Science of the Total Environment 476–477 (2014) 228–241

Contents lists available at ScienceDirect

Science of the Total Environment

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

A method for improving reliability and relevance of LCA reviews: The case of life-cycle greenhouse gas emissions of tap and bottled water

Valentina Fantin *, Simona Scalbi, Giuseppe Ottaviano, Paolo Masoni

ENEA — Italian National Agency for New Technologies, Energy and Sustainable Economic Development, LCA and Ecodesign Laboratory, Bologna Research Center, Via Martiri di Monte Sole 4, 40129 Bologna, Italy

HIGHLIGHTS

- Proposal of a method to harmonise Life Cycle Assessment (LCA) literature studies
- The method is divided in six main steps aiming to rationalize the efforts needed.
- Application of the method to the comparison between tap and bottled water
- The method allows obtaining more consistent comparisons.
- A statistical decision test can validate the comparative review results.

ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form 12 December 2013
Accepted 27 December 2013
Available online 24 January 2014

Keywords:
Comparability
Life Cycle Assessment (LCA)
Tap water
Bottled water
Global warming potential

ABSTRACT

The purpose of this study is to propose a method for harmonising Life Cycle Assessment (LCA) literature studies on the same product or on different products fulfilling the same function for a reliable and meaningful comparison of their life-cycle environmental impacts. The method is divided in six main steps which aim to rationalize and quicken the efforts needed to carry out the comparison. The steps include: 1) a *clear definition of the goal and scope of the review*; 2) *critical review* of the references; 3) *identification of significant parameters* that have to be harmonised; 4) *harmonisation* of the parameters; 5) *statistical analysis* to support the comparison; 6) *results and discussion*.

This approach was then applied to the comparative analysis of the published LCA studies on tap and bottled water production, focussing on Global Warming Potential (GWP) results, with the aim to identify the environmental preferable alternative. A statistical analysis with Wilcoxon's test confirmed that the difference between harmonised GWP values of tap and bottled water was significant. The results obtained from the comparison of the harmonised mean GWP results showed that tap water always has the best environmental performance, even in case of high energy-consuming technologies for drinking water treatments.

The strength of the method is that it enables both performing a deep analysis of the LCA literature and obtaining more consistent comparisons across the published LCAs. For these reasons, it can be a valuable tool which provides useful information for both practitioners and decision makers. Finally, its application to the case study allowed both to supply a description of systems variability and to evaluate the importance of several key parameters for tap and bottled water production. The comparative review of LCA studies, with the inclusion of a statistical decision test, can validate and strengthen the final statements of the comparison.

1. Introduction

Life Cycle Assessment (LCA) is an internationally accepted and standardized technique (ISO, 2006a, 2006b), which is recognized as a strategic and effective tool to evaluate the potential environmental impacts occurring in the whole product's life cycle as well as to identify possible areas for improvement. However, the methodological choices and the hypotheses made by the practitioners as well as the data used can affect the comparability of the results of the assessment. Consequently, the comparability of different LCA studies on the same product or on different products that fulfil the same function is a complex and critical issue, which has been frequently discussed (Ingwersen and Stevenson, 2012). In fact, the results of studies on the same product carried out by different authors are often characterized by large results variability (Brandão et al., 2012), due to the different parameters used as well as the technological systems and impact assessment methods considered in the assessment. Some initiatives such as Product Environmental Footprint (PEF) (EC, 2013), Envifood protocol (Food SCP RT, 2013) and Product Category Rule Guidance

* Corresponding author. Tel.: +39 0516098532; fax: +39 0516098280.
E-mail address: valentina.fantin@enea.it (V. Fantin).

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http://dx.doi.org/10.1016/j.scitotenv.2013.12.115

Development Initiative (Ingwersen and Subramanian, 2013) have been developed in Europe and the U.S. to overcome this critical subject.

LCA literature reviews are common ways to discuss and summarize the key issues and features emerged from studies performed by different authors on a specific topic, product or technology. A review can also highlight how and to what extent the different methodological choices affect the results of the assessment. Therefore, it can be a starting point to facilitate a comparison of the results from the various studies analysed. In fact, an overview of reported results can provide reliable information about the environmental impacts of a product or system (Muench and Guenther, 2013). The review can aim to compare products (Lizin et al., 2013; Yan et al., 2011; Rugani et al., 2013) or energy production systems (Muench and Guenther, 2013; Cherubini and Strømman, 2011; Turconi et al., 2013), to define the environmental criticisms in the sector under study (Cabeza et al., 2014; Corominas et al., 2013; Martínez-Blanco et al., 2013), to define a framework for LCA application in specific production systems (Cerutti et al., 2013) and finally to provide reliable information for decision-making processes and policy evaluation (Yoshida et al., 2013; Tascione and Raggi, 2012).

Furthermore, other authors propose or develop a framework, often based on meta-analytical approach, for conducting systematic or structured review of LCA studies which aims either to identify and reduce results variability or to provide a comprehensive evaluation of assumptions and methodological choices. In some cases, authors of the review propose a method to correct the differences in choices and assumptions found in the studies (Whitaker et al., 2012; Burkhardt et al., 2012; Schreiber et al., 2012; Weiss et al., 2012).

All the approaches developed in the above mentioned studies propose a common framework, which is based on the following criteria:

- A selection of the most relevant published articles in terms of data robustness, type of product, goal and scope of the study, main impact assessment results;
- A comparison of the LCAs by means of the application of harmonised methods aiming to reduce the studies variability in terms of functional unit, reference flow and system boundaries.

In addition, some authors use statistical methods to address specific problems. Padey et al. (2013) propose a general method to produce simplified LCA models which is based on the application of global sensitivity analysis (GSA). The approach allows the identification of key parameters to be used, by means of Sobol variance decomposition, to harmonise LCA results and literature variability. Burkhardt et al. (2012) address the problems of reducing variability and of the assessment of central tendency of LCA results by means of inter-quartile ranges (IQR). The method proposed by Menten et al. (2013) is a meta-regression analysis (MRA) applied to the results of a literature review and focused on the estimates of advanced biofuel GHG emissions. Using econometrics methods, which are specific statistical techniques, MRA provides a quantitative summary of estimate results, such as mean estimates and confidence intervals of the quantitative results among studies.

The aim of this paper is to propose a method to harmonise LCA literature studies on different products fulfilling the same function for a reliable and meaningful comparison of their life-cycle environmental impacts. This approach was applied to the comparative analysis of the LCAs on tap and bottled water production, focussing on the Carbon Footprint (CF) (or Global Warming Potential — GWP) results in terms of CO_2 eq., with the aim to identify which alternative, tap or bottled water, is preferable as CF.

The method was applied using well-defined criteria for choosing the most relevant literature articles on this topic and several harmonisation procedures which enabled comparing the GWP results of the LCA studies. Moreover, a statistical analysis was performed aiming to assess whether the difference between GWP values of tap and bottled water is significant or simply a statistical fluctuation.

The paper describes the various steps of the method proposed, its application to the case study on tap and bottled water, the results obtained from the case study as well as a discussion on the validity and reliability of the method, combined with a highlight of its main strengths and limits.

2. Materials and methods

2.1. Description of the method

The method is based on an iterative procedure and can be applied to products, systems and technologies. Due to its iterative nature, the main steps of the method (Fig. 1), which are explained below, can be revised during the study in order to refine the results obtained. The steps are:

1. Clear definition of the “goal and scope of the review”. In fact, ISO 14040 series require that the comparison of LCA studies on different products, systems or technologies can be performed only if they fulfil the same function. Consequently, it is essential to clearly define the goal of the review, the function of the system analysed, the functional unit and the system boundaries in terms of phases, processes and activities which have to be included in the comparative review.
2. “Critical review”, which consists of three sub phases:
   a) “Literature selection”: the LCA studies shall be identified with the help of electronic bibliographic databases of scientific literature and web search engines. The references could include peer-reviewed papers published in international journals, project reports and Environmental Product Declarations (EPD), depending on the scope of the review.
   b) “Screening phase” to select articles and reports that fit with the goal of the review and are compliant (or declared as compliant) with ISO 14040. A first screening is done reading the abstracts. A second screening on the whole papers aims at rejecting those studies which present evident incongruence in the results.
   c) “Analysis of references”: The papers selected are critically analysed, with the help of a form, which has to be compiled for a set of mandatory information such as: goal of the study, functional unit, system boundaries, assumptions, impact assessment method, impact assessment results. Moreover, further key information could be identified such as: name of the commissioner of the study, geographical location, types of technologies used, primary data sources and databases used, handling of multi-functional processes, notes.
3. “Identification of significant parameters”. On the basis of the information collected in the step 2, the main significant parameters, that have to be harmonised in order to facilitate the comparison of LCA results, are identified by expert judgement and with the support of a “table for cross comparison”. This table identifies and describes the major parameters of each reference such as the functional units and their unit of measurements, the system boundaries, the considered environmental impact categories as well as the impact assessment methods, the results of each impact category identified as significant and their environmental indicator. Further characteristics useful to the goal of the review can be identified as well (for example the reference country, the type of technologies considered etc.).
4. “Harmonisation phase”. The parameters identified in step 3, are harmonised by means of calculations and homogenisation of methodological choices. The types of calculations and methodological procedures that have to be applied depend on the kind of harmonisation needed and the aim of the review. All studies have to be reported at the same functional unit in terms of amount and unit of measurement, by a conversion of the unit of measurements and a proportion between the amount of the functional unit of the study and the one selected for the comparative review. This permits to obtain a conversion factor, which is used to harmonise the environmental impact results of each study. Another important element is the harmonisation of system boundaries. In fact, all the studies analysed in the comparative review shall include the same

