Environmental assessment of underdrain designs for a sand media filter

Josep Bové , Joan Pujol, Gerard Arbat, Miquel Duran-Ros, Francisco Ramírez de Cartagena, Jaume Puig-Bargués [1]

Department of Chemical and Agricultural Engineering and Technology, University of Girona, C/Maria Aurèlia Capmany 61, 17003 Girona, Spain

Abstract

Increasing energy demand is the main problem linked with the adoption of more efficient irrigation techniques, particularly microirrigation. In microirrigation systems, important pressure losses and therefore energy consumption, occur at the filters, which are a key component in preventing emitter clogging. Previous studies have shown that the main pressure drop across sand media filters, which are widely used in microirrigation, occurs in the underdrain elements. To minimise this problem, new underdrains should be designed but an issue is how their environmental impact can be reduced. Two alternative design strategies were found: firstly, keeping the original filter dimensions and reducing energy consumption during operation by 30%; and, secondly, reducing filter size and reducing construction material by 25% but keeping the original pressure losses. A life cycle assessment transforming environmental effects into monetary values was carried out comparing a commercial sand filter with the two filters designed following the two aforementioned strategies. Results show that both alternatives reduce the environmental impact of the sand commercial filter. Reduction of filter size is the optimum strategy if filtered volumes are below 63,000 m^3 along the filter life, while reduction of energy consumption was the best alternative for higher filtered volumes. This work shows the usefulness of life cycle assessment for assessing design strategies that could improve the sustainability of microirrigation equipment.

[1] Corresponding author. Tel: +34.972.41.84.59; Fax: +34.972.41.83.99. *E-mail address:* jaume.puig@udg.edu (J. Puig-Bargués)

Keywords

Drip irrigation; clogging, filtration; computational fluid dynamics; optimal design; life cycle assessment

Nomenclature

CO_2	carbon dioxide
CPD	computational fluid dynamics
E	energy consumed by the filter, MJ
HDPE	high density polyethylene
LCA	life cycle assessment
NBR	nitrile butadiene rubber
PO_4	phosphate
SO_2	sulphur dioxide
V	filtered volume, m^3
Δp	pressure drop produced by the filter, MPa
η	efficiency of pumping system, dimensionless

Highlights

- Two alternatives for designing a new sand filter underdrain were analysed
- These alternatives differed in material and energy consumption
- Eco-costs were determined for each alternative based on LCA results
- Both alternatives improved the environmental impact of a commercial sand filter
- The optimum alternative depends on water filtered volume along filter life

1. Introduction

Over the last 50 years, world agricultural production has grown to between 2.5 and 3 times, while the cultivated area has grown only by 12%. More than 40% of the increase in food production has come from irrigated areas, which have doubled in area. Over the same period, the cultivated area per person has gradually declined to less than 0.25 ha, a clear indicator of agricultural intensification. Irrigated agriculture currently uses 2.2% of the world's land surface and accounts for 70% of all water withdrawn from aquifers, streams and lakes (FAO, 2011). Within this context, irrigation sustainability assessment is important, especially in areas where rainfall is scarce and / or irregular. For example, Costa et al. (2016) noted that water is considered the most important and valuable resource in the Mediterranean basin. With the objective of increasing water use efficiency, a common strategy has been to replace surface irrigation with microirrigation; this approach has been prioritised by irrigation modernisation policies adopted in different countries (Tarjuelo et al., 2015). For example, the area using microirrigation in Spain increased by 14.0% from 2006 to 2016, reaching 50.6% of the irrigated surface in 2016 (MAPAMA, 2017). This achieved a 9.5% reduction of irrigation water consumption from 2005 to 2015 (INE, 2017). Together with water consumption, energy consumption must be considered because irrigation is the major energy consumer in agricultural systems (Pelletier et al., 2011). In this regard, energy accounts for approximately 40% of the costs of managing operating and maintaining the irrigation equipment (Rodríguez-Díaz, Pérez-Urrestazaru, Camacho-Poyato, Montesinos, 2011). Therefore, improving both water and energy use efficiency in microirrigation systems should be considered.

Filtration is a key operation for the successful operation of a microirrigation system since it prevents one of the main problems of this irrigation method, emitter clogging. Sand media filters offer the best performance (Capra & Scicolone, 2007; Duran-Ros et al., 2009). However, the pressure drop, and therefore the energy requirements, produced by sand filters are not negligible. The filter underdrain has an important effect on the pressure drop and different studies have analysed the performance of different underdrain designs (Arbat et al., 2011; Mesquita, Testezlaf, Ramirez, 2012; Arbat et al., 2013; Bové, Arbat, Pujol et al., 2015; Pujol et al., 2016; Bové et al., 2017). Although the environmental impact of sand filters has to be computed for a complete assessment of its performance, this aspect not has not been considered in previous studies because the focus was on reducing pressure drop across the filter.

The global environmental impact of the filter includes the impact from its construction and functional life until its disposal or recycling. Since different filter designs for reducing the overall environmental impact are possible, thus a method should be used to calculate and compare the impact of design alternatives. In this regard, Life cycle assessment (LCA) is a standard method used to analyse environmental sustainability of a process or system along its whole life cycle (ISO, 2006) and has been shown to play an important role in the environmental assessment of water use efficiency measures (Notarnicola et al., 2017).

Several recent works have carried out LCAs focusing on irrigation systems. When replacing sprinkler irrigation, microirrigation usually increases the eco-efficiency in different irrigation areas by improving water use efficiency (Maia, Silva & Costa, 2016) and reducing energy consumption (Mehmeti, Todorovic & Scardigno, 2016). Romero-Gámez, Audsley, and Suárez-Rey (2014), using LCA to analyse the sustainability of leafy crops, concluded that the reduction of the environmental impact of irrigation equipment should be a priority. However, most of the LCAs used in irrigation (e.g. Pradeleix et al., 2014; Foteinis & Chatzisymeon, 2016; Eranki et al., 2017) only consider pumps and driplines without including the filters. This is a crucial omission since filters assure the long term performance of microirrigation systems (Duran-Ros et al., 2009) and, thus, increase its sustainability.

To our knowledge, LCA has not been used for considering sustainability issues when designing filters for microirrigation systems. Thus, in this study the main goal is to assess alternatives for the design of microirrigation sand filters from an environmental perspective following LCA methodology.

