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Assessing the sustainability of small wastewater treatment systems: A composite indicator approach

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HIGHLIGHTS

- Sustainability assessment of WWTPs involving economic, environmental and social dimension.
- Development of a composite indicator for seven wastewater treatment technologies for small communities.
- Application of the analytical hierarchical process (AHP) to assign weights to each indicator.
- A scenario analysis illustrates that constructed wetlands technology is the most sustainable in five out of the seven scenarios evaluated.

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ABSTRACT

The assessment of the sustainability of wastewater treatment (WWT) systems has gained interest in recent years. However, most previous studies have focused on environmental and/or economic dimensions ignoring social aspects. Moreover, they tend to be based on sets of indicators rather than providing a holistic assessment. To overcome this limitation, this paper proposes an innovative methodology to assess the sustainability of WWT systems based on the development of a composite indicator embracing economic, environmental and social issues. Subsequently, the global sustainability of seven WWT technologies for secondary treatment in small communities is compared. The joint application of the analytical hierarchical process (AHP) to assign weights to each indicator allows the incorporation of the preferences of experts. Initially, the global sustainability of the WWT technologies evaluated is quite similar. However, a scenario analysis illustrates that constructed wetlands technology is the most sustainable in five out of the seven scenarios evaluated. Moreover, extended aeration and rotating biological contactors are identified as the technologies with the lowest variability in their sustainability. Hence, in an uncertain context, they might be considered the preferred options. The proposed approach contributes to ease of interpretation of a complex problem such as the selection of the most sustainable WWT alternative.

1. Introduction

Lack of wastewater treatment (WWT) can be a source of pollution, a hazard for the health of human populations and the environment alike. Hence, in the last few decades significant efforts have been made worldwide to implement or improve sanitation systems and wastewater treatment plants (WWTPs). However, in 2010, 2500 million people were still without access to improved sanitation (UNICEF and WHO, 2012). Therefore, the construction and operation of WWT facilities is a challenge that cannot be neglected by authorities. Although in developed regions almost all the wastewater generated (95%) is collected and treated, in the near future, additional WWTPs should be built or updated. For example, to achieve good ecological status as stated by European Directive 2000/60/EC (Water Framework Directive), appropriate treatment of wastewater in small agglomerations should be implemented (Molinos-Senante et al., 2011). However, the legislation on urban WWT (Directive 91/271/EEC) does not state any duty in relation to agglomerations of less than 2000 people equivalent (p.e.).

The implementation of WWTPs requires investment, but the selection of the most appropriate WWT technology is not only an economic issue as other criteria such as environmental and social aspects must be taken into account in the decision process (Popovic et al., 2013). There is clearly a need for a paradigm shift in WWT, considering environmental

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and social aspects in the decision-making-process, not just technical and economic issues (Møller et al., 2012). In this context, the selection of the most appropriate plant design involves the accomplishment of a variety of objectives and the consideration of multiple criteria; therefore, it is a complex problem (Flores-Alsina et al., 2010).

Since the 1990s, there has been an increasing emphasis on defining and measuring the sustainability of service systems (Lundin et al., 1999). The WWT industry is not excluded from this trend and there is widespread recognition of the need to implement more sustainable WWT technologies the performance of which are balanced by environmental, economic and societal sustainability (Muga and Mihelcic, 2008).

The assessment of the sustainability of different WWT technologies would provide very useful information to support the decision-making process (Høibye et al., 2008), but a major limitation is the lack of consensus on the definition of sustainability in general and in particular in the framework of WWT (Hoffmann et al., 2000). In other words, the incorporation of sustainability aspects in the decision-making process is challenging because the definition of sustainable development only sketches a concept rather than giving a rigid rule that can be applied right away (Balkema et al., 2002). Although sustainability can and will be interpreted differently by different people, what it is clear is that it involves three dimensions namely, economic, environmental and social (WCED, 1987).

Despite the limited methods available at present that are widely accepted in measuring sustainability (Lozano-Oyola et al., 2012), several studies have aimed to assess the sustainability of WWT systems following two main approaches: (i) the development of a single indicator integrating different criteria; (ii) the development of a set of multi-disciplinary indicators. For instance, the outcome of exergy analysis, economic analysis, or life cycle assessment (LCA) is a single indicator. As noted by Corominas et al. (2013), during the last decade the use of LCA as a tool to assess the environmental performance of WWTPs has been widespread. Moreover, some studies have refined the standard LCA methodology to focus the assessment on some environmental effects (Wang et al., 2012). Nevertheless, it should be noted that LCA is limited to the evaluation of the environmental sustainability of products and/or processes. Hence, additional indicators introducing economic and social dimensions are needed to measure the sustainability of WWT technologies. Regarding economic analysis in the framework of WWT systems, cost-benefit analysis (CBA) is one of the tools most commonly applied to support the decision-making process (Fan et al., in press; Guest et al., 2009). Although market and non-market costs and benefits can theoretically be included in economic assessment, in practice, due to the complexity of valuing environmental externalities, very few studies introduce them in the evaluation of the economics of WWT technologies (Hardisty et al., 2013; Molinos-Senante et al., 2013). Even in such exceptions, the social dimension is not incorporated in the assessment of sustainability despite the fact that it is known that social aspects play an important role in the implementation of technology (Balkema et al., 2002).

