Journal of Cleaner Production 137 (2016) 997–1003

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles

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ARTICLE INFO

Article history:
Received 3 March 2016
Received in revised form
26 July 2016
Accepted 31 July 2016
Available online 2 August 2016

Keywords:
Drinking water
Glass bottle
Life cycle assessment
Mineral water
Plastic bottle
Reverse osmosis

ABSTRACT

This study evaluated the environmental impacts caused by drinking water consumption in Barcelona (Spain) using the Life Cycle Assessment (LCA) methodology. Five different scenarios were compared: 1) tap water from conventional drinking water treatment; 2) tap water from conventional drinking water treatment with reverse osmosis at the water treatment plant; 3) tap water from conventional drinking water treatment with domestic reverse osmosis; 4) mineral water in plastic bottles, and 5) mineral water in glass bottles. The functional unit was 1 m^3 of water. The water treatment plant considered in scenarios 1, 2 and 3, treats around 5 $m^3\ s^{-1}$ of surface water. The water bottling plants considered in scenarios 4 and 5 have a production capacity of 200 m^3 of bottled water per day. The LCA was performed with the software *SimaPro*®, using the CML 2 baseline method. The results showed how tap water consumption was the most favourable alternative, while bottled water presented the worst results due to the higher raw materials and energy inputs required for bottles manufacturing, especially in the case of glass bottles. The impacts generated by domestic reverse osmosis were between 10 and 24% higher than tap water alternative depending on the impact category. It was due to the higher electricity consumption. Reverse osmosis at the water treatment plant showed impacts nearly twice as high as domestic reverse osmosis systems scenario, mainly because of the higher energy inputs. Water treated by domestic reverse osmosis equipment was the most environmentally friendly solution for the improvement of tap water organoleptic characteristics. An economic analysis showed that this solution was between 8 and 19 times cheaper than bottled water.

1. Introduction

Drinking water is essential to sustain life, and an adequate, safe and accessible supply must be available to all. Improving drinking water quality is a major concern worldwide in order to protect human health (WHO, 2004). During the last decades, water quality regulation has become more stringent and the general public has become more knowledgeable and also more discriminating about drinking water quality (Crittenden et al., 2005). The European Directive 98/83/CE on the quality of drinking water, defines water for human consumption as "all water either in its original state or after treatment, intended for drinking, cooking, food preparation or other domestic purposes, regardless of its origin and whether it is supplied from a distribution network, from a tanker, or in bottles or containers" (European Commission, 1998). This Directive sets quality standards for drinking water quality, including microbiological, chemical and organoleptic parameters. In order to meet specified goals and standards set by the regulation, water must be treated and/or processed. However, even if tap water meets the standards set by the regulation, during the last decades an increasing tendency to replace tap water by bottled water has been observed in most European countries (Doria, 2006). Such an increasing consumption of bottled water has been attributed to two main factors affecting consumers' preferences: (i) dissatisfaction with tap water organoleptic characteristics (especially taste), and

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http://dx.doi.org/10.1016/j.jclepro.2016.07.218
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(ii) health risk concerns (Doria et al., 2009).

Conventional water treatment includes coagulation and flocculation, sedimentation, filtration, adsorption and disinfection. These are physical-chemical processes which remove turbidity, organic matter and pathogens (Crittenden et al., 2005). In addition, reverse osmosis may be applied to separate dissolved solutes from water by means of membranes, and improve the water quality. Thanks to technological advances reverse osmosis is also available at domestic level, where it is mainly used to treat water for drinking and cooking. Domestic reverse osmosis improves water quality and organoleptic characteristics, and therefore it can enhance consumers' confidence in tap water. Furthermore, it can help reducing environmental impacts associated with bottled water consumption.

The bottled water industry is generally proclaimed as having negative environmental impacts, as an excess of energy and resources are used in the process of bottles manufacturing. For a long time, bottled water was only available in glass containers; but nowadays polyethylene terephthalate (PET) is widely used for packaging. Thus, the most important impacts are attributed to the production of bottles, transport and disposal of solid waste resulting from packaging (Lagioia et al., 2012; McRandle, 2004; Papong et al., 2014).

Previous studies, which compared the environmental impacts of tap water and bottled water, pointed out that tap water from conventional drinking water treatment always had the best environmental performance, even in case of high energy-consuming technologies for drinking water treatment (e.g. reverse osmosis) (Fantin et al., 2014; Lagioia et al., 2012; Nessi et al., 2012). To the best of our knowledge, there are no studies which compare reverse osmosis at the treatment plant with domestic reverse osmosis and also with conventional water treatment and bottled mineral water.

The aim of this study is to compare the environmental impacts and costs associated with different drinking water consumption alternatives. To this end, a Life Cycle Assessment (LCA) was carried out considering the following scenarios: 1) tap water from conventional drinking water treatment; 2) tap water from conventional drinking water treatment with reverse osmosis at the treatment plant; 3) tap water from conventional drinking water treatment with domestic reverse osmosis. Also, mineral water in PET bottles (scenario 4) and mineral water in glass bottles (scenario 5) were taken into account, since they are widely used by consumers.