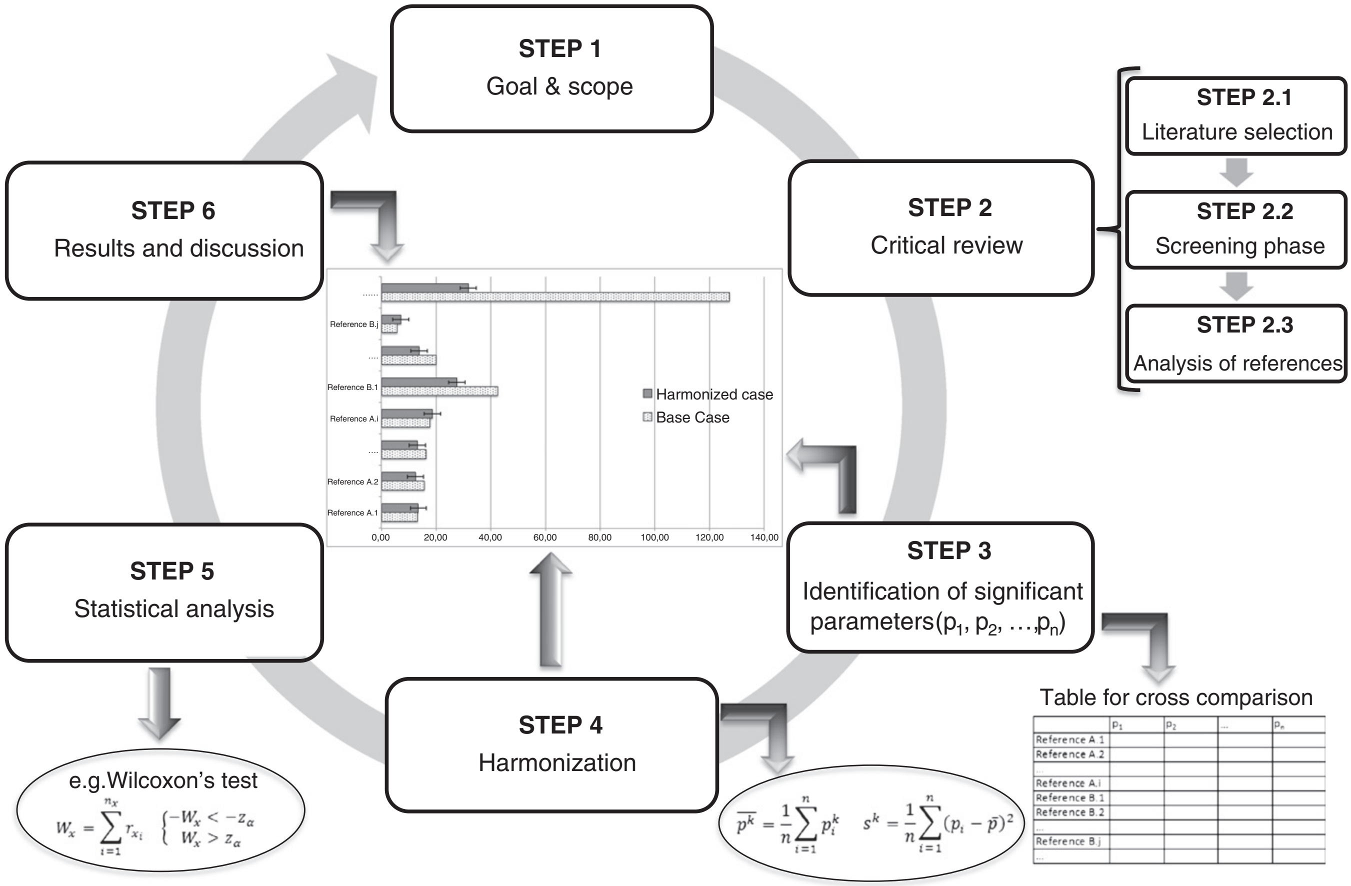

Fig. 1. Scheme of the proposed method.

phases, process and activities, as mentioned in step 1. Therefore, it is necessary to check whether the studies analysed contain all the phases, processes and activities defined in the system boundaries of the comparative review. The unnecessary phases or processes as well as their contribution to the total results have to be identified and subtracted from the results of the study. On the other hand, the missing phases, processes and activities have to be added. In such cases, the values to be added have to be carefully evaluated and the most suitable procedure for their calculation has to be chosen. The procedure can be different depending on the data availability. For example, the values could be calculated by means of an average value extrapolated from other studies. The standard deviation has to be calculated as well, in order to examine the influence on the total results. In other cases, when the missing phase is characterized by imperfect data and other uncertainties, the Monte Carlo analysis could be used. This method, by tracking the propagation of uncertainties, allows the measurement of the effects on the results, caused by the uncertainty of the input data and processes. The Monte Carlo technique consists of repeated assessments using input values randomly chosen in a probable range. The effect of uncertainty in input can be measured by the variability of the assessment output (Raynolds et al., 1999). Furthermore, when the harmonisation procedures are performed for a same technology or a supply chain, i.e. wind power electricity, Padey et al. (2013) suggest the use of GSA, based on the Sobol's method, to identify the key parameters which affect the variability of impact assessment results. The application of GSA permits to obtain a hierarchy among significant parameters, according to their contribution to the whole variance of environmental impacts.

After having performed the harmonisation procedures suggested above, the harmonised results of the LCA studies will be available.

5. "Statistical analysis". When comparing LCA studies, it is often necessary to compare different sets of observations. In this regard, a statistical analysis is strongly recommended, which aims to support the conclusion reached. Furthermore, this step is highly advisable when the results of the observed values are close. The statistical analysis consists of two sub-phases:
   a) "Identification of the general statistical procedure". When the sets of values are independent random samples drawn from larger populations, their comparison is between the mean values obtained. In statistical terms, the problem is solved by means of statistical inference method using an appropriate test (i.e. parametric or non-parametric), (Galeotti, 1983; Spiegel, 1979; Gnedenko, 1979). Statistical inference is the general category of the statistical procedures which include decisions based on probability. In general, a statistical decision stems from one of the two following mutually exclusive conditions:
      I. Statistical significance: the examined samples are non-homogeneous because they have been extracted from different populations; in other words, the observed difference is real;
      II. Statistical fluctuation: the samples are homogeneous because they have been extracted from the same population; in other words, the observed difference is random.
   b) "Identification of the statistical test". The choice of the most suitable test to be used is influenced by the knowledge of the random variables probability density functions (PDFs) of the populations from which the samples have been extracted. If the PDFs are known, parametric tests can be used, (e.g. Student's t-test, Fisher's test). On the contrary, if the PDFs are unknown, non-parametric tests should be used (e.g., χ^2 test, Wilcoxon's test).

6. "Results and discussion". In this phase the results of previous steps and the harmonised LCA results are analysed and discussed. On the basis of the results obtained, following the iterative procedure of the method, some parameters can be modified or adjusted and further ones can be added. Finally, the hotspots of the product systems analysed are identified.

3. Application of the method to a case study: Life-cycle greenhouse gas emissions of tap and bottled water

3.1. Step 1: Goal and scope of the review

A large Italian retailing company launched in 2010 an information campaign addressed to consumers in order to provide data on the environmental impacts on climate change of bottled and tap water production, in terms of CO_2 equivalents emitted in their life cycle. ENEA provided the scientific background for that campaign, based on a survey of LCA studies on tap and bottled water available in literature. The analysis of the LCA studies was then focussed on the CF results in terms of CO_2 eq., which were then compared and harmonised with the aim to identify which alternative, tap or bottled water, is preferable as CF. The comparison of LCA studies on tap and bottled water was updated in September 2013 with the latest published LCA studies.

The function of the system is to quench people's thirst, neglecting other functions, such as dietary aspects. As a basis for the comparison, a standard situation was defined: 100 l of drinking water (neither refrigerated, nor carbonated) available at the final consumer. A distance of 100 km by truck, in polyethylene terephtalate (PET) bottles was chosen as reference for distribution of bottled water.

3.2. Step 2: Critical review

3.2.1. Literature selection

The review covered about thirty-five LCA studies on tap and bottled water, identified by means of relevant queries on Scopus and Google Scholar. Furthermore, some studies were directly supplied by the performers. The types of references identified were the following:

- Peer-reviewed articles available in scientific journals;
- Environmental Product Declarations (EPDs);
- Project reports.

3.2.2. Screening phase

This step eliminated the references that had the following characteristics:

1. LCAs not compliant with Standard ISO 14040, i.e. the studies published before 1997;
2. Studies which did not show CF values;
3. Studies from a same author which presented conflicting results;
4. Studies which showed only end-point indicators;
5. Studies on carbonated water;
6. Studies on water bottled in glass, aluminium or other type of packaging, different from PET.

3.2.3. Analysis of references

After this screening, only twenty-eight references were selected for the further analysis.

The second step was the compilation of a form for each LCA study, containing all the information described at Section 2.1.

The LCA studies, which had passed the screening phase, were critically analysed. They presented some key differences as regards the functional unit used, the system boundaries, the transport distances considered for bottled water distribution as well as other differences such as the bottle end of life treatments. Moreover, the tap water studies presented very different scenarios in terms of water supply, distribution networks and pipelines as well as capacity load of waterworks.

The functional unit used in the studies analysed varied widely both for tap and bottled water.

As regards system boundaries for tap water, some studies consider the extraction from the ground or the surface, purification treatments, storage, distribution to the households as well as wastewater treatment (Tarantini and Ferri, 2003; Jungbluth, 2006; Botto, 2009; Friedrich et al., 2009a, 2009b; Peters and Rouse, 2005; Homäki et al., 2003; Nessi et al., 2012; Lundie et al., 2004), whereas the remaining ones consider only the extraction and water purification treatments (Barrios et al., 2008; Vince et al., 2008; Friedrich, 2002). Significant differences were found in the tap water studies with respect to the type of waterworks and distribution networks (for example pumping equipment) as well as the pipeline lengths.

As regards system boundaries for bottled water, all the references included the extraction, the bottling operations and the distribution to the consumer. Three studies considered also the household water refrigeration (Franklin Associates, 2009; Jungbluth, 2006; Dettling et al., 2010). Finally, Dettling et al. (2010) and Nessi et al. (2012) include the life cycle of the jug or glass used at home and their washing. Other differences were found in the disposal of PET bottles. In fact their end of life treatments varied from landfill (Franklin Associates, 2009) to recycling (Studio Life Cycle Engineering, 2008). However, most studies considered a mix of several end of life treatments (i.e. recovery, landfilling and recycling) according to national disposal scenarios. Finally, Botto (2009) and EPD Coop (2012) did not include bottle end of life phase. Furthermore, the country electricity mix used in the studies is an important issue for both tap and bottled water, which can affect the results obtained.