The second approach used to assess the sustainability of WWT technologies is based on the development of a battery of indicators embracing economic, environmental and social issues. Following this approach, several lists of sustainability indicators have been proposed. Most studies have focused on evaluating one WWT process rather than comparing different WWT technologies. Moreover, as in the first approach, the majority of studies do not address social issues; therefore, they do not fully capture the concept of sustainability (Lundin et al., 1999; Balkema et al., 2002; Dixon et al., 2003; Tsagarakis et al., 2003; Møller et al., 2012; Popovic et al., 2013). Despite being a minority, there are some studies which have compared the sustainability of WWT processes. In this context, Muga and Mihelcic (2008) were pioneering in comparing seven WWT technologies grouped into three categories, namely mechanical, lagoon and land treatment systems. In doing so, a set of indicators that incorporate economical, environmental and societal issues was developed and estimated. Høibye et al. (2008) compared five advanced WWT technologies. However, their assessment included technical, economical and environmental aspects, but did not consider societal sustainability. More recently, Estrada et al. (2011) compared seven odor treatment technologies in WWTPs based upon the triple-bottom-line, which includes the assessment of environmental performance, social responsibility and process economics. These three studies – Muga and Mihelcic (2008), Høibye et al. (2008) and Estrada et al. (2011) – proposed and applied an indicator system made up of a considerable number of elements, making them difficult to use by decision makers in some cases (Lozano-Oyola et al., 2012).

A major limitation of assessing sustainability based on a set of indicators is that it does not provide a holistic assessment. Using this approach, the value of each indicator relates separately to each sustainability issue. Hence, the outcome of the evaluation process is not a measure of global sustainability, which indicates the overall state of all the factors integrated in the assessment (Blancas et al., 2010). To overcome this limitation, the initial indicators should be aggregated, converting the indicator system into a composite indicator which provides a multi-dimensional assessment of sustainability. This index is obtained as a mathematical combination of the indicators that represent the different components of the subject under analysis (Merz et al., 2013). Although there are many alternative methodologies for obtaining composite indicators (OECD, 2008), all of them assume that the subjectivity involved in developing the indicator is part of the process. Despite criticism of composite indicators on the basis of this subjectivity, they have been used widely as tools in the decision-making process (Blancas et al., 2011). Moreover, in the framework of sustainability assessment, composite indicators are simple and suitable tools for carrying out comparative analysis. Hence, they have been used to assess the sustainability of a wide range of activities, services and processes, such as tourism destinations (Blancas et al., 2011; Pérez et al., 2013), farming practices (Roy et al., 2014), solid waste management systems (Menikpura et al., 2012) and manufacturing industries (Voces et al., 2012), among others. However, to the best of our knowledge, there is no theoretical development nor empirical application that uses composite indicators to assess and/or compare the sustainability of WWT technologies.

Taking into account that composite indicators are useful tools for aiding public policy decisions and the dissemination of information to the general public (Lozano-Oyola et al., 2012), the objectives of this paper are twofold. The first is to propose a set of indicators to assess the sustainability of WWT technologies, embracing economic, environmental and social issues. Subsequently – and for the first time in the framework of the assessment of WWT technologies – the system of indicators is aggregated into a composite indicator, providing a global measure of sustainability. The second objective is to assess and compare the sustainability of seven different technologies established for secondary treatment in small WWTPs. Two of the seven technologies evaluated are extensive, whereas the others are intensive technologies. Hence, our study also provides some insights into the differences between both types of technology in relation to sustainability.

The outcome of the assessment developed in this study is a composite indicator for each WWT technology evaluated. Hence, this study contributes to facilitating access by stakeholders and decision makers to an interpretation of a complex and multidimensional decision problem, such as the selection of the most sustainable technologies from a wide set of possibilities.

2. Materials and methods

2.1. Indicator system for assessing the sustainability of wastewater treatment technologies

The definition of sustainability indicators is an important step as the selection of sustainable options is based on these indicators (Balkema et al., 2002). Various lists of sustainability indicators can be found in

Table 1
Set of indicators to assess the sustainability of WWT technologies.

Dimension	Indicator	Acronym	Direction	Formula	Source of information*	Unit
Economic	Investment cost	IECS1	Negative	$IECS1 = \frac{\text{Investment cost}}{\text{p.e.}}$	LR	€/p.e
	Operation and maintenance costs	IECS2	Negative	$IECS2 = \frac{\text{Operation costs}}{\text{m}^3\ \text{treated water}}$	RD	€/m^3
Environmental	Organic matter efficiency removal	IENS1	Positive	$IENS1 = \frac{[COD]_{inf} - [COD]_{eff}}{[COD]_{inf}}$	LR	-
	Suspended solids efficiency removal	IENS2	Positive	$IENS2 = \frac{[SS]_{inf} - [SS]_{eff}}{[SS]_{inf}}$	LR	-
	Nitrogen efficiency removal	IENS3	Positive	$IENS3 = \frac{[N]_{inf} - [N]_{eff}}{[N]_{inf}}$	LR	-
	Phosphorus efficiency removal	IENS4	Positive	$IENS4 = \frac{[P]_{inf} - [P]_{eff}}{[P]_{inf}}$	LR	-
	Energy consumption	IENS5	Negative	$IENS5 = \frac{\text{KhW}}{\text{m}^3\ \text{treated water}}$	LR and RD	KhW/m^3
	Land area required	IENS6	Negative	$IENS6 = \frac{\text{m}^2\ \text{land}}{\text{p.e.}}$	LR	m^2/p.e.
	Sewage sludge production	IENS7	Negative	$IENS7 = \frac{\text{Kg sludge}}{\text{m}^3\ \text{treated water}}$	LR and RD	Kg/m^3
	Potential for water reuse	IENS8	Positive	Qualitative	LR and EK	-
	Potential to recover products	IENS9	Positive	Qualitative	LR and EK	-
	Reliability	IENS10	Negative	Qualitative	LR	-
Social	Odors	ISS1	Negative	Qualitative	LR and EK	-
	Noise	ISS2	Negative	Qualitative	LR and EK	-
	Visual impact	ISS3	Negative	Qualitative	LR and EK	-
	Public acceptance	ISS4	Positive	Qualitative	LR and EK	-
	Complexity	ISS5	Negative	Qualitative	LR and EK	-

* LR: literature review, RD: real data, EK: expert knowledge.

the literature (Balkema et al., 2001, 2002; EcoSanRes, 2009; Murray et al., 2009). The differences in these originate from the varied goals and scopes of the researchers as well as the range of sustainable principles on which the selection of indicators is based (Balkema et al., 2001). Hence, we first clearly defined the concept of sustainable WWT technology. To this end, we followed the definition suggested by Balkema (2003), who identified sustainable technology as technology that does not threaten the quantity and quality of resources and has the lowest costs with respect to the physical, sociocultural and economic environments. Following the traditional vision of sustainability (WCED, 1987), the concept of sustainable technology was split into three components or dimensions: environmental, economic and social.