2. Material and methods

LCA is a systematic method for identifying, quantifying, and assessing environmental aspects and potential impacts through the whole life cycle of a product, process or activity (ISO, 2006). It includes energy and material uses and releases to the environment from cradle to grave (e.g. raw materials extraction, production, use and final disposal). LCA basically comprises mass and energy balances applied to the studied system, plus an assessment of potential environmental impacts related to the inputs and outputs. Therefore, it helps to identify “hot spots” of potential environmental impacts and to establish baselines for improvement in further research. According to the ISO 14040, there are four main stages in an LCA: i) goal and scope definition, ii) inventory analysis, iii) impacts assessment and iv) interpretation of the results (ISO, 2006). The present study includes the mandatory phases of impacts assessment (classification and characterisation) as defined by this standard (ISO, 2006).

2.1. Goal and scope definition

The aim of this study is to compare the potential environmental impacts associated with five drinking water consumption alternatives:

1) tap water from conventional drinking water treatment;
2) tap water from conventional drinking water treatment with reverse osmosis at the treatment plant;
3) tap water from conventional drinking water treatment with domestic reverse osmosis;
4) mineral water in PET bottles;
5) mineral water in glass bottles.

The functional unit is 1 m^3 of water.

2.1.1. System boundaries

The system boundaries were as follows:

a) Input and output flows of material (mainly chemicals) and energy resources (electricity) were studied in depth for all scenarios.
b) In the conventional water treatment, transport and distribution of water and sludge were excluded from the model, since their contribution only represents a minor fraction of the overall impact (Lemos et al., 2013; Loubet et al., 2014; Lundie et al., 2004).
c) In the case of domestic reverse osmosis, the electricity needed for regulating the pump pressure was taken into account but reject water was not considered, since it can be reused (i.e. for toilet flushing). Also, carbon filters replacement was not taken into account. Their contribution to the overall impact can be neglected, since they are made of an environmentally friendly material (i.e. coconut shell) (Bhatnagar et al., 2010; Vanderheyden and Aerts, 2014).
d) Regarding the bottled water alternatives, mineral water uptake (by pumping), raw materials and energy consumption for bottles manufacturing (PET and glass) were considered. Bottled water distribution was not taken into account, since local transportation accounts for a minor contribution to the overall environmental impact (Pasqualino et al., 2011).
e) The system boundaries excluded the phases of construction, maintenance and decommissioning of the facilities as well as the disposal of reverse osmosis equipment. Indeed, these phases only account for minor environmental impacts (Bonton et al., 2012; Igos et al., 2014).

2.2. Inventory analysis

Inventory data on systems design and operation referred to the functional unit (1 m^3 of water) are shown in Tables 1 and 2 for each scenario.

Scenario 1 included conventional surface water treatment, composed of the following processes: coagulation, flocculation, sedimentation, filtration (in sand filters), adsorption (in activated carbon filters) and disinfection (by ozone and chlorine). Inventory data (annual average values) was provided by a water treatment plant located in Sant Joan Despí (Barcelona), which treats around 5 $m^3 s^{-1}$ of surface water from Llobregat river and supplies drinking water to the Barcelona Metropolitan Area.

Scenario 2 included the same surface water treatment processes as Scenario 1, plus reverse osmosis and remineralization (through a calcite bed) in the water treatment plant. Inventory data (annual average values) was also obtained from the water treatment plant in Sant Joan Despí (Barcelona).

Scenario 3 included the same surface water treatment processes as Scenario 1, plus domestic reverse osmosis. Inventory data (annual average values) on the operation of domestic reverse osmosis equipment was supplied by two specialised companies

Table 1
Summary of drinking water consumption inventory for scenarios 1, 2 and 3. Values are referred to the functional unit (1 m^3 of water).

	Stages	Elements	Unit	Amount		
				Scenario 1	Scenario 2	Scenario 3
Inputs	Water treatment (at plant)	Electricity	kWh m^{-3}	0.48	0.48	0.48
		Coagulant (aluminum sulfate)	kg m^{-3}	2.90E-02	2.90E-02	2.90E-02
		Activated carbon replacement	kg m^{-3}	1.30E-03	1.30E-03	1.30E-03
		Chlorine	kg m^{-3}	7.00E-03	7.00E-03	7.00E-03
		Ozone	kg m^{-3}	4.80E-03	4.80E-03	4.80E-03
	Reverse osmosis	Electricity for reverse osmosis	kWh m^{-3}	–	1.07	0.15
		$CaCO_3$ for remineralization	kg m^{-3}	–	0.12	–
Outputs	Waste	Sludge	kg m^{-3}	4.70E-02	4.70E-02	4.70E-02
		Activated carbon	kg m^{-3}	2.40E-02	2.40E-02	2.40E-02
		Reverse osmosis reject	L m^{-3}	–	100 (10%)	350 (35%)

Scenarios: (1) tap water from conventional drinking water treatment; (2) tap water from conventional drinking water treatment with reverse osmosis at the treatment plant; (3) tap water from conventional drinking water treatment with domestic reverse osmosis.