3.3. Step 3: Identification of significant parameters

The main significant parameters identified in the studies were the following:

- the geographical location of the studies, which indicates the reference country used for data collection in each study and the country of the electricity mix used;
- the functional unit, which varied widely across the studies;
- the system boundaries since some studies on tap water did not include the distribution phase, and the types of distribution for bottled water were dissimilar;
- the GWP results.

Therefore, two tables for cross comparison were constructed, one for each type of water analysed (Tables 1 and 2). For each reference, the table displays the geographical location, the functional unit and its unit of measurement, the system boundaries and the GWP results.

3.4. Step 4: Harmonisation phase

The harmonisation criteria were applied to the parameters identified, i.e. the functional unit and the system boundaries defined in each study as well as the transport distances used for the distribution of water to the consumer.

The *functional unit* of all studies was modified to 100 l of water. In case of the U.S. customary system they were firstly converted to the International System of units.

The harmonised *system boundaries* of bottled and tap water are presented in Figs. 2 and 3.

The analysis of the published LCA on tap water showed that some of them did not include the distribution phase. Actually, this phase is mainly affected by water losses, pipeline materials and pumping. For this reason, literature GWP data on this missing phase were added. In particular, Tarantini and Ferri (2003), Jungbluth (2006), Friedrich et al. (2009b) and the dataset on tap water production of the database Ecoinvent 2.2. (Althaus et al., 2007) report on the percentage contribution of the distribution phase to the total GWP results (Appendix A). As

Table 1
Table for cross comparison of LCA studies on tap water.

References	Country	Functional unit (FU)	System boundaries	System description used in the analysis	GWP for FU in kg of CO_2
Tarantini and Ferri (2003)	Italy	54.8 m^3	The study includes all the processes for the distribution and treatment of tap water and the production processes of chemicals, electricity and materials used in water treatment plants including their transport to the final user. Wastewater treatment is included.	The analysis includes only the production of tap water and not the wastewater treatment.	4.8E + 01
Botto (2009)	Italy	1.5 l	The study includes the extraction of water from the ground, abduction through pipes, water storage and distribution to the final user. Not included the waste end of life treatments.	Water is abducted by 110 km of pipes and distributed to the final users by a system of pipes whose total length is 220 km. In 2007, 7 Gl of water were distributed to the households.	9.1E-04
Nessi et al. (2012)	Italy	152 l	The study includes the processes involved in water purification and distribution to households, its quality improvement at domestic level as well as the life cycle and washing of a reusable glass jug.	The analysis includes only the processes involved in water purification and distribution to users.	7.5E-02
Barrios et al. (2008)	The Netherlands	1 m^3	The study includes the extraction of water and filtration treatments. Water storage and distribution are not considered.	The analysis includes the extraction of water and filtration treatments	8.6E-06
Jungbluth (2006)	Switzerland	1 l	The study includes water extraction and treatments, distribution via water pipes and plumbing.	The system refers to Swiss tap water production	4.4E-04
Jungbluth (2006)	Switzerland (country)			The system refers to tap water production in Switzerland country areas	4.3E-04
Jungbluth (2006)	Switzerland (urban)			The system refers to tap water production in Switzerland urban areas	4.1E-04
Jungbluth (2006)	Europe			The system refers to European tap water production	1.7E-05
Database Ecoinvent v.2.0, tap water	Switzerland	100 kg	The study includes the infrastructure and energy use for water treatment and transportation to the households. No emission from water treatment is considered.	The system refers to Switzerland tap water production	1.7E-01
Database Ecoinvent v.2.0, tap water	Europe			The system refers to European tap water production	6.2E-04
Geerken et al. (2006)	Belgium	1 m^3	The study includes water extraction, treatments, storage and distribution to households.	The analysis includes water extraction, treatments, storage and distribution to households.	2.9E-01
Vince et al. (2008)	Europe	1000 l	The study includes groundwater treatment, filtration and ultrafiltration treatments. Distribution is not included.	The analysis includes groundwater treatment, filtration and ultrafiltration treatments.	3.2E-05
Friedrich (2002), chemical–physical Treatment	South Africa	1000 l	The study includes construction and decommissioning of a water treatment plant, the water treatments in terms of pre-ozonation, addition of chemicals, flocculation, sedimentation, filtration, ozonation, chlorination and water storage. Distribution is not included.	The analysis includes construction and decommissioning of a water treatment plant, the water treatments in terms of pre-ozonation, addition of chemicals, flocculation, sedimentation, filtration, ozonation, chlorination and water storage.	1.9E-01
Friedrich (2002), membrane	South Africa		The study includes construction and decommission of water treatment plant, the water treatments in term of pre-filtration, membrane filtration, chlorination and storage. Distribution is not included.	The analysis includes construction and decommission of water treatment plant, the water treatments in term of pre-filtration, membrane filtration, chlorination and storage.	2.9E-01
Friedrich et al. (2009a), 1	South Africa	1000 l	The study includes the dam construction and management, water treatments, distribution network, wastewater collection and treatments.	The analysis does not consider the collection network for wastewater, primary treatment sewage works and the additional secondary treatment works.	4.1E-01
Friedrich et al. (2009b), 2	South Africa	1000 l	The study included the dam construction and management, drinking water treatments, distribution to the households, collection and treatment of wastewater.	The analysis does not consider the wastewater collection and treatment.	4.8E-01
Dettore (2006)	USA	1000 gallons	The study includes the production and distribution of tap water and the manufacturing and washing of the reusable drinking vessel (stainless steel bottle/cap, glass cup).	The analysis does not include the manufacturing and washing of the reusable drinking vessel (stainless steel bottle/cap, glass cup).	5.1E + 00
Dettling et al. (2010)	USA	500 ml	The study includes the production and distribution of tap water and the fabrication, washing and end of life of the reusable jug or glass	The analysis does not include the fabrication, washing and end of life of the reusable jug or glass	2.5E-04
Peters and Rouse (2005), desalination lake	South Australia	7.5 Ml/day	The study includes water supply, treatments and distribution.	In this system water is obtained from a dam on the Tod River and desalted locally. Dam management is included. Water treatments include a reverse osmosis desalination plant producing 7.5 Ml/day which uses a three-step membrane filtration process.	1.5E + 04
Peters and Rouse (2005), desalination sea	South Australia			The system considers the use of seawater 100% of the time from the Spencer Gulf. The water treatments include a reverse osmosis desalination plant capable of producing 7.5 Ml/day	5.0E + 04
Peters and Rouse (2005), pipeline 700 km	South Australia			This system requires water to be pumped over 700 km from its source to reach Ceduna in South Australia. The water treatments include a filtration plant.	1.7E + 04
Lundie et al. (2004)	South Australia	622 Gl	The study includes water supply, treatments, distribution, sewage treatment plants.	The analysis does not consider the sewage treatment plants.	2.5E + 08
Homäki et al. (2003), boiled water	Vietnam	8081 m^3	The study includes water extraction, treatments and distribution.	In this system boiling is required before consumption because the quality of water in the public network does not always meet the drinking water quality standards.	8.4E + 03
Homäki et al. (2003), efficient tap water	Vietnam	8081 m^3		The analysis considers that potable water is supplied directly through the public network.	1.5E + 03

Table 2
Table for cross comparison of LCA on bottled water.

References	Country	Functional unit (FU)	System boundaries	System description used in the analysis	GWP for FU in kg of CO_2
Botto (2009), small company 1	Italy (North)	1.5 l	The study includes extraction of water from the source and raw materials production; PET preforms production and transportation to the bottling water plant; bottling and packaging processes; distribution to supermarkets and from there to final users.	The system considers a small company producing 8 Ml/year of bottled water, with a small scale distribution (up to 500 km).	2.6E-01
Botto (2009), small company 2	Italy (North)	1.5 l		The system considers a small company producing 40 Ml/year of bottled water, with a small scale distribution (up to 500 km).	3.0E-01
Botto (2009), medium company 1	Italy (Centre)	1.5 l		The system considers an average Italian company, with an annual bottled water production between 50 Ml and 150 Ml. This system refers to a national market.	2.5E-01
Botto (2009), medium company 2	Italy (Centre)	1.5 l		The system considers an average Italian company, with an annual bottled water production between 50 Ml and 150 Ml. This system refers to a national market.	2.5E-01
Botto (2009), large company 1	Italy (Centre)	1.5 l		The system considers one of the biggest companies in the market, with an annual production of 300 Ml. This system refers to a national market.	2.4E-01
Botto (2009), large company 2	Italy (South)	1.5 l		The system considers one of the biggest companies in the market, with an annual production of 400 Ml. This system refers to a national market.	2.6E-01
EPD Cerelia (2012), 0.5 l	Italy	1 l	The study includes water withdrawal from spring; primary and secondary packaging manufacturing, bottling, distribution, end of life treatments of packaging (including PET bottle). PET bottle is supposed to be recycled for a percentage equal to 24.8%, incinerated for 30.3% and landfilled for 41.3%.	The system considers PET bottles with a capacity of 0.5 l capacity. Water is distributed from the company to an average distribution platform.	2.6E-01
EPD Cerelia (2012), 1.5 l	Italy			The system considers PET bottles with a capacity of 1.5 l. Water is distributed from the company to an average distribution platform.	1.8E-01
EPD San Benedetto (2012), 0.5 l	Italy	1 l	The study includes water extraction, filling, packaging, distribution and end of life. The product's end of life consists of various disposal scenarios (recycling, incineration and landfilling) according to the Italian situation.	The system considers PET bottles with a capacity of 0.5 l. Water is distributed from the company to an average distribution platform.	1.7E-01
EPD San Benedetto (2012), 1.5 l	Italy			The system considers PET bottles with a capacity of 1.5 l. Water is distributed from the company to an average distribution platform.	1.2E-01
EPD San Benedetto (2012), 2 l	Italy			The system considers PET bottles with a capacity of 2 l. Water is distributed from the company to an average distribution platform.	9.6E-02
LCE (2008), 1.5 l–1	Italy (North)	1.5 l	The study includes water extraction and treatment, bottling, production of bottles, distribution, end of life of PET bottle (recycling)	The system considers PET bottles with a capacity of 1.5 l. Water is distributed from the company to retailers for a distance of 250 km.	2.2E-01
LCE (2008), 1.5 l–2	Italy (North)			The system considers PET bottles with a capacity of 1.5 l. Water is distributed from the company to retailers for a distance of 123 km.	1.9E-01
EPD Coop (2012), 2 l	Italy	1 l	The study includes the pumping from the sources, production and the transportation of the bottle and the caps, the bottling phases, transportation from the plants to the distribution platforms (average distance is calculated). End of life treatment of the bottle is not included.	The system considers PET bottles with a capacity of 2 l.	9.4E-02
EPD Coop (2012), 1.5 l	Italy			The system considers PET bottles with a capacity of 1.5 l.	8.2E-02
EPD Coop (2012), 0.5 l	Italy			The system considers PET bottles with a capacity of 0.5.	1.8E-01
EPD Ferrarelle (2011), 1.5 l	Italy	1 l	The study includes the extraction of water, bottling, distribution and end of life treatments. The distribution considers a transport for a distance of 100 km. PET bottle is supposed to be recovered for a percentage equal to 58.7% and landfilled for 41.3%.	The system considers PET bottles with a capacity of 1.5 l.	1.1E-01
EPD Ferrarelle (2011), 1.25 l	Italy			The system considers PET bottles with a capacity of 1.25 l.	1.2E-01
EPD Ferrarelle (2011), 0.5 l	Italy			The system considers PET bottles with a capacity of 1.5 l.	1.6E-01
EPD Lete, acqua Sorgesana (2012), 2 l	Italy	1 l	The study includes the extraction of water, bottling, distribution and end of life treatments. Distribution phase considers the actual distances between the manufacturing plant and the cities where the product is sold. PET bottle is supposed to be recovered for a percentage equal to 37.8%, recycled for 36.3% and landfilled for 25.9%.	The system considers PET bottles with a capacity of 2 l.	1.3E-01
Nessi et al. (2012), 1	Italy	152 l	The study includes the packaging materials production, bottling plant operations, transportation to retailers and to consumers' houses, as well as the end of life of post-consumer packaging. The packaging mix is composed of 2 l bottles (6.3%), 1.5 l bottles (86.1%), 0.5 l bottles (7.6%) End of life for bottles/containers: 77% recycling, 23% incineration.	The system considers a one-way trip and virgin PET bottled water	2.4E + 01
Nessi et al. (2012), 2	Italy			The system considers a one-way trip and 50% recycled PET bottled water	2.5E + 01