To select an indicator as appropriate for assessing sustainability, it should be widely acknowledged by scientific criteria, transparent, representative, relevant and quantifiable (Nardo et al., 2005). In other words, the indicators should be capable of indicating progress towards sustainability or away from it.

Based on these criteria, Table 1 presents the three dimensions of sustainability and the seventeen indicators defined. Moreover, it shows a short summary of each indicator, providing information on the following aspects: (i) acronym; (ii) direction of improvement, i.e. for a positive indicator, a higher value represents an improvement in sustainability, whereas for a negative indicator, a higher value represents a detriment to sustainability; (iii) associated evaluation issues on which the system is built; (iv) source of the information, i.e. literature review, real data and/or expert knowledgement. Quantitative indicators that can be estimated directly should be differentiated from qualitative indicators, such as those related to social issues for which quantification is not direct. In this latter case, quantification was undertaken using a nine-point scale: the correspondence between the qualitative scale and the numerical value is defined in Table 2. It should be noted that odors and noise indicators, which have been defined as qualitative indicators, may be defined as quantitative indicators since they can be measured in olfs and decibels, respectively. Unfortunately, in the framework of WWT technologies there is not quantitative information available about these indicators. Hence, odors and noise have used as qualitative indicators.

Table 2
Correspondence between the qualitative scale and the numerical rate.

Qualitative scale	Very low	Low	Moderate	High	Very high
Numerical rate	1	3	5	7	9

A brief description of the sustainability indicators for the different dimensions is given below.

Economic indicators represent the costs associated with the construction and the operation of the WWTP. They are often decisive when choosing a technology in a practical situation (Balkema et al., 2002). The two most commonly used indicators are the costs of investment and operation and maintenance. It should be noted that when the investment costs of different WWT technologies are compared, it is essential to take into account the lifespan of each technology.

Environmental indicators refer to the environmental efficiency of the WWT technology in terms of quality of the effluent, resources used, emissions and the potential for the technology to be updated to implement additional processes. Because the conventional water quality constituents associated with WWT are organic matter,[1] suspended solids (SS), nitrogen (N) and phosphorus (P), the group of environmental indicators relates to the efficiency of the removal of such pollutants. Regarding the carbon footprint, the indicator chosen is the energy consumed to carry out the WWT. On the one hand, it has been considered better to propose the energy used as an indicator, rather than the emissions of $CO_{2\text{-eq.}}$ as in the LCA approach, as greenhouse gas (GHG) emissions not only depend on the consumption of electricity but also on the electrical production mix. On the other hand, although recently there has been increasing interest in measuring direct GHG emissions from WWTPs (Foley et al., 2010), empirical studies are still limited.

Although our study was focused on small communities, the land required by the different treatment technologies differs considerably as they include both intensive and extensive technologies. Hence, the land area required was proposed as the environmental sustainability indicator. Because sewage sludge is a by-product inevitably generated in WWTPs, the management of which is one of the most complex problems facing the WWT industry (Metcalf and Eddy, 2004), sewage sludge production was considered an environmental indicator of the performance of WWT technologies. Another group of environmental indicators is the potential to reuse water and the potential to recover products from wastewater such as phosphorus. To conclude, reliability, understood as the probability of mechanical failures and the impact of failures upon effluent quality (Eisenberg et al., 2001), was defined as an environmental indicator.

The *social indicators* represent the impact of the WWT on society. Most of these are qualitative indicators and are therefore often not

[1] In our case study, organic matter is measured as chemical oxygen demand (COD).

addressed in the assessment of the sustainability of WWT technologies or WWTPs. However, it is essential to include the impact of the implementation of technology on society as a whole. Indicators in this category are as follows: (i) odors; (ii) noise; (iii) visual impact; (iv) public acceptance; (v) complexity of construction and operation. It should be noted that simplicity might be a key factor in the selection of the WWT system, especially in developing regions.

To facilitate decision making, once a battery of sustainability indicators was proposed and defined, the next step was to aggregate them in a composite indicator.

2.2. Composite indicator for assessing the sustainability of wastewater treatment technologies

According to the OECD Glossary of Statistical Terms, a composite indicator "is formed when individual indicators are compiled into a single index, on the basis of an underlying model of the multi-dimensional concept that is being measured" (OECD, 2014). Moreover, a composite indicator should be based on a theoretical framework/definition that allows individual indicators/variables to be selected, combined and weighted in a manner which reflects the dimensions or structure of the phenomena being measured. On the other hand, the OECD defines a sustainable development indicator as "a statistical measure that gives an indication of the sustainability of social, environmental and economic development" (OECD, 2014). The merging of both definitions means that the assessment of the sustainability of WWT technologies should be carried out based on a composite indicator that integrates the environmental, economic and social dimensions. Several methods are available for generating compositing indicators. Nevertheless, it is often quite difficult to construct objective composite indicators as they may involve different kinds of concerns. One of the ways of developing composite indicators with greater legitimacy and acceptance by society is by involving individuals in their construction (Maggino and Ruviglioni, 2009).

The first step in obtaining a suitable indicator for WWT technologies was to distinguish between positive and negative indicators based on the direction of change, i.e. improvement/detriment. As has been reported on the definition of the individual indicators (Section 2.1), positive indicators are those for which a higher value signifies an improvement in the sustainability of the technology, e.g. efficiency in the removal of pollutants. On the other hand, negative indicators are those for which a higher value implies a worsening in the sustainability of technology, e.g. energy consumed per cubic metre of treated water.