2. Materials and methods

2.1. Description of alternatives

Several types of sand filter underdrains are found in the market. The aim of the underdrain is to evacuate, as fast as possible, the water from the filter. Significant pressure drop takes place in the drainage zone (Arbat et al., 2013; Bové, Arbat, Pujol et al., 2015). An underdrain design associated with reduced pressure loss includes a nozzle inserted into a plate (Burt, 2010; Mesquita et al., 2012). To improve the hydraulic behaviour of these filters, a new concept of drainage, formed by a low height cylinder filled with a granular confined coarse medium, was designed and shown to reduce the total pressure drop over the filter by 30% (Bové et al., 2017). The new filter was constructed as a prototype, but for comparison, a new design that could allow it to be commercial produced without modification to its hydraulic performance was considered.

Three designs were considered, all with the same flowrate (3 l s^{-1}). This flowrate is frequently recommended by manufacturers for these types of filters. Alternative 0 was a commercial design with 500 mm internal diameter and 12 nozzles inserted in plate as a drainage element; with this geometry, the superficial filtration velocity at the design flow was 0.015 m s^{-1}. Alternative 1 was the same filter but the nozzle plate substituted with the new underdrain design and kept the same diameter; the velocity filtration at the design flow was 0.015 m s^{-1}, but the pressure drop was reduced. Alternative 2 reduced the filter diameter to 400 mm, so the filtration velocity at the design flow was increased to 0.024 m s^{-1}, drainage was improved and the pressure drop was close to alternative 0.

All designs had a steel housing, where the inlet and outlet water connections were inserted, and two access ports, one vertical located at the top of the filter and the other horizontal located at the bottom of the filter column. Access ports were sealed with nitrile butadiene rubber (NBR) covers. The thickness of the steel plates was the same for all three designs (3 mm).

The commercially available drainage system was formed by 12 high density polyethylene nozzles (HDPE) with 45 slots per nozzle 0.45 mm wide that allowed the passage of water and retained the filter bed. The new design was formed by a HDPE cage with the openings covered by stainless steel mesh. The cage was full of coarse granules, which allowed the water passage and retained the filter bed. With the new design, the stream lines in the filter were more rectilinear than in commercial filters (Bové et al., 2017).

Figure 1 shows the three studied design alternatives, noting the differences in the drainage zone and the filter diameter.

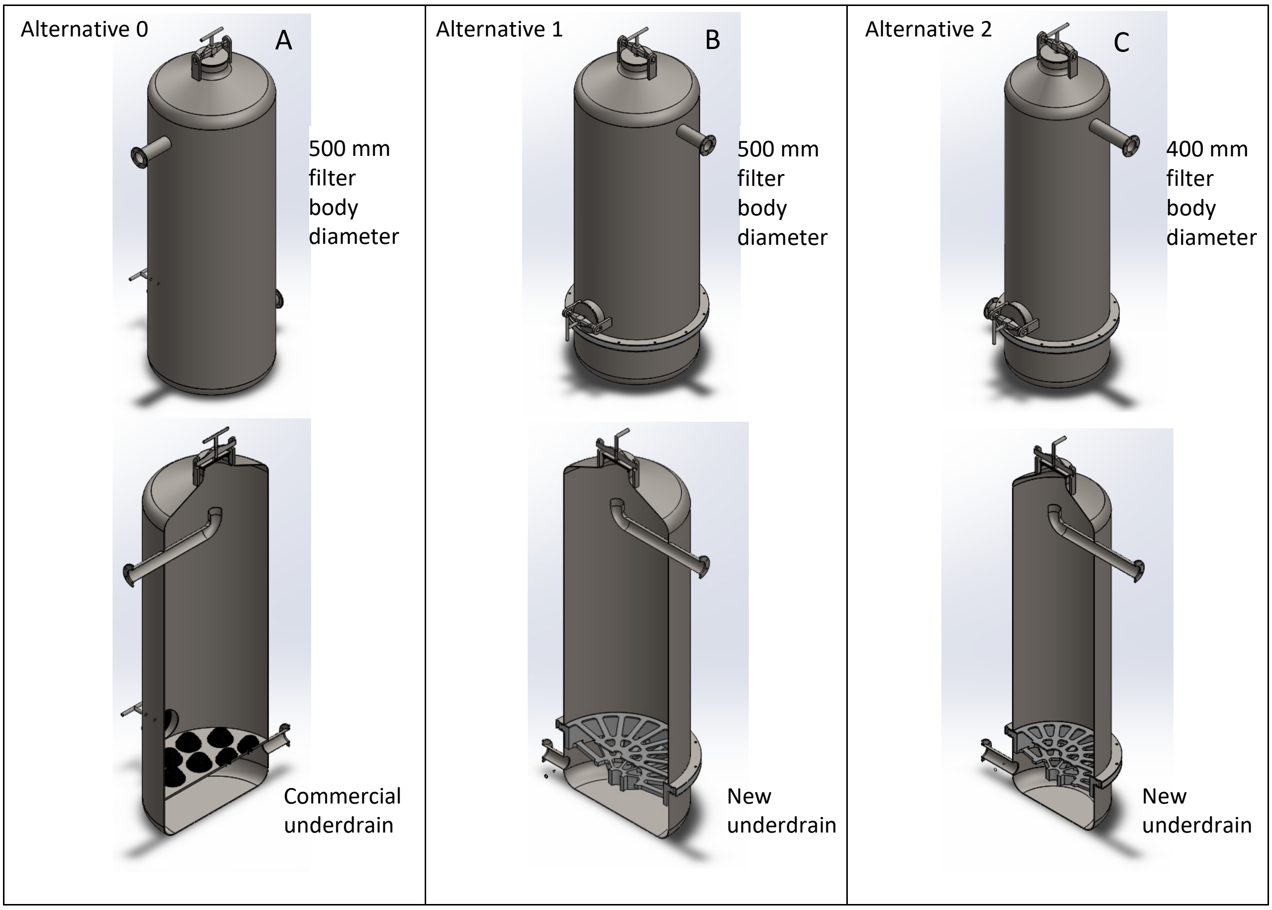


Fig. 1. Section and underdrain used in A) alternative 0, B) alternative 1, C) alternative 2.