(continued on next page)

Table 2 (*continued*)

References	Country	Functional unit (FU)	System boundaries	System description used in the analysis	GWP for FU in kg of CO_2
Jungbluth (2006)	Switzerland	1 l	The study includes water extraction, production of bottles, bottling, distribution.	The system considers 1.5 l PET bottles, produced in Switzerland	1.8E-01
Jungbluth (2006)	Europe			The system considers 1.5 l PET bottles, produced in Europe.	4.3E-01
Franklin Associates (2009), average case	USA — Oregon	1000 gallons	The study includes all steps in the production of bottles: extraction of spring water, distribution, end of life of bottles.	The system is an average of 22 systems presented in the report.	7.6E + 02
Franklin Associates (2009), best case	USA — Oregon			It is the best system presented in the report. It considers a PET bottle with 25% of recycled PET, a weight of 9.8 g and a volume of 16.9 oz; the distribution distance is 5 miles; plastic recycling 100%.	2.2E + 02
Franklin Associates (2009), worst case	USA — Oregon			The system is the worst system presented in the report. It considers a PET bottle with virgin PET weight of 12.3 g and a volume of 8 oz; distribution distance of 500 miles, plastic recycling 0%.	4.8E + 03
Dettling et al. (2010)	USA	500 ml	The study includes water supply, PET bottle production, bottling phase, distribution and end-of-life treatments. The distribution phase considers the transportation of bottled water from point of manufacture to point of sale and transport to the user's home. Disposal of all materials by either landfilling, waste-to-energy or recycling.	The system considers 0.5 l PET bottles.	1.4E-01
Dettore (2006), virgin PET	USA	1000 gallons	The study includes the water extraction, bottle and secondary packaging production, operations at the bottling plant including water treatment and bottle filling, distribution of bottles, end of life of bottles.	This system considers a 500 ml virgin PET bottle, a distribution distance of 128 miles and landfill as end of life treatment of bottles	9.3E + 02
Dettore (2006), recycled PET	USA			This system considers a 500 ml bottle, made of virgin PET (75%) and 25% of recycled PET (25%), a distribution distance of 100 miles and recycling as end of life treatment of bottles	8.4E + 02
Dettore (2006), transport 1528 miles	USA			This system considers a 500 ml bottle, made of virgin PET (75%) and 25% of recycled PET (25%), a distribution distance of 1528 miles and recycling as disposal treatment of bottles	1.4E + 03
Dettore (2006), transport 4928 miles	USA			This system considers a 500 ml bottle, made of virgin PET (75%) and 25% of recycled PET (25%), a distribution distance of 4928 miles and recycling as end of life treatment of bottles	1.3E + 03
Dettore (2006), transport 6328 miles	USA			This system considers a 500 ml virgin PET bottle, a distribution distance of 6328 miles and landfill as end of life treatment of bottles	2.0E + 03

a first step, the actual GWP impact of distribution phase was calculated for each of the above mentioned studies. Then both an average GWP impact of this phase and a standard deviation were calculated using these data. Finally, the mean value obtained was added to the LCA studies which did not include water distribution to the consumer in order to harmonise the results. The calculations performed, the mean as well as the standard deviation obtained are included in Appendix A.

The analysis of the LCA studies on bottled water showed that the types of truck and the travelled distances for the distribution phase were different in each study, whereas the standard situation defined by the customer considered 100 l of bottled water travelling by truck for a distance of 100 km. Therefore, it was necessary to harmonise the Life Cycle Inventory (LCI) data of the analysed studies with the aim to compare the GWP results.

As a first step, some analysed studies (EPD Coop, 2011; Nessi et al., 2012; Studio Life Cycle Engineering, 2008; Dettling et al., 2010) and some transport datasets of commercial LCA databases (i.e. database Ecoinvent v.2.0, 2007, ETH,[1] BUWAL,[2] ELCD 2.0 European Commission, JRC-IES, 2008) contained in software Simapro 7.3.3 (Pré Consultants, 2013), were used to calculate an average GWP result for the distribution of 100 l of water transported on a truck, considering an average distance of 100 km (Appendix B). These datasets were chosen because representative of an average transport via truck or lorry considering an average load.

Then both an average GWP result and the standard deviation for the distribution of 100 l of water for a distance of 100 km were calculated from the above-mentioned studies and datasets.

In the second step of the harmonisation procedure, the actual GWP results of the distribution phase were subtracted from the total GWP impacts in all the studies which considered a distribution distance different from 100 km, and the calculated average GWP result (see Appendix B) was added.

3.5. Step 5: Statistical analysis

3.5.1. Definition of the problem

The case study requires the assessment of the lowest GWP impact caused by tap and bottled water. Therefore, two sets of LCA results are available, expressed in the same unit of measurement (kg CO_2 eq.), which have to be compared with the aim to determine the environmental preferable alternative.

3.5.2. Identification of the statistical test

The PDFs of the random variables (RV) associated with the populations from which the two samples have been extracted are unknown. In

[1] Swiss Federal Institute of Technology Zurich, http://www.ethz.ch/index_EN (accessed on September 2013).

[2] Bundesamt für Umwelt, Wald und Landschaft — Swiss Agency for the Environment, Forests and Landscape, http://www.bafu.admin.ch/index.html?lang=de (accessed on September 2013).

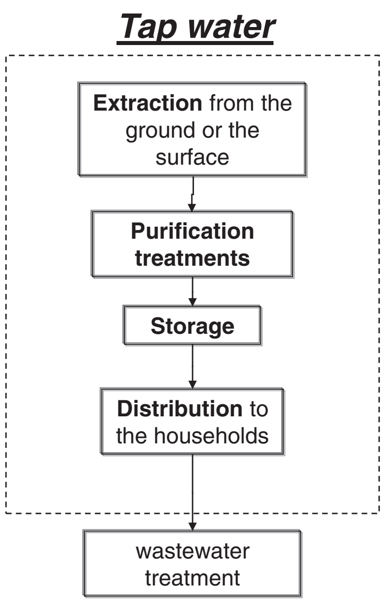

Fig. 2. System boundaries of tap water.

this case it is necessary to use methods not dependent on the knowledge of the parameters of the populations and which are based only on the sample data. The most suitable non-parametric test is the "Wilcoxon's test" (or rank sum test). A detailed description of the Wilcoxon's test is contained in Appendix C (Galeotti, 1983; Spiegel, 1979; Taylor, 1996).

3.5.3. Results of the Wilcoxon's test

The result of the Wilcoxon's test is quantified by the comparison between the calculated value for the variable sample W_x^* and the critical value z_α identified as the upper limit of the critical region R (see Appendix C).

The calculated value for the reduced Wilcoxon variable W_x^*, is:

$$W_x^* = \frac{300-684}{60.4} = -6.36. \quad (1)$$

This means that W_x^* lies in the critical region R of the left tail of the Gaussian reduced distribution (Fig. 4).

The Table C.1 of Appendix C shows the critical values z_α for some α values. So, choosing the lower α value, the condition C.5 (Appendix C, Eq. (C.5)) is still verified:

$$W_x^* = -6.36 < z_\alpha = -2.88. \quad (2)$$

Therefore, the null hypothesis H_0 must be rejected.

In other words, the decision to reject the assumption of homogeneity (H_0) is correct, i.e. the alternative hypothesis H_1 is correct. Consequently the tap-water population PDF f(x) is different from the bottled water population PDF g(y), which confirms the statistical significance of the difference between the mean GWP values of tap and bottled water.

3.6. Step 6: Results and discussion

The results (Figs. 5 and 6) present the GWP impact values of the following scenarios:

- Base case scenario results, which consider only the harmonised functional units;
- Harmonised scenario results, which include the harmonisation of both system boundaries and functional units.

The results of GWP impacts for tap water are reported in Fig. 5, which also displays the standard deviation for each GWP value. Some studies show several results because they analysed different scenarios for water production and distribution (see Table 1 for details).