Let I_{ij} denote the value of the ith technology in the jth positive indicator, with $j \in J$, where J is the set of positive indicators in the system. Regarding negative indicators, let I_{ik} denote the value that provides the ith technology in the kth negative indicator with $k \in K$, where K is the set of negative indicators in the system. Hence, to normalize both types of indicator, two approaches should be followed (Eqs. (1) and (2)):

$$IN_{ij} = \frac{I_{ij} - I_j^{\min}}{I_j^{\max} - I_j^{\min}} \text{ for positive indicators} \tag{1}$$

$$IN_{ik} = \frac{I_k^{\max} - I_{ik}}{I_k^{\max} - I_k^{\min}} \text{ for negative indicators} \tag{2}$$

where IN_{ij} is the normalized value of the ith technology in the jth positive indicator, IN_{ik} is the normalized value of the ith technology in the kth negative indicator, $I_j^{\min}$ and $I_j^{\max}$ are the minimum and the maximum values respectively of the jth indicator and $I_k^{\min}$ and $I_k^{\max}$ are the minimum and the maximum values respectively of the kth indicator.

These quotients (Eqs. (1) and (2)) allow the indicator values to be expressed using a dimensionless scale with values ranging between 0 and 1. Hence, the units used and the range of variation in measuring the initial indicators do not affect the sustainability results.

Once the indicators were normalized, the next step was to aggregate them. In this step, it is necessary to establish the commensurability or incommensurability of the initial battery of indicators. Following the weak comparability concept of ecological economics and as other studies have done (Shmelev and Rodríguez-Labajos, 2009; Blancas et al., 2010), we adopted the incommensurability approach. In other words, it was assumed that there is no common unit of measurement (whether in monetary or physical terms) within the different sustainable indicators defined (Martínez-Alier et al., 1998).

Subsequently, the weights representing the relative importance of each initial indicator should be defined. The choice of the weighting method is always controversial as it involves a certain level of subjectivity (Nardo et al., 2005). To obtain weights there are two main approaches, namely direct and indirect methods. On the one hand, some methods, such as correlation analysis, principal components analysis (PCA) and data envelopment analysis (DEA), use the data of the units evaluated to estimate the weights. Whereas correlation analysis and PCA provide a unique weight for each indicator for all the units evaluated, DEA generates a different weight for each unit assessed. The main advantage of such approaches is that weights are derived based on an objective principle. However, they should be considered carefully as by removing any control over the weighting procedure, the results change.

On the other hand, other methods estimate the weights externally to the data of the units evaluated. They are often applied because are considered more stable than those produced by direct evaluations (Maggino and Ruviglioni, 2009). Within these models two approaches can be distinguished. First, there is multi-criteria decision making, which refers to making preference decisions over available alternatives that are characterized by multiple conflicting criteria. The method of pair comparison included in the analytic hierarchy process (AHP) is one of the best-known techniques in this field. Second, there are multi-attribute compositional models, which are based upon a statistical de-compositional approach through which it is possible to manage subjective comparisons of attributes on different levels. Within this approach, conjoint analysis is the technique most commonly applied (Wu and Hamada, 2011).

The different approaches to obtaining weights in the development of composite indicators have their pros and cons. However, in our case study, the indirect approach is more suitable than the direct approach since the number of technologies to be evaluated is small (Peters and Zelewski, 2008). Within this latter approach, the application of AHP enables the consideration of social, environmental and economic objectives in assessing the sustainability of WWT technologies (Ellis and Tang, 1991; Zeng et al., 2007). In particular, the advantages of AHP to establish weights are its flexibility, its ability to check inconsistencies and the possibility of recognizing whether one indicator is more important than another, even in case of qualitative indicators (Loghmanpoor et al., 2013). Hence, in this study, the AHP technique was employed to assign weights to each indicator as it allows the preferences of experts to be included in an intuitive manner. In spite of the advantages of AHP method, it is not free of pitfalls. Since AHP decomposes the decision problem into a number of subsystems, the number of pairwise comparisons to be made may become very large and thus become a lengthy task (Macharis et al., 2004). Another pitfall of the AHP method is the artificial limitation of the use of the Saaty's scale. Sometimes, the decision maker might find difficult to distinguish among the preferences. Finally, it should be noted that in AHP, as in other indirect methods to allocate weights, the results are dependent on the participants (Belton, 1986).

Using Saaty's scale (Table 3), the sustainability dimensions and indicators (criteria and sub-criteria respectively in the AHP nomenclature) are compared in pairs to assess their relative importance with respect to the goal evaluated, i.e. the sustainability of WWT technologies. The basic scale proposed by Saaty (1980) was used to assess the degree of preference between two criteria or sub-criteria. First, preferences

Table 3
Saaty's scale of preferences.

Scale	Numerical rate
Extremely preferred	9
Very strong to extremely preferred	8
Very strong preferred	7
Strongly to very strongly preferred	6
Strongly preferred	5
Moderately to strongly preferred	4
Moderately preferred	3
Equally to moderately preferred	2
Equally preferred	1

Source: Saaty (1980).

regarding the three dimensions of sustainability were investigated, i.e. economic, social and environmental issues. For example, if the social and economic dimensions of sustainability are compared, a value of 1 means that they are of equal importance, whereas a value of 9 indicates that social issues rather than economics are of absolute importance in the assessment of the sustainability of WWT technologies. In a second step, the preferences for the different indicators within each sustainability dimension were evaluated.

Each set of comparisons was then entered into a matrix which was normalized to obtain the eigenvectors, which are the weights of the sustainability dimensions and the weights of the indicators within each dimension. As the comparisons are carried out through personal judgements, consistency verification is needed to guarantee the judgements are consistent. In doing so, the consistency ratio (CR) should be computed for each pairwise comparison. This is a measure of how a given matrix compares to a purely random matrix in terms of the consistency index (CI) (Bottero et al., 2011). For matrices greater than 3 × 3 a value of CR ≤ 0.1 (i.e. 90% consistent or 10% inconsistent) is considered acceptable (Saaty, 1996); where CR is greater than 0.1, pairwise comparisons should be revised to improve the consistency.