Table 2
Summary of drinking water consumption inventory for scenarios 4 and 5. Values are referred to the functional unit (1 m^3 of water).

	Stages	Elements	Unit	Amount	
				Scenario 4	Scenario 5
Inputs	Water production	Electricity	kWh m^{-3}	12	12
		Plastic bottle (PET)	kg m^{-3}	20	–
		Glass bottle	kg m^{-3}	–	125
		Plastic caps (LDPE)	kg m^{-3}	1	2.35
		Paper labels	kg m^{-3}	0.94	0.83
		Glue	kg m^{-3}	0.07	0.10
		Plastic packaging (PE)	kg m^{-3}	2.91	–
		Water for cleaning	L m^{-3}	–	37.50
		Caustic soda for cleaning	kg m^{-3}	–	7.50
Outputs	Waste	PET (recycling)	kg m^{-3}	10.60	–
		PET (landfilling)	kg m^{-3}	10	–
		Glass (reuse)	kg m^{-3}	–	125

Scenarios: (4) mineral water in PET bottles; (5) mineral water in glass bottles.

located in Barcelona.

Scenarios 4 and 5 included water packaging, and PET or glass bottles manufacturing, respectively. The water bottling plants are located close to the city (<100 km) and have a production capacity of 200 m^3 of mineral water per day. The same energy consumption was considered in both scenarios, according to Lagioia et al. (2012). A recycling rate of 50% of PET bottles was considered. It was assumed that glass bottles would be reused 8 times, and a caustic soda consumption of 7.5 kg/m^3 for bottles cleaning, according to Cutrín (2012).

All environmental data regarding inputs and emissions of each different material and waste analysed were obtained from *Ecoinvent 2* databases (Ecoinvent, 2010). For all electricity requirements the Spanish electricity mix was used. It is as follows: coal 19.30%; natural gas 24.10%; hydro 7.70%, nuclear 22.10%, photovoltaic 2.90%, wind 18.10%, liquid fuels 2.70%, solar 1.30% and solid biomass 1.80%.

2.3. Impact assessment

Potential environmental impacts were evaluated using the software *SimaPro*® (Pré Consultants, 2009) and the CML 2 baseline method. This analytical tool is in accordance with ISO 14040 standards (ISO 14042, 2000). The following impact categories were evaluated: Abiotic Depletion, Acidification, Eutrophication, Global Warming Potential, Ozone Layer Depletion and Photochemical Oxidation.

2.4. Sensitivity analysis

A sensitivity analysis was carried out by modifying the most relevant assumptions of the drinking water alternatives and comparing the environmental impacts with those of the base case scenario. For this purpose, selected parameters were changed into plausible ranges of variation to check the robustness of LCA results. Three parameters were evaluated: i) energy consumption in scenario 5; ii) plastic bottles recycling rate in scenario 4; and iii) energy consumption in scenario 3. In the first case, three alternatives of energy consumption were considered: 10 (lower than the base case – 12 kWh/m^3), 20 and 30 kWh/m^3. Regarding the recycling rate, three alternatives were considered: 25 (lower than the base case – 50%), 75 and 100% of plastic recycling. With regards to the energy consumption of domestic reverse osmosis equipment (29 W in the base case, which means 0.15 kWh/m^3), three alternatives were considered (50, 100 and 200 W, which corresponded to 0.26, 0.52 and 1.04 kWh/m^3) according to the data provided by two local manufacturers.

2.5. Economic assessment

A cost analysis was carried out for each drinking water alternative, considering the cost of water from the consumers' point of view.

In scenario 1, the cost of tap water (including fees) supplied by the Municipal Water Agency in Barcelona was considered.

In scenario 2, the cost was estimated from conventional water treatment and desalination plants in the Mediterranean region (Salcedo et al., 2012; Triki et al., 2014).

In scenario 3, the cost of tap water (including fees), amortization of domestic reverse osmosis equipment, annual replacement of filters (activated carbon) and membranes were taken into account. A lifespan of 10 years and, a water consumption of 12 L/day for drinking and cooking in a family of four members were assumed.

All data needed were provided by local companies.

In scenarios 4 and 5, mean bottled water prices in supermarkets in Barcelona were considered, namely 0.40 € for plastic bottles of 1.5 L and 0.60 € for glass bottles of 1 L.

3. Results and discussion

3.1. Life cycle assessment

Environmental impacts associated with each water consumption alternative are summarised in Fig. 1.

