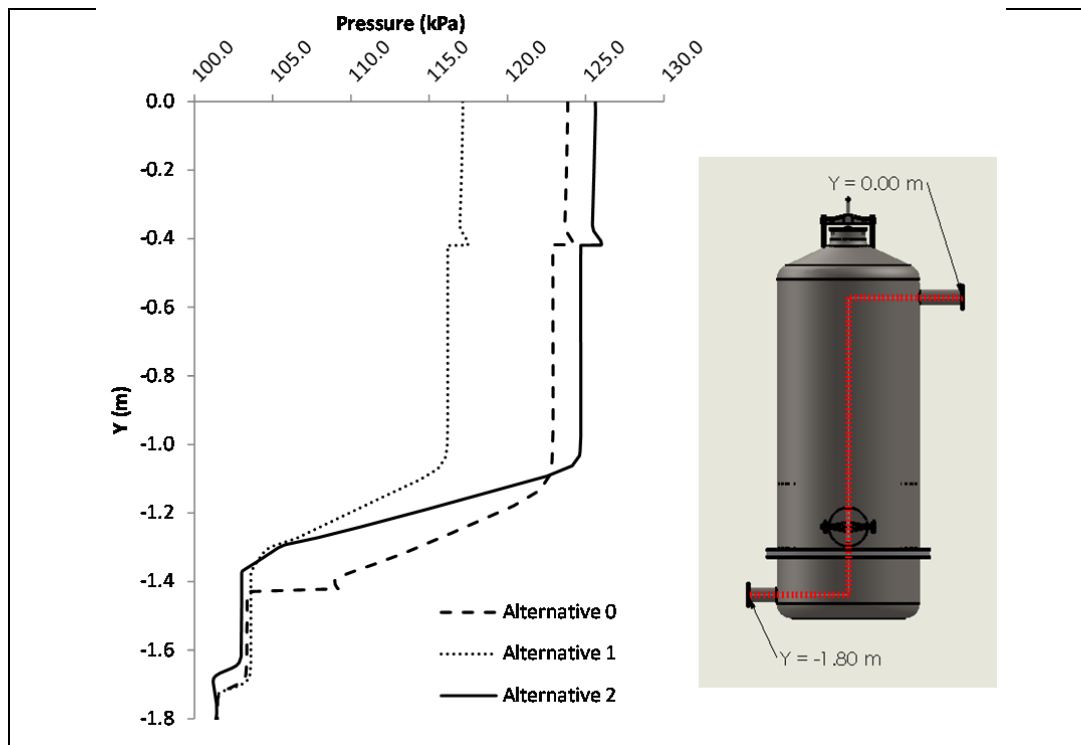


Figure 4. Pressure drop for the three alternatives under water flow of 3.00 L s^{-1} .

3.2. Energy consumption during functional filter life

According to the description of the orchard (Table 1), total irrigation time was fixed in 264 hour per year. Using this data, energy consumption during functional filter life was computed (Table 3).

Table 3. Energy consumption during functional filter life for all the three alternatives.

	Alternative 0	Alternative 1	Alternative 2
Flow (L s^{-1})	3,00	3,00	3,00
Pressure drop (kPa)	22,52	15,82	24,29
Annual operation (h year^{-1})	264	264	264
Functional life (years)	15,0	15,0	15,0
Energy consumption during functional life (MJ)	891,8	626,5	961,9

Alternative 1 was the best because it showed less energy consumption along the functional filter life. However, energy consumption during the functional life is not the only parameter to consider, but also material consumption during filter construction.

3.3. Life cycle impact evaluation

Table 4 shows the total material mass for the three evaluated alternatives.

Table 4. Material mass consumption (kg) for the three different alternatives.

	Alternative 0	Alternative 1	Alternative 2
Material (kg)	76.4	70.9	57.3

Alternative 1 and 2 implied a reduction in the construction material of 7% and 25%, respectively, compared with alternative 0.

Energy consumption and emissions during filter life cycle are shown in table 5. Energy consumption includes construction, transportation, utilization and waste/recycling phases.

Table 5. Energy consumption and emissions during filter life cycle.

		Global warming potential (kg equivalent CO ₂)	Energy consumption (MJ)	Atmospheric acidification potential (kg equivalent SO ₂)	Freshwater eutrophication potential (kg equivalent PO ₄)
Alternative 0	Material	172.3	2,343.5	0.4406	4.40·10 ⁻⁰²
	Construction	18.3	329.4	0.0783	3.85·10 ⁻⁰³
	Transportation	3.9	57.3	0.0188	4.12·10 ⁻⁰³
	Utilization	167.9	891.8	0.3520	1.56·10 ⁻⁰⁵
	Waste/recycling	19.4	264.0	0.1209	1.58·10 ⁻⁰²
	<i>TOTAL</i>	<i>382.4</i>	<i>3,771.5</i>	<i>1.01</i>	<i>0.0679</i>
Alternative 1	Material	159.6	2,442.9	0.4031	4.01·10 ⁻⁰²
	Construction	21.7	400.0	0.1078	4.72·10 ⁻⁰³
	Transportation	3.6	53.6	0.0177	3.81·10 ⁻⁰³
	Utilization	118.0	626.5	0.2470	1.68·10 ⁻⁰⁵
	Waste/recycling	17.9	222.6	0.1059	1.51·10 ⁻⁰²
	<i>TOTAL</i>	<i>321.5</i>	<i>3,749.2</i>	<i>0.88</i>	<i>0.0637</i>
Alternative 2	Material	132.4	1929.3	0.3345	3.34·10 ⁻⁰²
	Construction	17.2	319.3	0.0837	3.70·10 ⁻⁰³
	Transportation	3.0	44.6	0.0146	3.11·10 ⁻⁰³
	Utilization	181.1	961.9	0.3800	1.68·10 ⁻⁰⁵
	Waste/recycling	12.9	174.1	0.0809	1.09·10 ⁻⁰²
	<i>TOTAL</i>	<i>349.0</i>	<i>3,446.0</i>	<i>0.90</i>	<i>0.0587</i>

In order of importance, the terms in the assessment were: Material > Utilization > Construction > Waste/recycling > Transportation, except for the eutrophication potential where the waste/recycling was more important than the construction and utilization phases.

Alternative 1 implied a reduction of 16% of global warming potential, 6% of energy consumption, 13% of atmospheric acidification potential and 6% of freshwater eutrophication potential compared with alternative 0. Alternative 2 implied a reduction of 9% of global warming potential, 9% of energy consumption, 11% of atmospheric acidification potential and 13% of freshwater eutrophication potential compared to alternative 0. Therefore alternatives 1 and 2 were better than alternative 0 in terms of environmental impact. Probably, there is a functional life time that equals the results for both designs.

4. Conclusions

A change in the micro-irrigation granular media filter design that reduces the pressure drop across the filter allowed developing strategies for improving the environmental behaviour of these filters. On one hand, it was possible to reduce energy consumption during the functional life; and, on the other hand, to diminish material and energy consumption during the filter construction.

Life cycle assessment has demonstrated to be useful to evaluate environmental impact of one design and compare it with other designs. The results of the present study show that both improved designs reduced the environmental impact, being the results very similar for the considered functional life. However, in the alternative that reduced the filtration surface there is a reduction of material consumption, which could be more interesting than to reduce energy consumption during functional life.

Further research is warranted for introducing economic criteria in order to select the best filter design alternative.

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