The CR was defined by Saaty (1980) as follows:

$$CR = {}^{CI}\!\big/_{RI} \tag{3}$$

where CI is the consistency index, which is a measure of the degree of inconsistency in the matrix of joint membership judgments. As shown in Eq. (4), CI depends on the maximum eigenvalue (λ_{max}) and the number of factors in the judgement matrix (n). RI is the consistency index of a randomly generated reciprocal matrix from the nine-point scale, with forced reciprocals (Saaty, 1980).

$$CI = \frac{1}{n-1}(\lambda_{max} - n) \tag{4}$$

Once the weights of each indicator have been defined, the economic sustainability *ECS*, environmental sustainability *ENS* and social sustainability *SS* for each WWT technology can be computed using the following formulae:

$$ECS_i = \sum_{c=1}^{C} W_c \cdot IN_{ic} \tag{5}$$

$$ENS_i = \sum_{v=1}^{V} W_v \cdot IN_{iv} \tag{6}$$

$$SS_i = \sum_{s=1}^{S} W_s \cdot IN_{is} \tag{7}$$

for $i = 1, 2, \ldots, n$ where n is the number of WWT technologies; $c = 1, 2, \ldots, C$ where card (c) is the number of economic indicators; $v = 1, 2, \ldots, V$ where card (v) is the number of environmental indicators; $s = 1, 2, \ldots, S$ where card (s) is the number of social indicators; W_c is the weight of the indicator c; W_v is the weight of the indicator v; W_s is the weight of the indicator s; IN_{ic} is the normalized value of the ith technology in the cth indicator; IN_{iv} is the normalized value of the ith technology in the vth indicator; IN_{is} is the normalized value of the ith technology in the sth indicator.

Following the same approach and considering the relative importance of each dimension of sustainability obtained through the AHP model, the overall sustainability of each WWT technology evaluated can be computed as follows:

$$GS_i = W_{ECS} \cdot ECS_i + W_{ENS} \cdot ENS_i + W_{SS} \cdot SS_i \tag{8}$$

where GS_i is the global sustainability indicator of the ith WWT technology; W_{ECS}, W_{ENS} and W_{SS} represent the importance (weights) of the economic, environmental and social dimensions of sustainability respectively; ECS_i is the economic sustainability of the ith WWT technology; ENS_i is the environmental sustainability of the ith WWT technology; SS_i is the social sustainability of the ith WWT technology.

The final step in developing a composite indicator is to assess its robustness in terms of producing correct and stable measures. In other words, a scenario analysis employing "what-if" questions should be performed. The scenario analysis carried out in this paper was based on changing the weights of the sustainability dimensions to check whether the changes modified the ranking of the WWT technologies in terms of their sustainability.

2.3. Case study description

The assessment of the sustainability of a set of WWT technologies is always situational. This premise was even more central to our study as the weight of each sustainability indicator was computed based on AHP methodology. Thus, for performance pairwise comparisons it is always necessary to have a scenario in mind (Bottero et al., 2011). Hence, to assess the sustainability of WWT technologies in small WWTPs, a hypothetical but common scenario was assumed. This considered a WWTP with a capacity of 1500 p.e. capable of treating an average flow rate[2] of 400 m^3 per day as it was assumed that the sewerage system would be mixed (including wastewater and rainwater). The source of water is municipal; therefore, the water pollutants and their concentrations are standardized accordingly.[3] Moreover, it was assumed that the treated water is discharged to non-sensitive areas without reuse.

Regarding the WWT technologies to be evaluated in order to carry out a more thoroughly and focused comparison, the seven secondary treatment technologies usually applied in small WWTPs were assessed in this study (Ortega de Ferrer et al., 2011). The main reason for limiting our study to seven WWT technologies is that according to AHP methodology, to achieve consistency in relation to preferences, the maximum number of alternatives should be a maximum of seven (Kalbar et al., 2012).

The WWT technologies assessed comprised two extensive technologies: (i) constructed wetlands (CW); (ii) pond systems (PS). The intensive technologies evaluated were as follows: (iii) extended aeration (EA); (iv) membrane bioreactor (MBR); (v) rotating biological contactor (RBC); (vi) trickling filter (TF); (vii) sequencing batch reactor (SBR).

[2] Within the small WWTP context, capacity and flow rate was arbitrary, but this choice does not influence the main conclusions extracted from the sustainability assessment.

[3] Based on the values provided by Poch Espallargas (1999), Metcalf and Eddy (2004) and Molinos-Senante et al. (2012), the concentrations of the pollutants in the influent were assumed to be as follows: biological oxygen demand 310 mg/l; chemical oxygen demand 750 mg/l; suspended solids 285 mg/l; phosphorus 11.5 mg/l; total Kjeldahl nitrogen 62.5 mg/l; nitrate 2 mg/l; nitrite 1 mg/l.

Table 4
Initial sustainability indicators for each WWT technology for the case study defined.

	CW	PS	EA	MBR	RBC	TF	SBR
IECS1	219	199	239	355	355	347	391
IECS2	0.119	0.179	0.203	0.303	0.173	0.180	0.185
IENS1	0.70	0.75	0.85	0.89	0.80	0.85	0.80
IENS2	0.80	0.70	0.90	0.99	0.85	0.70	0.90
IENS3	0.50	0.30	0.70	0.70	0.50	0.45	0.65
IENS4	0.40	0.55	0.45	0.50	0.20	0.45	0.45
IENS5	0.06	0.06	0.50	0.70	0.30	0.30	0.41
IENS6	4.50	4.00	0.52	0.25	0.40	0.35	0.35
IENS7	1.73	0.85	1.22	0.85	0.85	0.85	0.85
IENS8	Moderate	Low	Moderate	Very high	Moderate	Moderate	High
IENS9	Low	Low	Moderate	High	Moderate	Moderate	High
IENS10	Moderate	Moderate	High	Moderate	High	Low	High
ISS1	High	High	Low	Low	Moderate	Moderate	Low
ISS2	Low	Low	High	High	Moderate	Moderate	High
ISS3	Very low	Very low	High	High	High	Very High	Moderate
ISS4	High	High	Moderate	Moderate	Moderate	Low	Moderate
ISS5	Low	Low	High	Very high	High	High	Moderate

Source: Tsagarakis et al. (2003); Comas et al. (2003); Metcalf and Eddy (2004); Balaguer et al. (2007); Monclus et al. (2009); Cedex (2008); Gavasci et al. (2010); Centa (2010); Ortega de Ferrer et al. (2011); expert knowledge and real data from Spanish WWTPs.