To determine the pressure drop in the studied designs, SolidWorks FlowSimulation 2015 (Dassault Systèmes SolidWorks Corp., Waltham, Massachussets, USA) was used. This is a computational fluid dynamics (CFD) software module integrated in the design program SolidWorks that generates a Cartesian finite element mesh that captures all of the singularities of the filter geometry (SolidWorks, 2014). Meshes used in the study were composed of 600,000 cells; a turbulent intensity and turbulence length model was used with values of 2% for intensity and 0.00692 m for length (SolidWorks, 2012). The porous medium was modelled using experimental results obtained in previous works (Bové, Arbat, Duran-Ros et al., 2015). With this information, the pressure drop as function of flowrate was obtained for each filter design and this was used to determine the energy consumption throughout the use phase of the filter life cycle, using Eq. 1 (Clark, Haman, Prochaska, Yitayew, 2007):

$$E = V \Delta p \; \eta^{-1} \quad (1)$$

where: E: energy consumed by the filter (MJ); V: filtered volume (m^3); Δp: pressure drop produced by the filter (MPa); and η: efficiency of pumping system (dimensionless). According to Moreno, Ortega, Córcoles, Martínez, and Tarjuelo (2010), a η of 0.65 can be considered to be typical for irrigation systems.

2.2. Life cycle assessment approach, functional unit and scope

To evaluate the environmental behaviour of each design, a cradle-to-grave LCA was used. Cradle-to-grave is the full LCA from resource extraction ('cradle') to the use phase and disposal phase ('grave'). The analysis followed the procedure recommended by the ISO 14044 (2006) standard: definition of the goal and scope of the study, life cycle inventory, evaluation and impact interpretation. In a second step, the environmental effects were assessed using their associated environmental costs (eco-costs), in order to make possible their comparison.

The functional unit was the unit at which all inlets and outlets to the system were referred. In this study this was defined as "m^3 of water filtered by a sand filter working with a flow of 3 l s^{-1}".

The life cycle phases were simplified as: obtaining raw material, filter production, transport, use, and waste/recycling phase. The raw material obtaining phase included obtaining the unprocessed material that enters to the next phases; these materials came from mine extraction or from recycling plants. The fabrication phase included all of the necessary processes for obtaining a ready-to-use filter. In this part of the life cycle, manufacture of the components, assembly and all auxiliary operations were considered. For use phase, energy consumption through the functional life of the filter was considered, as well as the periodic renewal of filter media. Waste/recycling phase included the material recovery and energy and/or soil deposition of the filter parts at the end of life. Transport was considered as a single phase but transport was necessary in all phases; to move raw material to the fabrication, move components from fabrication to assembly, move completed filters from assembly to their point of use and from their point of use to a recycling/waste centre. In this way, the life cycle of the filters can be summarised, as shown in Figure 2.

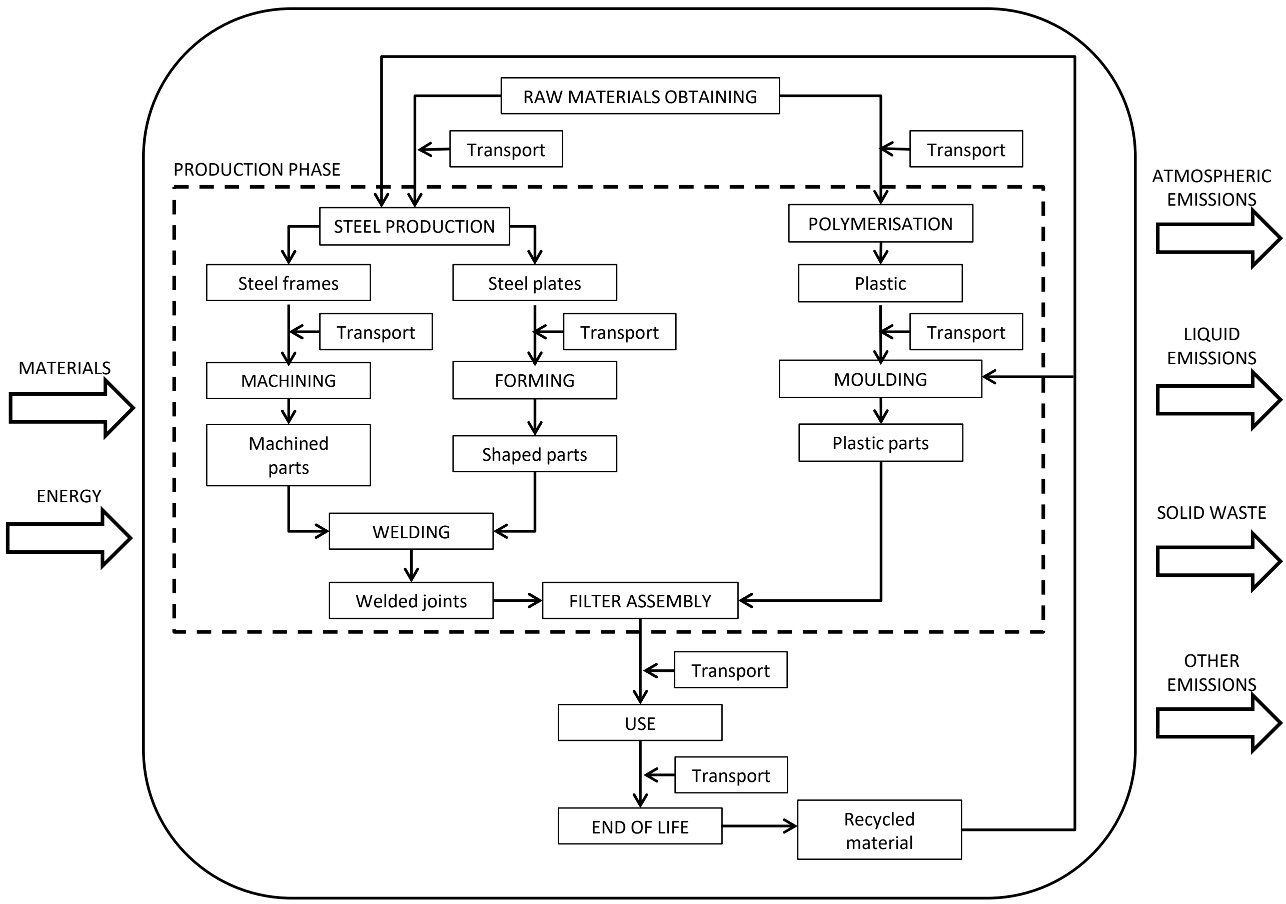


Fig. 2. Filter life cycle flow diagram.