The results of tap water show little variation between the results of the base case scenario and the harmonised scenario because the calculated average GWP value of distribution phase does not contribute

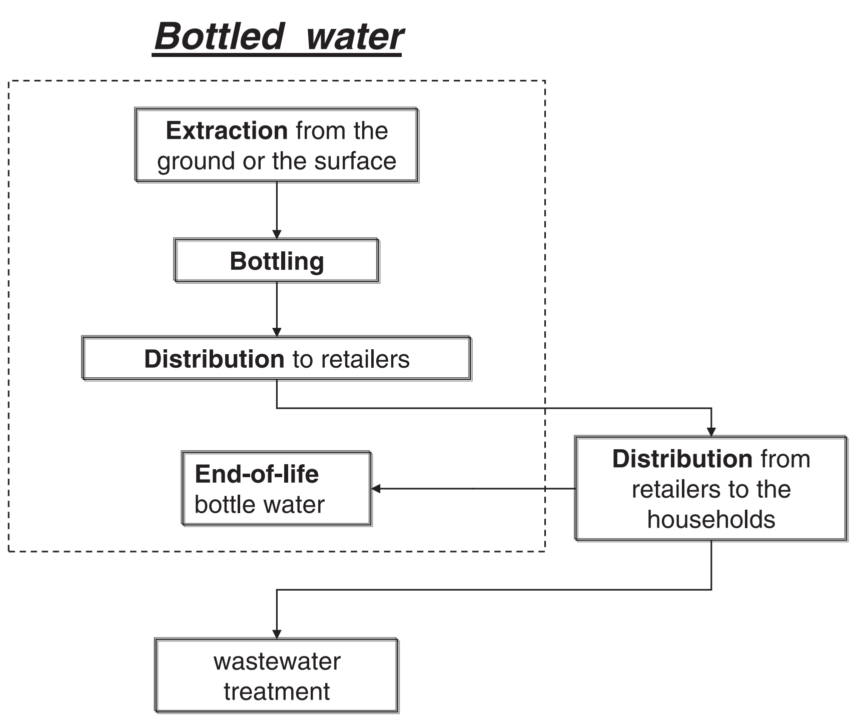

Fig. 3. System boundaries of bottled water.

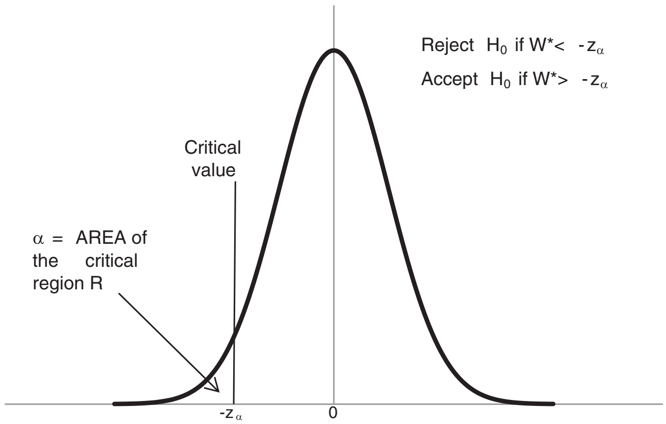

Fig. 4. Gaussian reduced distribution (generic curve).

significantly to the GWP results (Table 3). Nevertheless, the results of the harmonised scenario are very dissimilar. This is due to a major variability of tap water production systems, which strongly affects the GWP results. In fact, the analysed studies use different water withdrawal sources such as sea or ocean (Peters and Rouse, 2005; Barrios et al., 2008), reservoirs (Tarantini and Ferri, 2003; Lundie et al., 2004; Friedrich et al., 2009a,b), groundwater (Vince et al., 2008; Jungbluth, 2006; Botto, 2009; Nessi et al., 2012) or a mix of the above sources (Dettling et al., 2010). Therefore different technology systems were required for drinking water treatments i.e. filtration treatments (Lundie et al., 2004; Friedrich, 2002), reverse-osmosis (Dettore, 2006, Peters and Rouse, 2005), desalination (Peters and Rouse, 2005), boiling (Homäki et al., 2003) and disinfection treatments (Tarantini and Ferri, 2003; Friedrich et al., 2009a,b; Vince et al., 2008; Barrios et al., 2008; Nessi et al., 2012), which need different energy consumption rates, leading to a significant variability of GWP values obtained.

The studies with GWP higher than 0.10 kg CO_2 eq., are reported in grey in Table 3. The worst GWP result is presented in Peters and Rouse (2005) *desalination sea*, who apply desalination treatments to seawater. These kind of drinking water treatments present very high energy consumption, i.e. 3300 kWh per Ml treated, and the authors consider a scenario in which the use of seawater is 100% of time, thus explaining the outstanding result. The remaining GWP results highlighted in grey use energy-consuming technologies as well, such as reverse-osmosis, microfiltration treatments and boiling of municipal and river water respectively (Dettore, 2006; Peters and Rouse, 2005; Homäki et al., 2003) or require water to be pumped into the pipeline over 700 km (Peters and Rouse, 2005 *pipeline 700 km*).

The results of GWP impacts for bottled water are reported in Fig. 6, which also displays the standard deviation for each GWP value. Some studies show several results because they analysed different scenarios for water production and distribution (see Table 2 for details).

The results of bottled water show a remarkable difference between the base case and harmonised scenarios because the distribution phase significantly contributes to the GWP results, depending on the different distribution distances (Table 4). However, almost all the harmonised results present a GWP lower than 20 kg CO_2 eq. Moreover, unlike tap water results, the values of the harmonised results for bottled water are quite similar. In fact, all the analysed studies use groundwater as a supply source and bottling systems are actually quite homogeneous, as they are based on similar technologies.

The studies of the harmonised scenario showing GWP results higher than 20 kg CO_2 eq. (reported in grey in Table 4) are: 1) Franklin Associates (2009) *worst case*, which represents a worst case scenario of all the bottled water production systems studied by the author; 2)

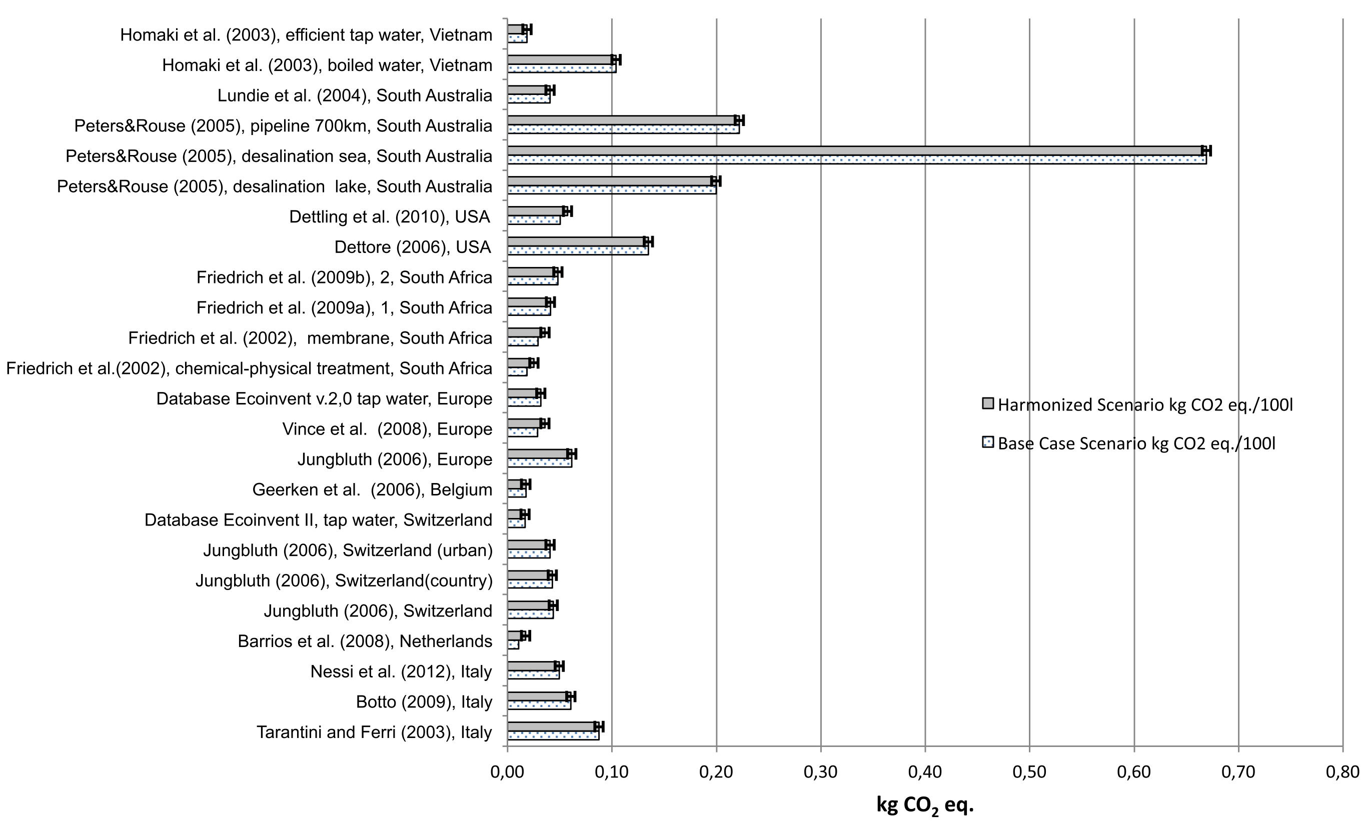

Fig. 5. GWP results of the base case and harmonised scenarios for tap water; the error bars are not drawn to scale, for the correct value please refer to the standard deviation value in Table B.1.