Following Muga and Mihelcic (2008), the WWT operational life stage was chosen for this study as the length of time of this stage is considerably higher than the other life stages. Moreover, the environmental impacts in this stage are significantly greater than those during the construction and demolishing/disposal stages (Lassaux et al., 2007).

3. Results and discussion

3.1. Individual sustainability indicators

To obtain the value of the initial sustainability indicators we employed a variety of sources, comprising a literature review (research articles published in international journals, proceedings of conferences and handbooks on WWT), interviews with experts performed in the framework of the NOVEDAR project (with the cooperation of 11 research groups, 29 relevant water companies and 14 public entities related to water management) and real data from a sample of Spanish WWTPs.

Several cost functions were used to quantify the investment costs. These show the relationship between the dependent variable (cost) and the independent variable (p.e. or flow-rate). Operating and maintenance costs were estimated using real data from a sample of Spanish WWTPs. Although they may also be quantified using cost functions, following Molinos-Senante et al. (2013), it was assumed that the data provided directly by the operating companies would be more reliable than information provided by cost functions. Regarding the indicators within the environmental dimension, most of the references used provide a range of values rather than a concrete value. Hence, our assessment was based on the average value of such a range. Nevertheless, it should be noted that uncertainty in the performance of the treatment units affects all technologies equally. Hence, a change in these or other variables would not necessarily involve a change in the ranking of alternatives (Molinos-Senante et al., 2012). To conclude, the information on social indicators was derived primarily from handbooks on WWT and data were obtained using contributions from members involved in the NOVEDAR project. Detailed information concerning the references, cost functions and environmental performance indicators are provided in Appendix A.

While it is not our intention to comment on the value of the 17 indicators for each WWT technology, Table 4 shows the relevant differences between technologies for most of the initial indicators. We can verify that both the investment costs and operating and maintenance costs of extensive technologies are lower than those of intensive technologies. Within intensive technologies, although extended aeration is the technology with the lowest investment costs, the operating and maintenance costs are considerably higher than those associated with other technologies, such as rotating biological contactor, trickling filter and sequencing batch reactor. Regarding environmental indicators, the high performance of the membrane bioreactor in the removal of COD and SS, which involves a significant consumption of energy per cubic metre of treated water is remarkable. Regarding other environmental indicators, such as land area required, extensive technologies are of course impaired in comparison to intensive technologies. From the social point of view, some indicators, for example visual impact and complexity, favor extensive technologies, whereas odor pollution works against the social sustainability of such alternatives.

Although the proposed indicator system was made up of a moderate number of elements in comparison to other studies assessing the sustainability of other services or products, Table 4 evidences the difficulty of obtaining conclusions concerning the sustainability of WWT technologies from a global point of view. The quantification of the battery of indicators illustrates the need to aggregate the initial indicators within a composite indicator, as each indicator exhibits the position for each sustainability issue but not from a holistic point of view.

3.2. Composite indicator of sustainability

Once we had quantified the indicator system, the next step was to obtain the composite indicators using the methodology proposed in Section 2.2 to aggregate the system information in three phases. In the first phase, following an AHP approach and based on experts' opinions,[4] the weights of the sustainability dimensions and indicators were obtained. In the second phase, a composite indicator for each dimension (economical, environmental and social) was constructed. In the third phase, a global composite indicator providing a multidimensional measure of the sustainability of WWT technologies was obtained. This indicator simultaneously considers all the indicators for each sustainability dimension.

To obtain the weights of each sustainability dimension and initial indicator, a team of 45 international experts on WWT from the academic, research and industrial fields were asked to complete a carefully designed questionnaire. Thirty-five out of 45 experts sent us the complete questionnaire. However, after checking the consistency ratio of the

[4] For example to determine experts' preferences among the environmental and economic dimensions, the following question was asked: *Do you believe that the economic criterion is more important/preferred over the environmental criterion in the context of sustainable wastewater treatment technologies in small WWTPs? If your answer is YES, please indicate your preference for the economic criterion over the environmental criterion using the preference scale. If your answer is NO, please indicate your preference for the environmental criterion over the economic criterion using the preference scale.*

responses, only 25 questionnaires were considered acceptable. The other 10 questionnaires were dismissed since at least one consistence ratio was larger than 0.1. As an AHP approach was followed, the experts were faced with pairwise comparisons; first, they were asked to compare the importance of the dimensions of sustainability; subsequently, they were asked about the importance of the sustainability indicators previously defined within each dimension (Table 1).

In aggregating peoples' preferences, different approaches can be followed, but two are used most commonly (Bernasconi et al., 2014): (i) aggregating the individual judgments (AIJ) for each set of pairwise comparisons into an "aggregated hierarchy"; (ii) aggregating individual's priorities (AIP), an approach which synthesizes each of the individual hierarchies and aggregates the resulting priorities. In our study, the AIJ approach was adopted because of the large number of individuals consulted. Moreover, we employed the geometric mean as the aggregation method because this is consistent with the meaning of both judgements and priorities in AHP (Aull-Hyde et al., 2006).

Based on expert opinion, the environmental dimension of sustainability is the most important (47.0%), the economic dimension of sustainability is second (30.8%) and finally, social sustainability (22.2%) is third. The attribution of the lowest weight to social aspects is not surprising as most previous studies that have assessed the sustainability of WWT technologies have focused predominantly on environmental and/or economic aspects, omitting the social dimension (Rodriguez-Garcia et al., 2011; Hardisty et al., 2013).