Some elements of little expected importance were excluded from the study. This was the case for water and energy use in filter backwashing during the operational life of the filter. According to previous studies (Tajrishy, Hills, Tchobanoglous, 1994; Duran-Ros et al., 2009; Elbana, Ramírez de Cartagena, Puig-Bargués, 2012), the water volume used for filter backwashing using reclaimed effluents ranged from 1.14 to 5.7% of the volume of pumped effluent. When better water qualities are used, such as those considered in this study, water consumption for backwashing should be even lower. Despite the fact that the energy consumption for backwashing is higher than in normal filter operation, both water and energy consumed in backwashing were not taken into account due here to the small amount of water consumed and the lack of experimental data.

2.3. Life cycle inventory

For the assembly of an inventory, a system mass and energy balances were carried out for the inlet (consumption) and outlet (emissions), assuming that the process was located in Europe. Data related to the construction materials, which affect phases of raw material, production and waste/recycling, are summarised in the Table 1.

The global transportation at the end of life cycle was considered to be 1,000 km by truck. However, this value was the same for all of the alternatives, and the relative importance of transportation was not a critical parameter when comparing the different strategies.

Emissions during the use phase were calculated from the energy consumption (Eq 1), and the following equivalence factors between energy and emissions were considered: 0.188 kg equivalent CO_2 MJ^{-1}, $3.95 \cdot 10^{-4}$ kg equivalent SO_2 MJ^{-1} and $1.74 \cdot 10^{-8}$ kg equivalent PO_4 MJ^{-1} (EC, 2016).

Another input for the use phase was the mass of the sand media used for filtered volume. According to filter manufacturer's instructions (Elbana et al., 2012), sand media operating time was considered to be 1000 h. Taking into account the nominal flow, sand media replacement per filtered volume was calculated as 0.0088 kg of sand per m^3 of filtered water.

Other emissions, and the final destination of the materials at the end of their functional life, were estimated from EUROSTAT (2016) database, which showed that more than 90% of the materials were recycled. Environmental cost of sand waste is negligible because replaced sand can be used as filling material in the same farm without any associated environmental impact.

Table 1. Data related to the filter construction materials.

Parameter		Material		
		Steel	Polyethylene	NBR
Type of manufacture process		Shaping / machining	Moulding	Moulding
Recycled material content		15%	0%	0%
Material loss in the manufacture		10%	2%	5%
End of life (EUROSTAT, 2016)	Recycling	99.90%	93.00%	0.00%
	Waste	0.10%	7.00%	100.00%
Amount of material present in a filter (kg)	Alternative 0	75.50	0.74	0.22
	Alternative 1	64.48	5.90	0.47
	Alternative 2	52.80	4.05	0.35

2.4. Life Cycle Impact Assessment

The first step was the selection of the categories of environmental impact that should be considered. According to the goal of the present study, the main selected categories were related with energy and materials, which were most important differences between alternatives. Thus, energy and material consumption (expressed as MJ and kg, respectively) and global warming potential (expressed as kg of equivalent CO_2), which is linked to energy consumption, were selected. Two other categories that might have some effect such as atmospheric acidification potential (expressed as kg of equivalent SO_2) and freshwater eutrophication (expressed as kg of equivalent PO_4) were also chosen.

All of these impact categories were analysed for every phase of life cycle. The value of the aforementioned parameters for the raw material obtaining phase, fabrication phase and waste/recycling phase 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 with this method, which integrates raw material production, transformation processes, transport and waste/recycling. Both the CML model and GaBi database are integrated into the SolidWorks software. With this information, the characterisation of impacts was completed.

The results of the assessment can lead to a complex election of the best alternative because it is possible that an alternative shows a very good result for some parameters and worse for other ones.

In the present work, each impact category was weighed through its environmental costs, yielding a single value in monetary units for each alternative, which was the eco-cost. The eco-costs are the environmental costs related to the measures which have to be taken to fabricate and recycle a product in line with Earth's estimated carrying capacity. Van Harmelen et al. (2007) pointed out that it is an advantage to express preferences in monetary units because measures can then be prioritised in relation to production costs and other economic activities. The use of eco-costs makes the comparison explicit, although qualitative differences should be evaluated as well.

The calculation of the eco-cost of each impact (each one measured in different units) allowed its value to be measured in monetary units. The total eco-cost for every alternative was obtained by adding the eco-costs of the different impacts caused by the alternative, measured by their shadow prices. The shadow price gives the value that environmental quality has for the society and it is obtained from the valuation and comparison among many substitute goods made by many individuals (Zhang & Li, 2005). However, Vogtländer, Brezet and Heindricks (2001) pointed out that eco-costs of material depletion are set equal to the market value of the virgin materials when the materials are not recycled. So, for impacts with market price, such as materials and energy, these prices were used in the present study. For those parameters without market price, such as global warming, freshwater eutrophication and atmospheric acidification, damage-costs were used. For damage-costs, which are usually used for assigning values to externalities, environmental quality is computed on the basis of the estimated damage occurring as a result of emissions, and proceeds from people's willingness to pay for not damaging the environment (de Bruyn et al., 2010)

The eco-costs considered in this study are listed in Table 2. With these data, eco-costs for every alternative related to filtered volume were computed in order to make selection of the optimum alternative easier.

Table 2. Eco-costs for the impacts considered.

Parameter		Unit cost (€ $unit^{-1}$)
Energy consumption[1] (MJ)		0.025
Material consumption (kg)	Steel[2]	0.530
	Polyethylene[3]	0.620
	NBR[4]	1.620
	Silica sand[5]	0.155
Global warming[6] (kg CO_2 eq.)		0.025
Atmospheric acidification[6] (kg SO_2 eq.)		0.638
Freshwater eutrophication[6] (kg PO_4 eq.)		1.780

[1]EUROSTAT (2016), [2]SteelBenchmarker (2017), [3]Plasticker (2017), [4]IRSG (2017), [5]Sibelco (2017), [6]de Bruyn et al (2010).