Tap water consumption from conventional water treatment (scenario 1) appeared as the most favourable alternative in all impact categories analysed, while mineral water in PET and glass bottles presented the most negative results (Fig. 1). Indeed, the impacts of tap water with or without reverse osmosis (scenarios 1 through 3) were between 10 and 717 times lower than those of bottled mineral water (scenarios 4 and 5) for the considered impacts categories (Fig. 1). This was attributed to the high input of materials and energy of bottled mineral water as compared to tap water (Tables 1 and 2). Similar results were found by Lagioia et al. (2012), who analysed the key environmental issues related to the Italian drinking water supply system. The results obtained highlighted that bottled water (either in PET or glass bottles) required much more materials (130 and 154 kg/m^3 of water in PET and glass bottles, respectively) and energy (1000 and 4900 MJ/m^3 of water in PET and glass bottles, respectively) than tap water, which had average materials and energy inputs around 0.5–1.3 kg/m^3 and 2–3 MJ/m^3 of water, respectively. Raw materials required for bottles manufacturing accounted for the major impact of bottled mineral water (around 90% of the impact in all indicators), while energy consumption accounted for 5–10% of the impact in all indicators, which is in accordance with previous studies (Papong et al., 2014).

As shown in Fig. 1, the environmental impacts of mineral water in glass bottles (scenario 5) were higher than in PET bottles (scenario 4) for all the categories analysed, with the exception of Global Warming and Photochemical Oxidation Potentials. As far as Abiotic Depletion, Acidification, Eutrophication and Ozone Layer Depletion Potentials are concerned, the higher impact of glass bottles versus PET bottles was due to the amount of packaging material needed per cubic meter of water (125 and 20 kg/m^3 of water in glass and PET bottles, respectively), which is in accordance with Lagioia et al. (2012). In regards to Global Warming and Photochemical Oxidation Potentials, the higher impact of PET bottles as compared to glass bottles was due to CO_2, oxides of sulphur and nitrogen emissions during PET production. Taking into account the high contribution of bottle materials, recycling of PET and reuse of glass bottles would reduce the overall impact by some 30% in both scenarios (Fig. 1). Previous studies suggested that the use of biopolymers such as polylactic acids (PLA) could also reduce the impact generated by bottles production (Lagioia et al., 2012; Papong et al., 2014). However, due to the experimental nature of biopolymers, the debate on the effective environmental convenience of PLA production is still open, considering its limited use and the difficulty of recycling and disposal (Lagioia et al., 2012; Nessi et al., 2012).

The major impact of tap water from conventional water treatment (scenario 1) was due to electricity consumption (around 80% of the total impact in all indicators) and the use of coagulants (between 5 and 10% of the total impact in all indicators). It was in accordance with previous studies, which analysed the environmental impacts of drinking water production by conventional treatment in different countries (Amores et al., 2013; Barrios et al., 2008; Bonton et al., 2012; Lemos et al., 2013; Loubet et al., 2014; Vince et al., 2008). These authors agreed that critical aspects in water treatment processes were the use of chemicals for coagulation-flocculation, softening and disinfection, as well as energy consumption and activated carbon production and regeneration.

The scenarios which included reverses osmosis (2 and 3) showed higher impacts than the conventional water treatment, especially in the case of reverse osmosis at the water treatment plant (scenario 2) (Fig. 1). The impacts generated by domestic reverse osmosis (scenario 3) were about 10–24% higher than in scenario 1 in all environmental indicators, due to electricity consumption by domestic reverse osmosis equipment (Fig. 1). When reverse osmosis was applied at the treatment plant, energy consumption accounted for 95% of the total impact in all indicators. This is in accordance with previous studies which analysed the environmental impacts of water treated by reverse osmosis, ultrafiltration and nanofiltration (Bonton et al., 2012; Mohapatra et al., 2002; Vince et al., 2008). Indeed, reverses osmosis requires a large amount of energy for water filtration through the membranes (Bonton et al., 2012). Therefore, improving the energy efficiency of reverse osmosis processes is a major challenge for the reduction of its environmental impacts (Qiu and Davies, 2012). Reverse osmosis at the treatment plant (scenario 2) showed impacts nearly twice those of domestic reverse osmosis (scenario 3) because of the higher energy consumption (Table 1). Indeed, in scenario 2 membranes treat high water flows; they work with higher pressures and require more energy per cubic meter of water compared to domestic reverse osmosis equipment which only treats water used for drinking or cooking.

On the whole, the most environmentally friendly solution is conventional water treatment, followed by reverse osmosis, particularly at domestic level. Mineral water causes the highest impact, especially in the case of using glass bottles, even if they are reused.

However, if we take into account organoleptic characteristics of drinking water, the worst scenario is 1 (conventional water treatment). Mineral water is generally more pleasing in organoleptic terms than tap water because it does not undergo disinfection treatments. Indeed, chlorination causes the formation of byproducts that give water an unpleasant taste (De Giglio et al., 2015). However, it has been demonstrated that reverse osmosis can improve considerably the organoleptic characteristics of tap water (Devesa et al., 2007).

3.2. Sensitivity analysis

Table 3 shows the results of the sensitivity analysis. It considered 3 parameters: i) energy consumption in scenario 5; ii) plastic bottles recycling rate in scenario 4; and iii) energy consumption in scenario 3.