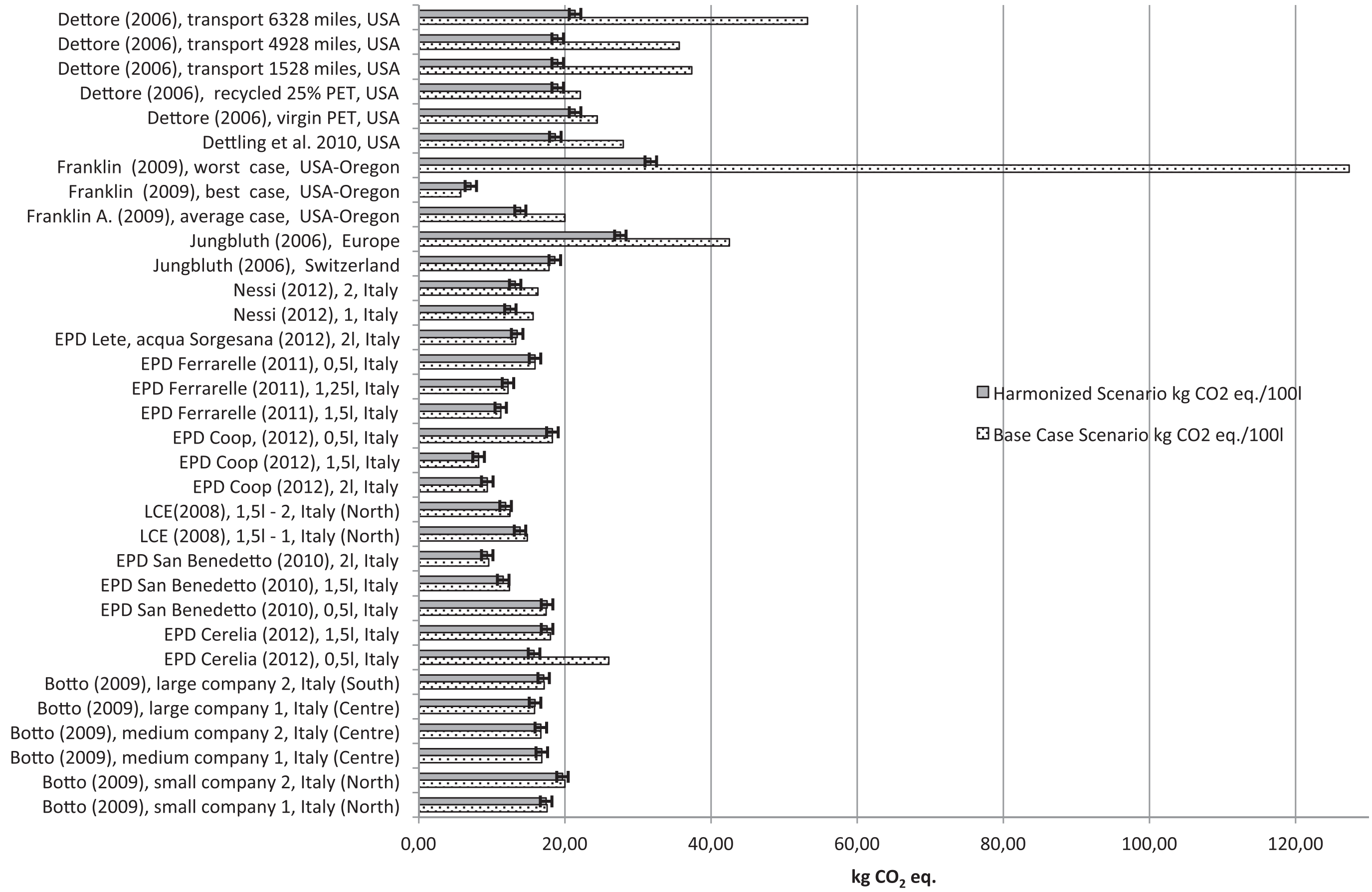

Fig. 6. GWP results of the base case and harmonised scenarios for bottled water; the error bars are not drawn to scale, for the correct value please refer to the standard deviation value in Table B.1.

Dettore (2006) *transport 6328 miles* and 3) Dettore (2006) *PET*, who both consider virgin PET for bottles production and 4) Jungbluth (2006), who refers to an average European bottled water production.

The high GWP values of the above mentioned studies can be explained considering that they contain several key characteristics which strongly affect the results, such as the type (i.e. virgin or recycled)

Table 3
GWP results of the base case and harmonised scenarios for tap water; the standard deviation was calculated as the uncertainty of the mean value.

Name of the study	Base case scenario (kg CO_2 eq./100 l)	Harmonised scenario (kg CO_2 eq./100 l)
Tarantini and Ferri (2003), Italy	0.09	0.09
Botto (2009), Italy	0.06	0.06
Nessi et al. (2012), Italy	0.05	0.05
Barrios et al. (2008), Netherlands	0.01	0.02
Jungbluth (2006), Switzerland	0.04	0.04
Jungbluth (2006), Switzerland (country)	0.04	0.04
Jungbluth (2006), Switzerland (urban)	0.04	0.04
Database Ecoinvent II, tap water, Switzerland	0.02	0.02
Geerken et al. (2006), Belgium	0.02	0.02
Jungbluth (2006), Europe	0.06	0.06
Vince et al. (2008), Europe	0.03	0.04
Database Ecoinvent v.2.0 tap water, Europe	0.03	0.03
Friedrich (2002), chemical–physical Treatment, South Africa	0.02	0.03
Friedrich (2002), membrane, South Africa	0.03	0.04
Friedrich et al. (2009a), 1, South Africa	0.04	0.04
Friedrich et al. (2009b), 2, South Africa	0.05	0.05
Dettore (2006), USA	0.13	0.13
Dettling et al. (2010), USA	0.05	0.06
Peters and Rouse (2005), desalination lake, South Australia	0.20	0.20
Peters and Rouse (2005), desalination sea, South Australia	0.67	0.67
Peters and Rouse (2005), pipeline 700 km, South Australia	0.22	0.22
Lundie et al. (2004), South Australia	0.04	0.04
Homäki et al. (2003), boiled water, Vietnam	0.10	0.10
Homäki et al. (2003), efficient tap water, Vietnam	0.02	0.02
Mean		0.09
Standard deviation		0.03

Table 4
GWP results of the base case and harmonised scenarios for bottled water; the standard deviation was calculated as the uncertainty of the mean value.

Name of the study	Base case scenario (kg CO_2 eq./100 l)	Harmonised scenario (kg CO_2 eq./100 l)
Botto (2009), small company 1, Italy (North)	17.53	17.44
Botto (2009), small company 2, Italy (North)	20.00	19.66
Botto (2009), medium company 1,Italy (Centre)	16.87	16.84
Botto (2009), medium company 2, Italy (Centre)	16.73	16.72
Botto (2009), large company 1, Italy (Centre)	15.87	15.94
Botto (2009), large company 2, Italy (South)	17.13	17.08
EPD Cerelia (2012), 0.5 l, Italy	26.00	15.79
EPD Cerelia (2012), 1.5 l, Italy	18.00	17.56
EPD San Benedetto (2012), 0.5 l, Italy	17.40	17.56
EPD San Benedetto (2012), 1,5 l, Italy	12.40	11.56
EPD San Benedetto (2012), 2 l, Italy	9.59	9.36
LCE (2008), 1.5 l–1, Italy (North)	14.87	13.85
LCE (2008), 1.5 l–2, Italy (North)	12.47	11.88
EPD Coop (2012), 2 l, Italy	9.40	9.40
EPD Coop (2012), 1.5 l, Italy	8.20	8.20
EPD Coop (2012), 0.5 l, Italy	18.30	18.30
EPD Ferrarelle (2011), 1.5 l, Italy	11.20	11.20
EPD Ferrarelle (2011), 1.25 l, Italy	12.20	12.20
EPD Ferrarelle (2011), 0.5 l, Italy	15.90	15.90
EPD Lete, acqua Sorgesana (2012), 2 l, Italy	13.24	13.46
Nessi et al. (2012), 1, Italy	15.66	12.52
Nessi et al. (2012), 2, Italy	16.32	13.18
Jungbluth (2006), Switzerland	17.80	18.63
Jungbluth (2006), Europe	42.50	27.58
Franklin Associates (2009), average case, USA — Oregon	20.02	13.90
Franklin Associates (2009), best case, USA — Oregon	5.74	7.11
Franklin Associates (2009), worst case, USA — Oregon	127.31	31.78
Dettling et al. (2010), USA	27.96	18.70
Dettore (2006), virgin PET, USA	24.45	21.39
Dettore (2006), recycled 25% PET, USA	22.10	19.04
Dettore (2006), transport 1528 miles, USA	37.36	19.04
Dettore (2006), transport 4928 miles, USA	35.62	19.04
Dettore (2006), transport 6328 miles, USA	53.20	21.39
Mean		16.24
Standard deviation		0.92

and the quantity of PET bottle used per litre, and the bottle end of life treatment. As regards the type of PET used, Franklin Associates (2009) *worst case*, Dettore (2006), *virgin PET*, Dettore (2006), *transport 6328 miles* and Jungbluth (2006) use only virgin PET for bottle production. As for the quantity of PET used per litre of bottled water, the worst case of Franklin Associates (2009) use an amount of PET equal to 53 g/l. However, this case refers to a low bottle capacity, i.e. 0.23 l, which explains the higher quantity of PET used per litre.

Finally, the bottle end of life treatment, with particular reference to landfilling (Dettore (2006) *PET*) has an important influence on GWP results.

The GWP harmonised results (Table 3) of tap water are lower than GWP harmonised results (Table 4) of bottled water in all the cases analysed. In fact, the lowest GWP result of the harmonised scenario for bottled water (7.11 kg CO_2 eq.) is obtained in the best case result of Franklin Associates (2009), who considers a hypothetical scenario that includes a PET bottle made of a mixture of 75% virgin and 25% recycled PET. Moreover, in the best case of Franklin Associates (2009), the capacity of the bottle is 0.48 l, the amount of PET used is 20 g/l and the bottle is supposed to be 100% recycled. The highest GWP value of the harmonised scenario for tap water (0.67 kg CO_2 eq.) comes from Peters and Rouse (2005) who consider desalination treatments of seawater.

Although a direct observation of the values leads to an immediate conclusion, the statistical analysis with non-parametric Wilcoxon's test, confirm that the difference between harmonised GWP values of tap and bottled water is significant. Therefore, the statistical test provides significant results which validates and strengthens the final statements of the comparison. In addition, the comparison of the mean GWP results of tap and bottled water (0.09 kg CO_2 eq. and 16.20 kg CO_2 eq. respectively) shows that the tap water has the best environmental performance. Moreover, the ratio between the best GWP value of bottled water and the worst GWP value of tap water is up to 190.