2.5 Sensitivity analysis

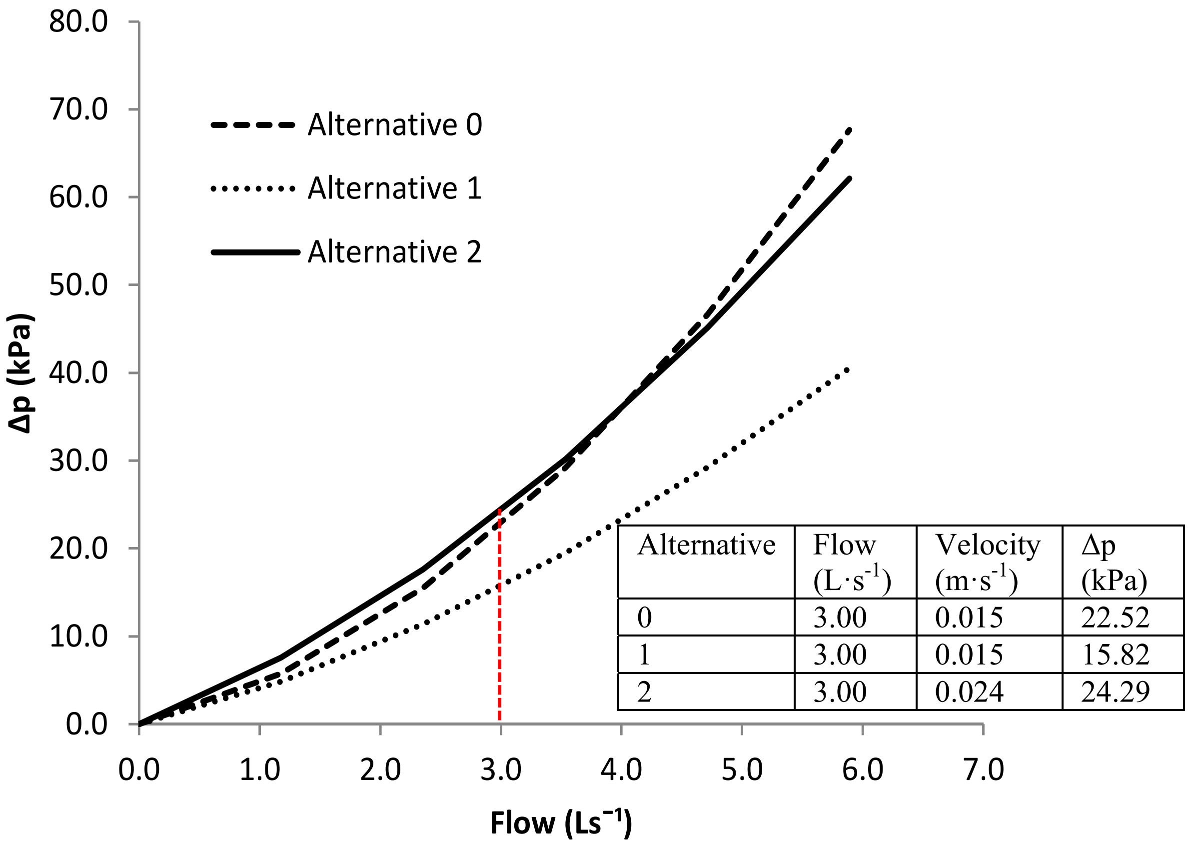
A sensitivity analysis was carried out by modifying the values of some model inputs in order to assess the robustness of the alternative election. As not enough empirical data were available, possible evolutions of the current situation in future scenarios were identified. There is a trend in some areas, such as Europe, for greenhouse gas emissions and fossil fuel consumption to be reduced and for recycling to be promoted (European Parliament and Council of the UE, 2013). On the other hand, as more extensive droughts are expected by climate change, a 0-20 % higher irrigation depth, and consequently irrigation time, was projected in the USA (Zhang, Lin, Rogers, Lamm, 2015). Similar trends could be expected in other many areas worldwide. Price increases of materials and energy are also likely. Variations in the amount of recycled material were not considered since the levels are for steel and polyethylene are already high (99.9 and 93.3%, respectively). For NBR, the recycled material rate was set at 0% because this rubber is not currently used in recycling facilities.

A percentage of variation with regard the present values was fixed for the aforementioned inputs. These variation percentages were intentionally high in order to make checking of the selected optimum easier. Thus, it was considered that global warming potential could be reduced by 5%, irrigation time could be increased by 10% and that material and energy costs could grow up to 10%. The different scenarios were all the possible combinations of these input variations, which meant that 16 different scenarios were analysed by computing their associated environmental costs.

3. Results and discussion

3.1. CFD modelling results

The pressure drops produced by the three different filter configurations at the different flowrates were calculated 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 (Fig. 3). Alternative 1 showed the lowest pressure drop for any water flow. Pressure losses for alternatives 0 and 2 were similar, but at lower flows alternative 0 had lower pressure loss but at higher flows it had higher. Comparisons between alternative designs were carried out at a flow of 3 $l\ s^{-1}$ because this is a common flowrate for commercial sand media filters with diameters similar to those used in this study. At this flow, pressure drops for alternatives 0 and 2 were similar (22.52 and 24.29 kPa, respectively), while that for alternative 1 was 30% lower (15.82 kPa).



Alternative	Flow ($L \cdot s^{-1}$)	Velocity ($m \cdot s^{-1}$)	Δp (kPa)
0	3.00	0.015	22.52
1	3.00	0.015	15.82
2	3.00	0.024	24.29

Fig. 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.

The pressure drop along the filter is shown in Fig. 4. Although alternatives 0 and 2 had similar values for total pressure drop, they showed different behaviour at the filter bed and underdrain element.