Concerning the energy consumption of mineral water in glass bottles (scenario 5), the results showed how increasing the energy consumption to 30 kWh/m^3 would increase all environmental indicators by 1–37%, depending on the impact category. Conversely, decreasing the energy consumption to 10 kWh/m^3 would reduce potential environmental impacts by 4% as compared to the base case (12 kWh/m^3). In both cases, potential environmental impacts caused by mineral water in glass bottles remained higher than in PET bottles, except for the Global Warming and Photochemical Oxidation Potentials, the same as for the base case.

Regarding the plastic bottles recycling rate in scenario 4, the results showed how by increasing the percentage of bottles recycled, all potential environmental impacts were reduced from 5 to 230% for 75 and 100% of recycling as compared to the base case (50%). It was mainly due to energy and raw materials savings for PET production. On the opposite side, when the recycling rate was

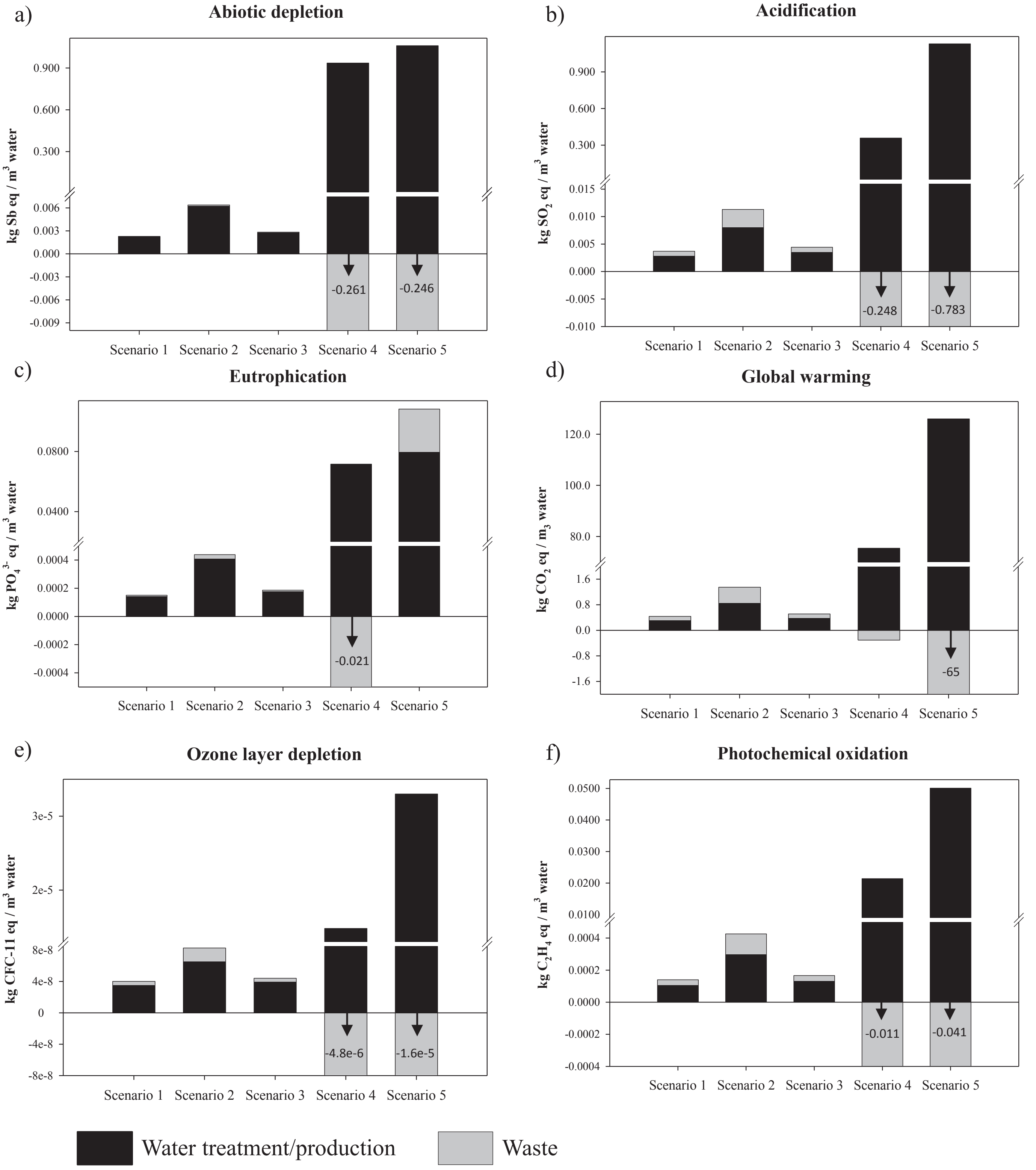

Fig. 1. Potential environmental impacts for the five drinking water alternatives. Values are referred to the functional unit (1 m^3 of water). Scenarios: (1) tap water from conventional drinking water treatment; (2) tap water from conventional drinking water treatment with reverse osmosis at the treatment plant; (3) tap water from conventional drinking water treatment with domestic reverse osmosis; (4) mineral water in PET bottles; (5) mineral water in glass bottles.

reduced to 25% all potential environmental impacts increased by 54% as compared to the base case (50%). Again, potential environmental impacts caused by mineral water in PET bottles remained lower than in glass bottles, except for the Global Warming and Photochemical Oxidation Potentials, the same as for the base case.