4. Discussion

The application of the method to the case study allowed both to supply a description of the system variability and to evaluate the importance of several key sensitive parameters for tap and bottled water production. Therefore, the harmonisation process coupled with the statistical analysis provided reliable and robust results from the comparison between life-cycle environmental impacts of tap and bottled water production. The method was applied to a case study, which compared two products fulfilling the same function, but it could also be applied to compare either environmentally-friendly technologies and processes or different scenarios (for example energy production scenarios).

Nevertheless, it is worth pointing out that the harmonisation efforts were very challenging due to the different distribution phases as well as the discrepancies in the methodological choices. For these reasons, it was not possible to harmonise all the significant issues found in the studies such as the type of water supply, the distribution networks, the country electricity mix and the end of life treatments of PET bottles.

Moreover, the application of the chosen statistical test to our comparative analysis is a border-line case because of the evident difference (up to two orders of magnitude) between the mean GWP values of the two statistical samples (i.e. tap and bottled water). However, the statistical test is particularly helpful in case of comparative assertions where the mean values of the statistical samples have the same magnitude.

5. Conclusions

The method proposed represents an important step beyond qualitative review. In fact, it was able to rationalize and quicken the efforts needed to carry out the comparison by means of a literature review, with the help of optimized steps and the use of a statistical test.

An important strength of the method is that the harmonisation process allows performing an in-depth analysis of the methodological choices carried out in the published LCA studies on a specific product or system, as well as of the variability of impact assessment results obtained. Consequently, the method enables obtaining more consistent comparisons across the literature LCAs and permits to clarify the varied potential environmental impacts obtained in the studies. For these reasons, the method could be useful for both practitioners and decision makers. In fact, it could be a starting point for conducting a comprehensive decision support analysis or for comparing different policy scenarios. In these cases, the suitable statistical test should be chosen according to the goal of the comparative review and could thus be different from the statistical test adopted for the case study described in this paper.

Conflict of interest

We declare that we do not have any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, our work.

Acknowledgments

The authors would like to acknowledge the contribution from Simone Nessi, Lucia Rigamonti and Francesca Falconi for having provided useful data necessary for the case study.

Appendix A

Table A.1

Calculation of a mean GWP value for the distribution phase of tap water referred to 100 l with the percentage contribution of the distribution phase to the total GWP; the standard deviation was calculated as the uncertainty of the mean value.

Name of the study/dataset	kg CO_2 eq. for 100 l	Percentage contribution of distribution phase	kg CO_2 eq. of distribution phase
Jungbluth (2006), Europe	6.2E-02	18%	1.1E-02
Jungbluth (2006), Switzerland	4,4E-02	18%	8.0E-03
Jungbluth (2006), Switzerland (country)	4.3E-02	18%	8.0E-03
Jungbluth (2006), Switzerland (urban)	4.1E-02	18%	7.0E-03
Tarantini and Ferri (2003), Italy	8.8E-02	3%	3.0E-03
Ecoinvent tap, Switzerland	1.7E-02	8.6%	1.0E-03
Ecoinvent tap, Europe	3.2E-02	4.5%	1.0E-03
Friedrich et al. (2009b), South Africa	4.8E-02	34%	1.4E-02
		Mean	7.0E-03
		Standard deviation	2.0E-03

Appendix B

Table B.1

GWP values for the distribution of 100 l of bottled water for a distance of 100 km; the standard deviation was calculated as the uncertainty of the mean value.

Name of the study/dataset	kg CO_2 eq. of distribution phase considering 100 l and 100 km
LCE (2008), 1	1.1E+00
LCE (2008), 2	1.1E+00
EPD Coop (2011)	9.3E-01
Nessi et al. (2012)	1.4E+00
Dettling et al. (2010)	1.4E+00
Lorry transport, Euro 0, 1, 2, 3, 4 mix, 22 t total weight, 17.3 t max payload RER (ELCD 2.0)	6.6E-01
Transport, Lorry, 16–32 t, EURO3/RER (Ecoinvent v2.2)	1.9E+00
Transport, Lorry, 16–32 t, EURO4/RER (Ecoinvent v2.2)	1.7E+00
Transport, Lorry, 16–32 t, EURO5/RER (Ecoinvent v2.2)	1.7E+00
Truck 16 t ETH (ETH)	2.4E+00
Truck 28 t ETH (ETH)	3.7E+00
Truck 16 t B250 (BUWAL)	1.6E+00
Truck 28 t B250 (BUWAL)	2.2E+00
Mean	1.7E+00
Standard deviation	2.8E-01

Appendix C

Description of a non-parametric test

A non-parametric test (such as the Wilcoxon's rank sum test), which involves a statistical decision, needs to define an appropriate estimator T (i.e. a random variable based only on the sample data) which, in a given sample of size n, takes a value t that is used to accept or reject the given hypothesis. The range of variability of the estimator T is divided into two disjoint regions: in the first one the hypothesis is accepted whereas in the second one (the critical region R) the hypothesis is rejected. The hypothesis on which the test is performed is called the null hypothesis H_0, usually related to the condition II (Section 2.1), in opposition to the contrary hypothesis H_1, usually related to the condition I (Section 2.1). Then a significance level α is chosen, which corresponds to a critical value t_α of the estimator T. The α value identifies the probability that the value t of the estimator T belongs to R; where R is the α-sized critical region delimited, at the top and/or bottom, by the value t_α. Then it is necessary to check if the assumption made is such that the t value obtained from the sample data is included or not in the critical region identified. If t belongs to the critical region R, the null hypothesis H_0 has to be rejected.

Description of the Wilcoxon's test

The "Wilcoxon's test" (or rank sum test) was chosen in this study as the appropriate test on statistical decision because the pdf of the populations from which the samples are extracted are unknown, and a non-parametric test is thus necessary. The test provides a method for deciding whether to accept or reject a given hypothesis. The test assumption (null hypothesis H_0) is that the two samples are homogeneous i.e. the tap-water population pdf f(x) is equal to the bottled water population pdf g(y):

$$H_0 : f(x) = g(y). \tag{C.1}$$

The alternative hypothesis H_1 is that the two samples are non-homogeneous i.e. the tap-water population pdf f(x) is different from the bottled water population pdf g(y):

$$H_1 : f(x) \neq g(y). \tag{C.2}$$

The test is a "one-tailed test" because the hypothesis is that a given value is lower than another value, so if the two samples are non-homogeneous the x_i terms are systematically lower than the y_j terms. If the null hypothesis is correct, there is only one population so the data of two samples can be arranged in ascending order resulting in a unified sequence:

$$x_1, x_2, x_3, \ldots, x_m, y_1, y_2, y_3, \ldots, y_n. \tag{C.3}$$

The method involves the introduction of the random variable of Wilcoxon, W, defined as the sum of the ranks i.e. the sum of the x_i (or y_j) positions in the unified sequence:

$$W_x = \sum_{i=1}^{n_x} r_{x_i}. \tag{C.4}$$

Then a significance level α is chosen which represents the area of the critical region delimited by the corresponding critical value z_α (Fig. 4 and Table C.1). At this point, the comparison between W and z_α determines whether to accept or reject the null hypothesis H_0. The null hypothesis H_0 must be rejected if the following conditions are satisfied:

$$\begin{cases} -W_x < -z_\alpha \\ W_x > -z_\alpha \end{cases}. \tag{C.5}$$

Table C.1
Significance levels and critical values of Gaussian reduced variable.

Significance level α	Significance level α [%]	Critical value z_α
0.10	10%	−1.28
0.05	5%	−1.64
0.01	1%	−2.33
0.005	0.5%	−2.58
0.002	0.2%	−2.88

In other words, the null hypothesis H_0 must be rejected if the W value belongs to the critical region R. The sample sizes are $n_x = 24$ and $n_y = 32$, with $n_x, n_y > 20$, so the Gaussian approximation can be used for the Wilcoxon random variable W:

$$Z_x \equiv W_x^* = \frac{W_x - E[W]}{\sqrt{VAR[W]}} = \frac{W_x - \mu}{\sigma} \tag{C.6}$$

$$E[W] = \frac{1}{2} n_x \left(n_x + n_y + 1\right) \tag{C.7}$$

$$VAR[W] = \frac{1}{12} n_x n_y \left(n_x + n_y + 1\right). \tag{C.8}$$

The calculated value for the reduced Wilcoxon variable W_x^*, is:

$$W_x^* = \frac{300-684}{60.4} = -6.36. \tag{C.9}$$

This means that W_x^* lies in the critical region R of the left tail of the gaussian reduced distribution (Fig. 4). Therefore the first condition of Eq. (C.5) has to be satisfied. Table C.1 shows the critical values z_α for some α values. So, choosing the lower value of α:

$$W_x^* = -6.36 < z_\alpha = -2.88 \tag{C.10}$$

and therefore the null hypothesis H_0 must be rejected.

Appendix D. Acronyms and symbols

BUWAL	(Bundesamt für Umwelt, Wald und Landschaft) — Swiss Agency for the environment, Forests and Landscape
CF	carbon footprint
ELCD 2.0	European Reference Life Cycle Database
EPD	Environmental Product Declarations
ETH	Swiss Federal Institute of Technology Zurich
GSA	global sensitivity analysis
GWP	global warming potential
IQR	inter-quartile ranges
ISO	International Organization for Standardization.
LCA	Life Cycle Assessment
PEF	product environmental footprint
PET	polyethylene terephtalate
PDFs	probability density functions
R	critical region
RV	random variables
U.S.	United States
W_x^*	Wilcoxon's normalized variable

References

Althaus HJ, Chudacoff M, Hischier R, Jungbluth N, Osses M, Primas A. Life cycle inventories of chemicals. Final report Ecoinvent Data v2.0 No.8. EMPA, Swiss Centre for Life Cycle Inventories, Dubendorf, Switzerland; 2007.