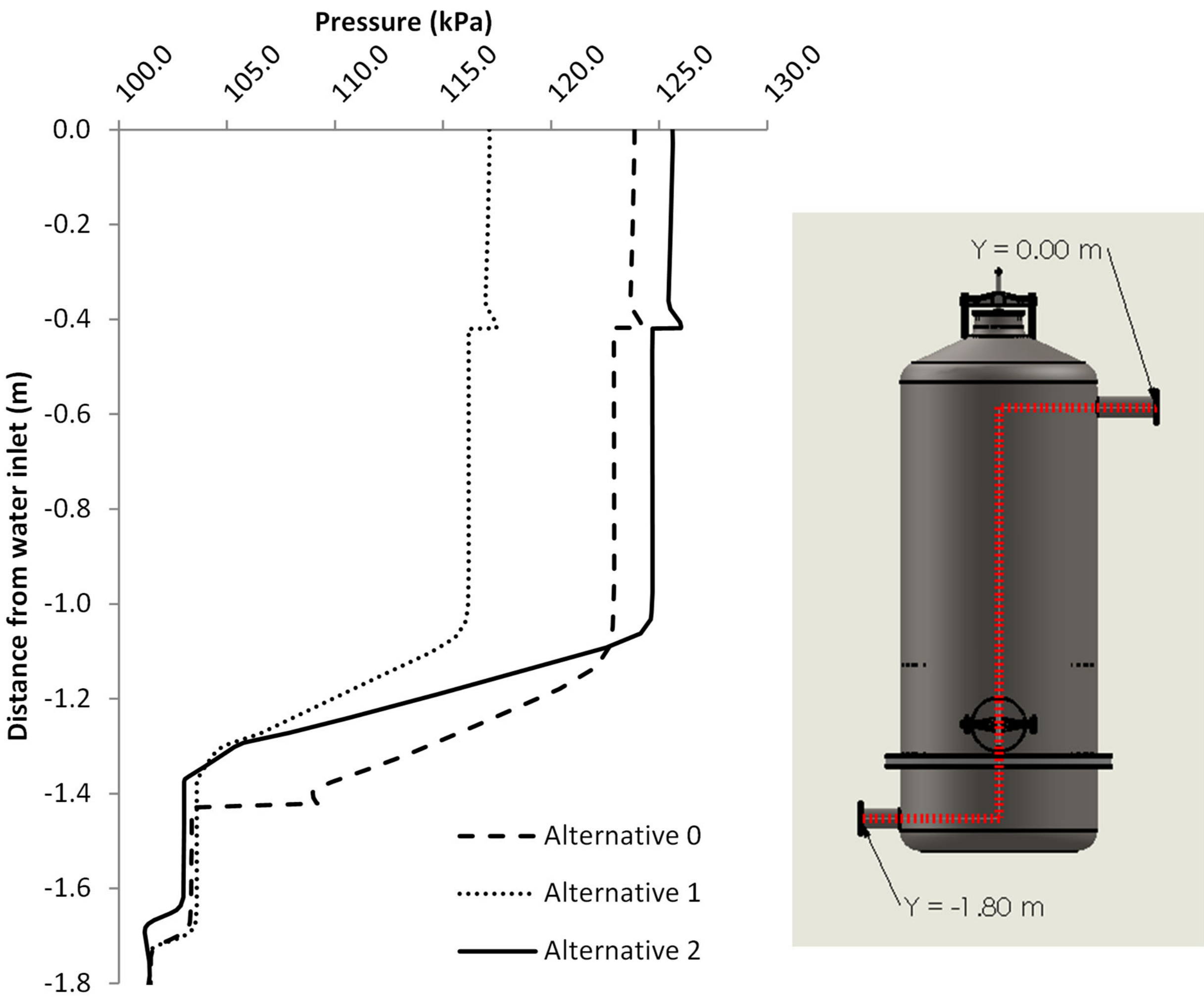


Fig. 4. Pressure evolution along the filter axis for all three alternatives under a water flowrate of 3.00 l s^{-1}.

3.2. Environmental impacts

Environmental impacts were classified into two groups (fixed and variable impacts), depending on their behaviour to changes in filtered water volume. Fixed environmental impacts for the different life cycle phases (except the use phase, which only causes variable impacts) are summarised in Table 3.

Table 3. Fixed environmental impacts (independents from filtered volume and referred to a filter unit).

		Energy consumption (MJ)	Material consumption (kg)	Global warming potential (kg CO_2 equivalent)	Atmospheric acidification potential (kg SO_2 equivalent)	Freshwater eutrophication potential (kg PO_4 equivalent)
Alternative 0	Raw material	2 343.5	72.3	172.3	4.41E-01	4.40E-02
	Production	329.4	0.0	18.3	7.83E-02	3.85E-03
	Transport	57.3	0.0	3.9	1.88E-02	4.12E-03
	Waste/recycling	264.0	0.0	19.4	1.21E-01	1.58E-02
	Total	**2 994.2**	**72.3**	**213.9**	**6.59E-01**	**6.78E-02**
Alternative 1	Raw material	2 442.9	67.4	159.6	4.03E-01	4.01E-02
	Production	400.0	0.0	21.7	1.08E-01	4.72E-03
	Transport	53.6	0.0	3.6	1.77E-02	3.81E-03
	Waste/recycling	222.6	0.0	17.9	1.06E-01	1.51E-02
	Total	**3 119.1**	**67.4**	**202.8**	**6.35E-01**	**6.37E-02**
Alternative 2	Raw material	1 929.3	54.4	132.4	3.35E-01	3.34E-02
	Production	319.3	0.0	17.2	8.37E-02	3.70E-03
	Transport	44.6	0.0	3.0	1.46E-02	3.11E-03
	Waste/recycling	174.1	0.0	12.9	8.09E-02	1.09E-02
	Total	**2 467.3**	**54.4**	**165.5**	**5.14E-01**	**5.11E-02**

Except for eutrophication potential where the waste/recycling phase was more important than construction, the terms were sorted in order of importance as follows: raw material, production, waste/recycling and transport.

Obtaining raw material was the most important phase concerning environmental effects because the filter was essentially constructed using steel, and steel production is an expensive process in terms of energy consumption. In alternative 0, which is the one that used the most material, the energy consumption associated with construction is less than alternative 1 (where material consumption was reduced by 7%). The reason why alternative 0 consumed less energy than alternative 1 is because the geometry of the second alternative was more complex, yielding that the reduction of material construction had no positive effect on the energy consumption. However, the rest of environmental effects associated with the material consumption were bigger in alternative 0. Alternative 2 showed the best results for each of the fixed impacts that were analysed.

However, variable impacts, which are related to use phase, were computed using pressure losses obtained from modelling (22.50, 15.82 and 24.29 kPa for alternatives 0, 1 and 2, respectively). Taken into account the head loss, it was possible to compute energy consumption per m^3 filtered and to transform this consumption into impacts, as it is shown in Table 4. For calculating variable impacts, sand consumption was also included.

Table 4. Environmental impacts due to filter use (per filtered water m^3).

Design	Energy consumption ($MJ\ m^{-3}$)	Material consumption (silica sand) ($kg\ m^{-3}$)	Global warming potential (kg [CO_2 equivalent] m^{-3})	Atmospheric acidification potential (kg [SO_2 equivalent] m^{-3})	Freshwater eutrophication potential (kg [PO_4 equivalent] m^{-3})
Alternative 0	3.46E-02	8.80E-03	6.50E-03	1.37E-05	6.03E-10
Alternative 1	2.43E-02	8.80E-03	4.60E-03	9.61E-06	4.23E-10
Alternative 2	3.74E-02	8.80E-03	7.00E-03	1.48E-05	6.50E-10

Alternative 1 was the option that showed a better improvement on all the impacts, except for sand consumption that was fixed at the same value for the different alternatives. It was considered that the operation life of sand media was dependent on the filtered volume. Thus, the smallest filter, which had the least sand mass, required more frequent sand replacement but, as the filtered volume considered was the same for the three alternatives, total sand consumption did not vary between alternatives. Conversely, alternative 2 worsened slightly the impacts of alternative 0.