With regards to the energy consumption of the domestic reverse osmosis equipment (scenario 3), the sensitivity analysis showed how all potential environmental impacts were doubled when the

Table 3
Results of the sensitivity analysis for the considered parameters: i) energy consumption in scenario 5; ii) plastic bottles recycling rate in scenario 4; and iii) energy consumption in scenario 3.

Parameters		Impact categories					
		Abiotic depletion	Acidification	Eutrophication	Global warming	Ozone layer depletion	Photochemical oxidation
		kg Sb eq	kg SO_2 eq	kg PO_4^{3-}eq	kg CO_2 eq	kg CFC-11 eq	kg C_2H_4 eq
Energy consumption (kWh m^{-3} water) – scenario 5	12 (base case)	8.12E-01	3.52E-01	1.08E-01	6.08E+01	1.68E+00	8.68E-03
	10	8.05E-01	3.42E-01	1.08E-01	5.97E+01	1.68E-05	8.32E-03
	20	8.42E-01	3.91E-01	1.10E-01	6.49E+01	1.70E-05	1.01E-02
	30	8.80E-01	4.40E-01	1.13E-01	7.00E+01	1.73E-05	1.19E-02
Plastic bottles recycling rate (%) – scenario 4	50 (base case)	6.74E-01	1.10E-01	5.06E-02	7.51E+01	1.00E-01	1.02E-02
	25	8.06E-01	2.36E-01	6.19E-02	7.92E+01	1.26E-05	1.66E-02
	75	5.42E-01	−1.63E-02	3.92E-02	7.09E+01	7.47E-06	3.84E-03
	100	4.10E-01	−1.43E-01	2.78E-02	6.68E+01	4.92E-06	−2.57E-03
Energy consumption (kWh m^{-3} water) – scenario 3	0.15 (base case)	2.83E-03	4.41E-03	1.87E-04	5.12E-01	4.42E-03	1.67E-04
	0.26	3.23E-03	4.92E-03	2.13E-04	5.66E-01	4.71E-08	1.85E-04
	0.52	4.17E-03	6.14E-03	2.75E-04	6.95E-01	5.41E-08	2.30E-04
	1.04	6.05E-03	8.57E-03	3.99E-04	9.52E-01	6.81E-08	3.20E-04

Scenarios: (3) tap water from conventional drinking water treatment with domestic reverse osmosis; (4) mineral water in PET bottles; (5) mineral water in glass bottles.

energy consumption exceeded 1.04 kWh/m^3 of water as compared to the base case (0.15 kWh/m^3 of water). Nevertheless, the impacts remained insignificant if compared with bottled water scenarios (from 13 to 271 times lower for all environmental indicators), and were also lower than for reverse osmosis at the treatment plant (around 1.5 times for all environmental indicators). However, it remained higher than for tap water from conventional drinking water treatment (between 2 and 3 times for all environmental indicators).

On the whole, it can be concluded that the outcomes of the LCA are not strongly dependent on the assumptions considered in this study.

3.3. *Economic aspects*

The economic analysis here presented was based on the cost of water from the consumers' point of view. As mentioned above, data for scenarios 1, 3, 4 and 5 were provided by local companies. Regarding scenario 2, the cost was estimated from conventional water treatment and desalination plants in the Mediterranean region. According to this, the consumption of tap water from conventional drinking water treatment (scenario 1) appeared as the most inexpensive alternative (0.95 €/m^3), followed by reverse osmosis at the treatment plant (scenario 2) (1.2 €/m^3), domestic reverse osmosis (scenario 3) (31 €/m^3), mineral water in PET bottles (scenario 4) (267 €/m^3) and mineral water in glass bottles (scenario 5) (600 €/m^3), which was the most expensive alternative. The results are in accordance with different surveys carried out in the US, Europe and Asia, which stated that the price of bottled water can be up to 1000 times higher than tap water (Dindarloo et al., 2015; Ferrier, 2001; Gleick, 2004). Besides, the cost per cubic meter of mineral water in glass bottles was about 2.2 times higher than mineral water in PET bottles; while the cost per cubic meter of treated drinking water with domestic reverse osmosis was lower than bottled water (between 8 and 19 times). This is in agreement with Elfil et al. (2007) who observed that the water treatment cost for brackish water with domestic reverse osmosis equipment was roughly the tenth of that of bottled water. On the other hand, the cost of the domestic reverse osmosis scenario was about 32 and 26 times higher than the consumption of tap water from conventional drinking water treatment and reverse osmosis at the treatment plant, respectively. This is due to the capital cost of domestic reverse osmosis equipment, replacement of filters and membranes, and energy consumption. In order to reduce these costs, household reverse osmosis equipment ought to be replaced by community equipment shared by several users.