Barrios R, Siebel M, van der Helm A, Bosklopper K. Environmental and financial life cycle impact assessment of drinking water production at Waternet. J Cleaner Prod 2008;16:471–6.
Botto S. Tap water vs. bottled water in a footprint approach. Available at: http://precedings.nature.com/documents/3407/version/1/files/npre20093407-1.pdf, 2009. [accessed in September 2013].
Brandão M, Heath G, Cooper J. What can meta-analyses tell us about the reliability of life cycle assessment for decision support? J Ind Ecol 2012;16(s1):S3–7. [April 2012].
Burkhardt III JJ, Heath Garvin, Cohen Elliot. Life cycle greenhouse gas emissions of trough and tower concentrating solar power electricity generation-systematic review and harmonisation. J Ind Ecol 2012;16(S1):S93–S109.
Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew Sustain Energy Rev 2014;29:394–416.
Cerutti AK, Beccaro GL, Bruun S, Bosco S, Donno D, Notarnicola B, et al. LCA application in the fruit sector: state of the art and recommendations for environmental declarations of fruit products; 2013. http://dx.doi.org/10.1016/j.jclepro.2013.09.017.
Cherubini F, Strømman AH. Life cycle assessment of bioenergy systems: state of the art and future challenges. Bioresour Technol 2011;102(2):437–51.
Corominas, L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S., Shaw, A.; 2013.
Dettling J, Tatti E, Ace J. Environmental life cycle assessment of drinking water alternatives and consumer beverage consumption in North America. Nestlè Waters North America Project Report. Available at: http://beveragelcafootprint.com/, 2010. [accessed on September 2013].
Dettore CG. Comparative life-cycle assessment of bottled vs. tap water systems, Report of the Center for Sustainable Systems, Report No. CSS09-11, University of Michigan. Available at: http://css.snre.umich.edu, 2006. [accessed on September 2013].
Ecoinvent database v.2.0. Swiss Centre for Life Cycle Inventories. Available at: http://www.ecoinvent.org/database/, 2007. [accessed in September 2013].
EPD (Environmental Product Declaration) Acqua Minerale Naturale Oligominerale San Benedetto in 0,5 l, 1,5 l, 2,0 l PET bottles, Rev 01, 2012. Registration number: S-P-00212, 24/09/2012. Available at: www.environdec.com (accessed on September 2013).
EPD (Environmental Product Declaration) of Acqua Minerale Coop. Registration number: S- S-P-00279, 24/10/2011; 2011.
EPD (Environmental Product Declaration) of Acqua Minerale Coop. Registration number: S-P-00279, 20/04/2012. Available at: www.environdec.com, 2012. [accessed on September 2013].
EPD (Environmental Product Declaration) of Cerelia natural mineral water bottled in: PET 0,5 l, PET 1,5 l, Glass non-returnable 1 l, 2012. Registration number: S-P-00123, 05/06/2012. Available at: www.environdec.com (accessed on September 2013).
EPD (Environmental Product Declaration) of Ferrarelle mineral water bottled in: PET 0,5 l, 1,25 l, 1,5 l; one-way glass 0,75 l; returnable glass 0,46 l, 0,75 l, 0,92 l, 2011. Registration number: S-P-00281, 26/05/2011. Available at: www.environdec.com (accessed on September 2013).
EPD (Environmental Product Declaration) of Lete mineral water, bottled in PET 0,5 l — 1,5 l, and Sorgesana natural mineral water, bottled in PET 2,0 l, rev 2., 2012. Registration number: S-P-00394, 30/08/2012. Available at: www.environdec.com (accessed on September 2013).
European Commission (EC). Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Recommendation 2013/179/EU. Bruxelles, Belgium; 2013.
European Commission, Joint Research Centre — Institute for Environment and Sustainability and DG Environment — Directorate G, 2008. European Reference Life Cycle Database, version 2.0. Available at: http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm (visited in September 2013).
Food SCP RT. ENVIFOOD Protocol, Environmental Assessment of Food and Drink Protocol, European Food Sustainable Consumption and Production Round Table (SCP RT), Working Group 1, Brussels, Belgium; 2013.
Franklin Associates. Life cycle assessment of drinking water system: bottle water, tap water, and home/office delivery water. Revised Final peer-reviewed LCA report, 2009. 09-LQ-104 22 october 2009. Available at http://www.deq.state.or.us/lq/pubs/docs/sw/LifeCycleAssessmentDrinkingWaterReportOnly.pdf, 2009. (accessed on September 2013).
Friedrich E. Life-cycle assessment as an environmental management tool in the production of potable water. Water Sci Technol 2002;46(9):29–36.
Friedrich E, Pillay S, Buckley CA. Carbon footprint analysis for increasing water supply and sanitation in South Africa: a case study. J Cleaner Prod 2009a;17:1–12.
Friedrich E, Pillay S, Buckley CA. Environmental life cycle assessments for water treatment processes — a South African case study of an urban water cycle. Available at: http://www.wrc.org.za, 2009. [accessed on September 2013].
Galeotti P. Elementi di probabilità e statistica. Editrice Universitaria Levrotto & Bella; 1983.
Geerken TH, Scholliers P, De Vooght D, Spirinckx C, Timmermans V, Van Holdebreke, et al. Sustainability developments of product systems, 1800–2000. Final report, Belgian Science Policy; 2006.
Gnedenko BV. Teoria della probabilità. Editori Riuniti; 1979.
Homäki K, Nielsen Per H, Sathasivan A, Bohe ELJ. Life cycle assessment and environmental improvement of residential and drinking water supply systems in Hanoi, Vietnam. Int J Sustainable Dev World Ecol 2003;10(1):27–42.
Ingwersen WW, Stevenson MJ. Can we compare the environmental performance of this product to that one? An update on the development of product category rules and future challenges toward alignment. J Clean Prod 2012;24:102–8.
Ingwersen WW, Subramanian V. Guidance for product category rule development: process, outcome, and next steps. Int J Life Cycle Assess 2013. http://dx.doi.org/10.1007/s11367-013-0659-0.
International Organization for Standardization (ISO), Environmental management- — life cycle assessment- — principles and framework. ISO 14040, 2006a.
International Organization for Standardization (ISO), Environmental management- — life cycle assessment- — requirements and guidelines. ISO 14044, 2006b.
Jungbluth N. Comparison of the environmental impact of tap water vs. bottled mineral water. Manuscript for the SGWA information bulletin and GWA (Gas Water Sewage). ESU-services, Kanzleistrasse 4, CH-8610 Uster, Switzerland; 2006.
Lizin S, Van Passel S, De Schepper E, Maes W, Lutsen L, Manca J, et al. Life cycle analyses of organic photovoltaics: a review. Energy Environ Sci 2013;6(11):3136–49.
Lundie S, Peters GM, Beavis PC. Life cycle assessment for sustainable metropolitan water systems planning. Environ Sci Technol 2004;38:3465–73.
Martínez-Blanco J, Lazcano C, Christensen TH, Muñoz P, Rieradevall J, Møller J, et al. Compost benefits for agriculture evaluated by life cycle assessment. A review. Agron Sustainable Dev 2013;33(4):721–32.
Menten F, Chèze B, Patouillard L, Bouvart F. A review of LCA greenhouse gas emissions results for advanced biofuels: the use of meta-regression analysis. Renew Sustainable Energy Rev 2013;26:108–34.
Muench S, Guenther E. A systematic review of bioenergy life cycle assessments. Appl Energy 2013;112:257–73.
Nessi S, Rigamonti L, Grosso M. LCA of waste prevention activities: a case study for drinking water in Italy. J Environ Manage 2012;108:73–83.
Padey P, Girard R, le Boulch D, Blanc I. From LCAs to simplified models: a generic methodology applied to wind power electricity. Environ Sci Technol 2013;47:1231–8.
Peters G, Rouse K. Environmental sustainability in water supply planning — an LCA approach for the Eyre Peninsula. 4th Australian Conference on Life Cycle Assessment South Australia; 2005.
Pré Consultants. SimaPro 7.3.3. software. Available at: http://www.pre-sustainability.com/software, 2013. [accessed on September 2013].
Raynolds M, Checkel M, Fraser R. Application of Monte Carlo analysis to life cycle assessment. SAE Technical Paper 1999-01-0011; 1999. http://dx.doi.org/10.4271/1999-01-0011.
Rugani B, Vázquez-Rowe I, Benedetto G, Benetto E. A comprehensive review of carbon footprint analysis as an extended environmental indicator in the wine sector. J Cleaner Prod 2013;54:61–77.
Schreiber A, Zapp P, Mar J. Analysis of life cycle assessment studies on electricity generation with carbon capture and storage. J Ind Ecol 2012;16(S1):S155–68.
Spiegel MR. Probabilità e statistica. Collana Schaum Etas Libri; 1979.
Studio Life Cycle Engineering (LCE). Supporto alla comunicazione ambientale — Life Cycle Assessment (LCA) applicata alla produzione ed uso di alcuni prodotti a marchio Coop- Acqua minerale naturale in bottiglie PET; 2008.
Tarantini M, Ferri F. A life cycle assessment study of the environmental sustainability of domestic water saving techniques. Proceedings of the First International Conference on Sustainable Planning and Development, Skiathos Island; 1–3 October 2003; 2003.
Tascione V, Raggi A. Identification and selection of alternative scenarios in LCA studies of integrated waste management systems: a review of main issues and perspectives. Sustainability 2012;4:2430–42.
Taylor JR. Introduzione all'analisi degli errori. Zanichelli; 1996.
Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renew Sustain Energy Rev 2013;28:555–65.
Vince F, Aosutin E, Breant P, Marechal F. LCA tool for the environmental evaluation of potable water production. Desalination 2008;220:37–56.
Weiss M, Haufe J, Carus M, Brandao M, Bringezu S, Hermann B, et al. A review of the environmental impacts of biobased materials. J Ind Ecol 2012;16(S1):S169–81.
Whitaker M, Heath Garvin A, O'Donoughue P, Vorum M. Life cycle greenhouse gas emissions of coal-fired electricity generation systematic review and harmonisation. J Ind Ecol 2012;16(S1):S53–72.
Yan M-J, Humphreys J, Holden NM. An evaluation of life cycle assessment of European milk production. J Environ Manage 2011;92(3):372–9.
Yoshida H, Christensen TH, Scheutz C. Life cycle assessment of sewage sludge management: a review. Waste Manage Res 2013;31(11):1083–101.