3.3. Environmental costs

Table 5 shows the environmental costs of the three alternatives. Fixed eco-costs were mainly due to energy and material consumption, respectively, followed by global warming potential, with smaller values. Fixed eco-costs for alternative 1 had 0.8% increase regarding alternative 0, while alternative 2 meant 19.7% decrease. It is interesting to comment that the atmospheric acidification and freshwater eutrophication only represented, on average, 0.34% and 0.09% of the environmental associated fixed costs, respectively. This means that the most important parameters in the life cycle of the filters are energy consumption, materials consumption, and, to a lesser extent, global warming potential.

Table 5. Environmental costs of the different alternatives.

Alternative	Type of eco-costs	Energy consumption	Material consumption	Global warming potential	Atmospheric acidification potential	Freshwater eutrophication potential	**Total**
0	Fixed (€ filter^{-1})	74.26	38.64	5.35	0.42	0.12	**118.78**
	Variable (€ m^{-3})	8.58E-04	1.36E-03	1.63E-04	8.74E-06	1.07E-09	**2.39E-03**
1	Fixed (€ filter^{-1})	77.35	36.81	5.07	0.40	0.11	**119.75**
	Variable (€ m^{-3})	6.03E-04	1.36E-03	1.15E-04	6.13E-06	7.53E-10	**2.09E-03**
2	Fixed (€ filter^{-1})	61.19	29.59	4.14	0.33	0.09	**95.33**
	Variable (€ m^{-3})	9.28E-04	1.36E-03	1.75E-04	9.44E-06	1.16E-09	**2.48E-03**

If variable eco-costs are analysed, atmospheric acidification and freshwater eutrophication are the impacts that caused smaller eco-costs, but, in this case, the relative importance of global warming potential increased regarding fixed eco-costs. Alternative 1 reduced variable eco-costs by 12.81% but alternative 2 increased them by 3.45% regarding those from alternative 0. Summarising, the lowest fixed environmental costs were achieved by alternative 2 but the eco-costs linked with operation (variable eco-costs) were the least with alternative 1. Thus, total eco-costs (obtained by summing fixed and variable eco-costs) referred to the functional unit varied depending on the volume of water filtered, as it is shown in Fig. 5.

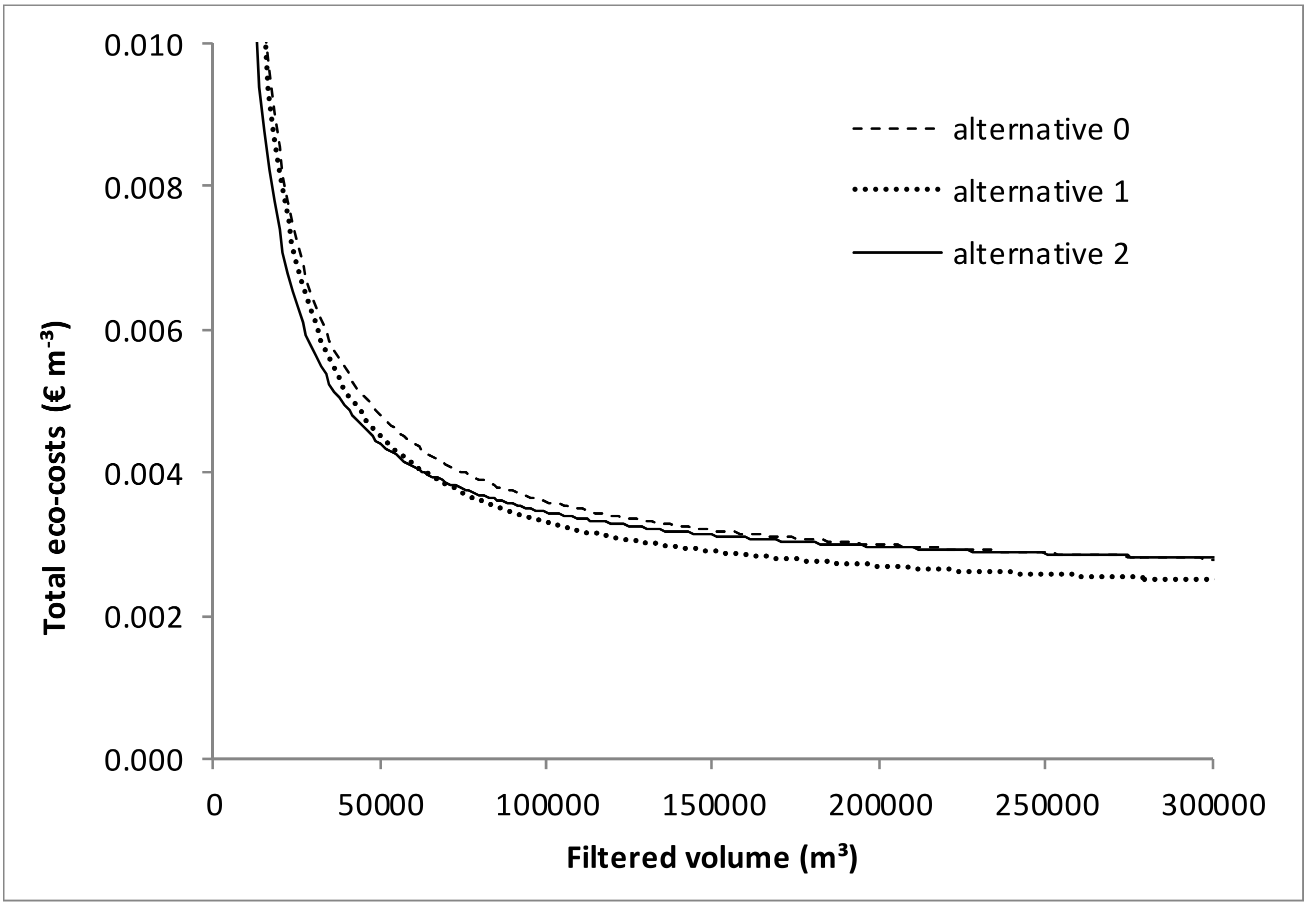


Fig. 5. Total environmental costs related to water filtered volume.

The optimum alternative depended on the volume filtered throughout the filter's life. Both alternatives 1 and 2 improved the environmental costs of the commercial filter. The cross-over point between alternatives 1 and 2 was set to 63,000 m³, which would be reached after 5,869 h of filter operation, at a nominal flow of 3 l s^{-1}. If a 15 years of filter life is assumed, that means that less than 4,200 m^3 of water is filtered annually or that annual irrigation time is 390 h. Most of irrigation facilities in Southern Europe for medium and large farms are above these values and, so, alternative 1 would be the most suitable for these cases.

