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

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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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(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