4. Conclusions

A life cycle assessment was carried out in order to compare five drinking water consumption alternatives. From this analysis, the following conclusions can be drawn:

- Tap water consumption from conventional drinking water treatment (scenario 1) presented the lowest potential environmental impacts in all the categories analysed and appeared as the most inexpensive alternative from the consumers' point of view.
- Tap water from conventional drinking water treatment with domestic reverse osmosis (scenario 3) showed similar results in all environmental indicators (although 10–24% higher), being the best alternative for improving tap water organoleptic characteristics from an environmental perspective.
- Tap water from conventional drinking water treatment with reverse osmosis at the treatment plant (scenario 2) showed nearly twice the environmental impacts of the domestic reverse osmosis scenario, due to the higher energy consumption of reverse osmosis at the treatment plant. However, its cost was much lower than domestic reverse osmosis, being the best alternative for improving tap water organoleptic characteristics in economic terms.
- The highest potential environmental impacts were found for bottled mineral water scenarios, which were also the most expensive. In particular, mineral water in glass bottles (scenario 5) showed the worst results. This was mainly due to the high consumption of raw materials and energy for bottles manufacturing, and to the higher weight of glass bottles per volume of water as compared to PET ones. Besides, if bottled water transportation had been considered, environmental impacts would have been higher. However, mineral water is generally more pleasing in organoleptic terms compared to tap water.

Acknowledgements

The authors acknowledge the financial support of Barcelona Metropolitan Area (*Ajuts a la recerca en prevenció de residus 2011–2012 de l'Àrea Metropolitana de Barcelona)*. Marianna Garfí is grateful to the Spanish Ministry of Economy and Competitiveness (Plan Nacional de I+D+i 2008–2011, Subprograma Juan de la Cierva (JDC) 2012). The authors are particularly grateful to M^{a} Nieves Vázquez from the Universitat Politècnica de Catalunya·BarceloinaTech (UPC) and Albert Torras from the Barcelona Metropolitan Area (AMB) for their contribution.

References

Amores, M.J., Meneses, M., Pasqualino, J., Antón, A., Castells, F., 2013. Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. J. Clean. Prod. 43, 84–92.

Barrios, R., Siebel, M., Van der Helm, A., Bosklopper, K., Gijzen, H., 2008. Environmental and financial life cycle impact assessment of drinking water production at waternet. J. Clean. Prod. 16, 471–476.

Bhatnagar, A., Vilar, V.J.P., Botelho, C.M.S., Boaventura, R.A.R., 2010. Coconut-based biosorbents for water treatment — a review of the recent literature. Adv. Colloid Interface Sci. 160, 1–15.

Bonton, A., Bouchard, C., Barbeau, B., Jedrzejak, S., 2012. Comparative life cycle assessment of water treatment plants. Desalination 284, 42–54.

Crittenden, J.C., Trussell, R.R., Hand, D.W., Howe, K.J., Tchobanoglous, G., 2005. Water Treatment: Principles and Design, second ed. John Wiley & Sons, Hoboken, New Jersey.

Cutrín, J., 2012. Reuse of Glass Containers in the Municipality of Barcelona: Study of Implementation of a DRS (Reutilització dels envasos de vidre al municipi de Barcelona: Estudi d'implantació d'un SDDR). Informe Técnico SDDR.

De Giglio, O., Quaranta, A., Lovero, G., Caggiano, G., Montagna, M.T., 2015. Mineral water or tap water? An endless debate. Ann Ig 27, 58–65. http://dx.doi.org/10.7416/ai.2015.2023.

Devesa, R., Cardeñoso, R., Matía, L., 2007. Contribution of the FPA tasting panel to decision making about drinking water treatment facilities. Water Sci. Technol. 55 (5), 127–135.

Dindarloo, K., Ghaffari, H.R., Kheradpisheh, Z., Alipour, V., Ghanbarnejad, A., Fakhri, Y., Goodarzi, B., 2015. Drinking water quality: comparative study of tap water, drinking bottled water and point of use (PoU) treated water in Bandar-e-Abbas, Iran. Desalin. Water Treat. 57 (10), 1–7.

Doria, M.F., 2006. Bottled water versus tap water: understanding consumers' preferences. J. Water Health 4, 271–276.

Doria, M.F., Pidgeon, N., Hunter, P.R., 2009. Perceptions of drinking water quality and risk and its effect on behaviour: a cross-national study. Sci. Total Environ. 407, 5455–5464.

Ecoinvent Centre, 2010. The Life Cycle Inventory Data v2.2.

Elfil, H., Hamed, A., Hannachi, A., 2007. Technical evaluation of a small-scale reverse osmosis desalination unit for domestic water. Desalination 203, 319–326.