According to Diotto, Folegatti, Duarte, and Romanelli (2014), the impact of filters in the global energy embodied in the irrigation networks is low, which reduces the importance of the energy consumed during the filtration stage. Following the same authors, the energy impact of the sand filters is 75% higher than screen filters, which are also commonly used in microirrigation systems. However, it should be pointed out that sand filters are often used when the water source is of low quality, such as the case of reclaimed or superficial water, because they guarantee the best emitter performance (Capra & Scicolone, 2007; Duran-Ros et al., 2009), extend the operational life of microirrigation systems and, therefore, increase its sustainability.

Our results confirm that materials used in the irrigation systems are crucial for achieving an optimised irrigation system from an environmental point of view, as Diotto et al. (2014) and Romero-Gámez et al. (2014) pointed out. Development of irrigation equipment built using environmental friendly materials is a research topic of great interest. An example is the work of Serrano et al. (2014), who considered the possibility of improving a water pump using recycled fibres from old newspaper instead of glass-fibres as polypropylene reinforcement.

3.4. Sensitivity analysis

Although eco-costs for 16 different scenarios were computed, only the following 5 highest impact scenarios will be discussed: a scenario with variation on all inputs, a scenario that was more favourable to alternative 1 (more energy consumption and costs), a scenario that was most favourable to alternative 2 (higher material costs), a combination that yielded the highest cost and a combination that produced the lowest cost. The results shown in Table 6 are the eco-costs for the aforementioned scenarios throughout filter life for 3 different filtration volumes: one close to the cross-over point (Fig. 5) and the half and the double of this point.

Table 6. Eco-costs for the whole filter life under different scenarios.

Scenario	Global warming potential reduction (%)	Irrigation time increase (%)	Material cost increase (%)	Energy cost increase (%)	Alternative	Eco-costs (€)		
						Low volume (32,000 m^3)	Medium volume (64,000 m^3)	High volume (128,000 m^3)
0	0	0	0	0	0	195.37	271.95	425.12
					1	186.56	**253.37**	**386.99**
					2	**174.56**	253.80	412.26
1	-5	+10	+10	+10	0	221.58	313.36	496.92
					1	211.12	**291.33**	**451.75**
					2	**199.12**	294.03	483.85
2	-5	+10	0	+10	0	212.92	299.90	473.86
					1	202.64	**278.05**	**428.87**
					2	**191.36**	281.47	461.69
3	-5	0	+10	0	0	203.07	283.76	445.14
					1	194.17	265.16	**407.14**
					2	**181.40**	**264.72**	431.35
4	0	+10	+10	+10	0	222.14	314.20	498.34
					1	211.58	**291.99**	**452.82**
					2	**199.63**	294.85	485.29
5	-5	0	0	0	0	194.84	271.16	423.82
					1	186.12	**252.75**	**386.00**
					2	**174.08**	253.03	410.93

The lowest eco-cost for each scenario, alternative and volume are presented in bold.

Scenario 0 is the case without changes and it is included in Table 6 for comparison. As could be anticipated, alternatives 1 and 2 are the most suitable for high and low filtration volumes, respectively, under all the scenarios shown in Table 6. The most interesting cases are those at medium volumes, which are close to the cross-over point and that will be discussed from now on. Scenario 1 shows the case where all the inputs parameters were changed. Under this scenario for medium volumes, alternative 1 was still the optimum alternative reaching a 7.03% reduction of eco-costs regarding the current design (alternative 0), while alternative 2 reduced the environmental costs by 6.17%.

Scenario 2 theoretically should favour alternative 1 because the prices of raw materials – which are the weakest point of this alternative - were set constant but energy cost – which is its strongest point- increased. Although alternative 1 was the best alternative, there were no important differences regarding alternative 2. The reduced environmental cost for this alternative versus alternative 0 (7.28%) was lower than that achieved by alternative 2 (6.14%).

Scenario 3 gave better performance than alternative 2, which reduced environmental costs compared to alternative 0 by 6.7%. Under scenario 4 (higher irrigation time and material and energy costs) there was an overall increase of environmental costs by 15.6%, with alternative 1 having the lowest value. On the other hand, environmental costs regarding the current situation were reduced in scenario 5 (lower warming potential) by on average 0.30%.

When the values of the different inputs were changed, the associated environmental costs for each alternative also varied, but alternative 2 always reached the minimum associated with low water volumes and alternative 1 for high volumes. Thus, for commercial irrigation, with high water use, alternative 1 shows the best environmental performance.

Under all the scenarios considered in this study, alternative 2 had the lowest eco-cost for water volumes throughout filter life less than 56,000 m^3 while alternative 1 was the best for volumes above 65,000 m^3. Although important variations regarding the current situation were considered in the different scenarios, only the alternative selected changed within the range 56,000 to 65,000 m^3, which gives an idea of the robustness of the results. In any scenario, both new design alternatives improved the environmental impact of the present commercial sand filter design.

4. Conclusions

A change in sand filter underdrain design, that reduced the overall pressure drop across the filter, allowed for the development of two strategies to improve the environmental behaviour of this type of filter which is widely used in microirrigation. The first possible strategy was to reduce the energy consumption during the functional life of the filter, whilst the second was to reduce material and energy consumption during its manufacture.

The life cycle assessment of both improvement alternatives showed a reduction in terms of environmental impact with respect to the original commercial design. Specifically, alternative 1 had 31% pressure drop reduction, 0.82% fixed eco-costs increase, and 12.77% variable eco-costs per filtered volume decrease. Alternative 2 needed 25% less construction material and had the same pressure drop as the commercial filter, but the fixed eco-costs were diminished by 19.74%, and the variable eco-costs per filtered volume were increased by 3.45%. The volume of filtered water throughout the life of the filter was the key for the selection of the optimum design alternative. For volumes higher than 63,000 m^3, that is intensive irrigation water consumption, alternative 1 had the lowest total eco-costs.

The LCA carried out confirmed that the energy saving during the utilisation phase with the new design of the drainage allow reducing the environmental impact of sand filters for microirrigation systems. However, the LCA also highlighted the importance of reducing the amount of materials used for filter construction. Further research should be carried out studying alternative designs to achieve lower pressure drop across sand filters and also to take into account other construction materials that were not considered in this study.

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