The weights attributed to each sustainability indicator within each dimension are shown in Table 5. Regarding economic sustainability, the weights attributed to the two initial indicators illustrate the importance of the operating and maintenance costs over investment costs. Within environmental sustainability, the indicators with the greatest weight are those associated with the efficiency of the removal of pollutants, i.e. the group of indicators related to the quality of the effluent. In general, although climate change is considered to be a significant environmental problem, the weight attributed by WWT experts to the consumption of energy is lower than that attributed to other indicators such as sludge production. However, this preference is not surprising as previous studies (e.g. Larsen et al., 2007) have verified that the potential for global warming is not among the most relevant impact categories for WWTPs. The potential to recover sub-products is identified as the least important indicator in terms of environmental sustainability. Although the recovery of products from wastewater would undoubtedly contribute to improving the sustainability of WWT, the truth is that in small WWTPs, on which our study is focused, the implementation of processes aimed at achieving this objective would be complex. Odor pollution is identified as the most important indicator (37.2%) within social sustainability. There is an increasing need for odor management as malodors are not only a direct threat to human health and welfare, but also represent a particulate secondary contaminant emission (Estrada et al., 2011). Visual impact is considered the indicator of least importance, attributed a weight of 9.2%.

Once the weights of each sustainability dimension and indicator were calculated and after normalizing the initial indicators defined in Table 1, the next step was to construct a composite indicator for each dimension of sustainability using Eqs. (5), (6) and (7). Hence, the rankings based on dimensional composite indicators are obtained. These rankings are shown in Table 6 and Fig. 1. The bar chart represents the rank reached by each WWT evaluated for each dimension.

From an economic point of view, extensive technologies are more sustainable than intensive technologies. The high costs of the membrane bioreactor should be noted as this means very low economic sustainability. Regarding the environmental dimension, the results are opposite to those for the economic dimension. On the one hand, constructed wetlands and pond systems are the two technologies rated as having the lowest environmental sustainability. At first, this result may seem surprising as some studies (Kalbar et al., 2012; Yildirim and Topkaya, 2012) have reported that extensive technologies are more environmentally friendly than intensive technologies. However, these studies have primarily focused on energy consumption using a set of environmental indicators rather than the composite indicator proposed in this study. On the other hand, the membrane bioreactor is the technology rated most sustainable from an environmental point of view. The large quantity of energy consumed by the membrane bioreactor is balanced by its excellent performance in the removal of COD and SS and also by its high potential to reuse the treated water. Finally, the social composite indicator places extended technologies in a better position than intensive technologies. However, with the exception of the trickling filter, the differences among technologies are not as marked as for the other two sustainability dimensions.

The example in which the membrane bioreactor is the best technology from an environmental point of view but the worst from an economic perspective, whereas constructed wetlands has the opposite result, illustrates the usefulness of developing composite indicators. From the information shown in Table 6 and Fig. 1, it is very difficult to determine which WWT technology is more sustainable as each presents some "favorable" and some "unfavorable" characteristics from a sustainability point of view. Hence, using Eq. (8), the three dimensions of sustainability were aggregated to obtain the ranking of the WWT technologies based on a global composite indicator as shown in Fig. 2.

Fig. 2 shows two surprising and important findings. First, the global sustainability of the seven WWT technologies evaluated is quite similar. Thus, although extended aeration is the most sustainable technology and the rotating biological contactor is the least sustainable technology according to our results, no final conclusions can be drawn. Moreover, it should be noted that the values of some initial indicators depend on the context and thus they can change with a region or country. Second, although the basis and the operation of extensive and intensive technologies is quite different, no significant differences are observed in terms of sustainability.

3.3. Scenario analysis

The composite indicator depends on the weights attributed to each sustainability dimension and although weights were calculated based on international WWT expert opinions, they were still subjective judgements reflecting the experts' preferences. In the previous composite analysis, slight differences among the WWT technologies were observed from a sustainability point of view. Therefore, to gain a greater understanding of the differences between dimensions and observe more clearly how the selection of the technologies depends on the weights assigned, a sensitivity analysis based on scenarios was performed.

Seven scenarios were defined, reflecting different views of the relative importance of the three dimensions of sustainability (Table 7). Three main groups embracing all the main possibilities were established (A, B and C). In scenario A, the three dimensions had the same level of importance. In scenarios B1, B2 and B3, the weights were changed and one dimension was considered more relevant at a time (weight equal to 50%) than the other dimensions, which were attributed the same importance (weight equal to 25%). Finally, scenarios C1, C2 and C3 were the most extreme, with a weight of 80% attributed to one dimension, as opposed to a weight of 10% for the other two dimensions.

Fig. 3 shows the different composite sustainability indicators for each WWT technology related to the seven scenarios defined in Table 7, as well as the original scenario based on the weights ascribed by the WWT experts.

When the weights attributed by experts are used to quantify the composite indicator, extended aeration is identified as the most sustainable technology in small communities; however, the assessment of global sustainability in different scenarios provides different results.

When the three dimensions of sustainability are equally prioritized (scenario A), all options show moderate variations with similar scores, constructed wetlands being the most sustainable. Similarly, for cases

Table 5
Weights of the sustainability dimensions and indicators expressed in percentage.