European Commission, 1998. The Drinking Water Directive (DWD). Council Directive 98/83/EC. Available: http://ec.europa.eu/environment/water/water-drink/index_en.html (accessed 15.02.12.).

Fantin, V., Scalbi, S., Ottaviano, G., Masoni, P., 2014. A method for improving reliability and relevance of LCA reviews: the case of life-cycle greenhouse gas emissions of tap and bottled water. Sci. Total Environ. 476–477 (2014), 228–241.

Ferrier, C., 2001. Bottled Water: Understanding a Social Phenomenon. Available: http://assets.panda.org/downloads/bottled_water.pdf (accessed 15.03.11.).

Gleick, P.H., 2004. The myth and reality of bottled water. In: Gleick, P.H. (Ed.), The World's Water, the Biennial Report on Freshwater Resources: 2004–2005, Washington D.C.

Igos, E., Dalle, A., Tiruta-Barna, L., Benetto, E., Baudin, I., Mery, Y., 2014. Life cycle assessment of water treatment: what is the contribution of infrastructure and operation at unit process level? J. Clean. Prod. 65, 424–431.

ISO (International Organization for Standardization), 2000. Environmental Management — Life Cycle Assessment — Life Cycle Impact Assessment. International Standard ISO 14042, Geneva, Switzerland.

ISO (International Organization for Standardization), 2006. Environmental Management - Life Cycle Assessment - Principles and Framework. International Standard ISO 14040, Geneva, Switzerland.

Lagioia, G., Calabrò, G., Amicarelli, V., 2012. Empirical study of the environmental management of Italy's drinking water supply. Resour. Conserv. Recycl. 60, 119–130.

Lemos, D., Dias, A.C., Gabarrell, X., Arroja, L., 2013. Environmental assessment of an urban water system. J. Clean. Prod. 54, 157–165.

Loubet, P., Roux, P., Loiseau, E., Bellon-Maurel, V., 2014. Life cycle assessments of urban water systems: a comparative analysis of selected peer-reviewed literature. Water Res. 67, 187–202.

Lundie, S., Peters, G.M., Beavis, P.C., 2004. Life cycle assessment for sustainable metropolitan water systems planning. Environ. Sci. Technol. 38, 3465–3473.

McRandle, P., 2004. The Green Guide, in State of the World 2004, the World Watch Institute Report. Available: http://www.rohan.sdsu.edu/faculty/dunnweb/StateofWorld2004.dat.pdf (accessed 15.10.15.).

Mohapatra, P.K., Siebel, M.A., Gijzen, H.J., Van der Hoek, J.P., Groot, C.A., 2002. Improving eco-efficiency of Amsterdam water supply: a LCA approach. J. Water Supply Res. Technol. — AQUA 51 (4), 217–227.

Nessi, S., Rigamonti, L., Grosso, M., 2012. LCA of waste prevention activities: a case study for drinking water in Italy. J. Environ. Manag. 108, 73–83.

Pré Consultants, 2009. SimaPro LCA Software. Available: http://www.pre-sustainability.com (accessed 15.09.01.).

Papong, S., Malakul, P., Trungkavashirakun, R., Wenunun, P., Chom-in, T., Nithitanakul, M., Sarobol, E., 2014. Comparative assessment of the environmental profile of PLA and PET drinking water bottles from a life cycle perspective. J. Clean. Prod. 65, 539–550.

Pasqualino, J., Meneses, M., Castells, F., 2011. The carbon footprint and energy consumption of beverage packaging selection and disposal. J. Food Eng. 103, 357–365.

Qiu, T., Davies, P.A., 2012. Comparison of configurations for high-recovery inland desalination systems. Water 4, 690–706.

Salcedo, R., Antipova, E., Boer, D., Jiménez, L., Guillén-Gosálbez, G., 2012. Multi-objective optimization of solar Rankine cycles coupled with reverse osmosis desalination considering economic and life cycle environmental concerns. Desalination 286, 358–371.

Triki, Z., Bouaziz, M.N., Boumaza, M., 2014. Techno-economic feasibility of wind-powered reverse osmosis brackish water desalination systems in southern Algeria. Desalin. Water Treat. 52, 1745–1760.

Vanderheyden, G., Aerts, J., 2014. Comparative LCA Assessment of Fontinet Filtered Tap Water Vs. Natural Sourced Water in a PET Bottle. Final Report. Futureproofed, Reviewed by Evelien Dils, VITO. Available: http://www.futureproofed.com/images/uploads/projects/13506_PWA_LCA_report_final_07.pdf (accessed 20.04.16.).

Vince, F., Aoustin, E., Bréant, P., Marechal, F., 2008. LCA tool for the environmental evaluation of potable water production. Desalination 220, 37–56.

World Health Organization (WHO), 2004. Guidelines for Drinking-water Quality. Available: http://whqlibdoc.who.int/publications/2011/9789241548151_eng.pdf (accessed 10.01.15.).