Dimension	Indicator	Weight of indicators (%)	Weight of dimensions (%)
Economic	Investment cost (IECS1)	33.6	30.8
	Operating and maintenance costs (IECS2)	66.4	
Environmental	Organic matter efficiency removal (IENS1)	14.6	47.1
	Suspended solids efficiency removal (IENS2)	12.4	
	Nitrogen efficiency removal (IENS3)	10.7	
	Phosphorus efficiency removal (IENS4)	12.4	
	Energy consumption (IENS5)	8.8	
	Land area required (IENS6)	7.8	
	Sewage sludge production (IENS7)	9.7	
	Potential for water reuse (IENS8)	9.4	
	Potential to recover products (IENS9)	6.5	
	Reliability (IENS10)	7.8	
Social	Odors (ISS1)	37.2	22.1
	Noise (ISS2)	18.2	
	Visual impact (ISS3)	9.2	
	Public acceptance (ISS4)	23.0	
	Complexity (ISS5)	12.4	

B1, B2 and B3, and depending on the scenario, the most sustainable technologies correspond to constructed wetlands and extended aeration. It should be noted that pond systems is one of the highest scoring technologies in almost all cases. As expected, scenario B2 shows results close to the original composite due its similar dimension prioritization. Nevertheless, applying a more extreme prioritization, the previous trend is still observed but showing clear differences between technologies. For C scenarios, it is evident that when the economic dimension is considered more important, low-cost extensive technologies such as constructed wetlands and pond systems are ranked highest. However, in a scenario in which the environmental weight predominates (C2), technologies that are high in consumption in terms of energy but are highly efficient in terms of pollutant removal lead the classification (membrane bioreactor, sequencing batch reactor and extended aeration). Finally, regarding the social dimension and similar to the situation in C1, the integration of the landscape and the capacity to create ecosystems seem to push for constructed wetlands and pond systems as the measures perceived most positively by the population, thus increasing their sustainability.

As can be seen from five of the seven scenarios, constructed wetlands was the most sustainable technology. Only when the environmental dimension is considered more important than economic and social aspects are intensive technologies placed in a better position. It should be highlighted that the membrane bioreactor occupies the first place in the ranking of sustainable WWT technologies in scenario C2, i.e. when the weight attributed to the environmental dimension is greater than the weight attributed to the other two dimensions. Although the hypothetical scenario initially defined in this study assumes that the effluent is discharged to non-sensitive areas, a scenario in which environmental aspects are accorded the utmost importance might be feasible in the short term as the European Commission has come to the conclusion that additional sensitive areas should be designated (Molinos-Senante et al., 2012). Hence, should the membrane bioreactor be implemented to update WWTPs rather than building new WWTPs, this technology might be identified as the most sustainable.

From a policy perspective, it is important to value the variability in the sustainability of technologies should the priorities in sustainability criteria change. The global sustainability of technologies with low variability does not depend on the weights assigned to the three pillars of sustainability. Hence, in an uncertain context, technologies with low variability might be considered the preferred option. Nevertheless, if the priorities of stakeholders and citizens regarding sustainability dimensions are clearly defined, the best option understood to be the most sustainable technology may not be any of those with the lowest variability.

Fig. 4 shows the variation intervals (represented by bars) in the global sustainability indicator of each technology based on the original scenario. Variability is understood as the difference between the best and the worst case scenario. The different length of the intervals denotes the level of stability of the technology under the scenarios evaluated. Extended aeration and the rotating biological contactor are very stable technologies as their indicators of global sustainability remain almost constant independent of the weights assigned to economic, environmental and social criteria. The opposite is observed for the membrane bioreactor and constructed wetlands, the variabilities of which are the greatest. For example, for the membrane bioreactor, the minimum value of the global indicator of sustainability is 0.19, whereas the maximum reaches 0.74. Finally, pond systems, the trickling filter and the sequencing batch reactor are technologies with moderate variability in relation to the original scenario.

The results of the scenario analysis confirm that the evaluation of the sustainability of WWT technologies is always situational, as highlighted by most of the experts consulted in this study. Hence, it was revealed that in the selection of the most appropriate WWT technology, different groups whose opinions and preferences can diverge should be involved. In this context, two main groups, namely standard stakeholders and interest groups, can be identified (Bao et al., 2013). Standard stakeholders are decision makers, experts, planners and analysts involved in preparing and managing the process. Interest groups comprise political parties, civic organizations and residents in the area in which there will be an impact (Lahdelma et al., 2000). Because the point of view

Table 6
Dimensional composite indicators for the WWT technologies evaluated.

Sustainability	CW	PS	EA	MBR	RBC	TF	SBR
Economic (*ECS*)	0.964	0.783	0.629	0.063	0.533	0.520	0.427
Environmental (*ENS*)	0.325	0.395	0.617	0.856	0.485	0.614	0.684
Social (*SS*)	0.628	0.628	0.551	0.510	0.456	0.318	0.616

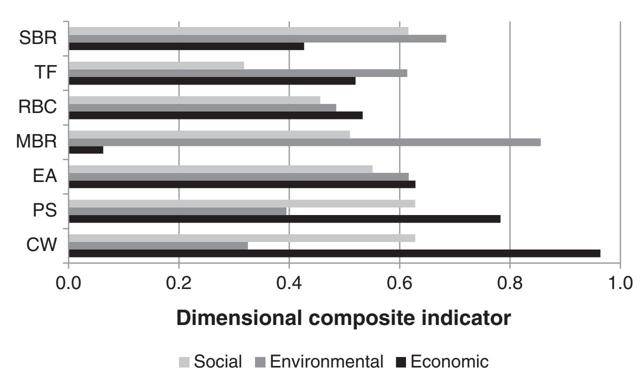

Fig. 1. Dimensional composite indicators for the WWT technologies evaluated.

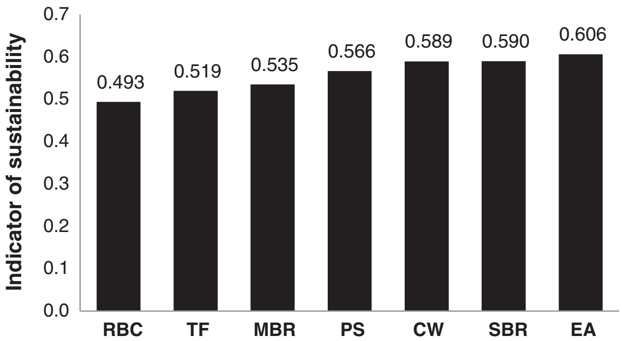

Fig. 2. Global sustainability composite indicator for the WWT technologies evaluated.

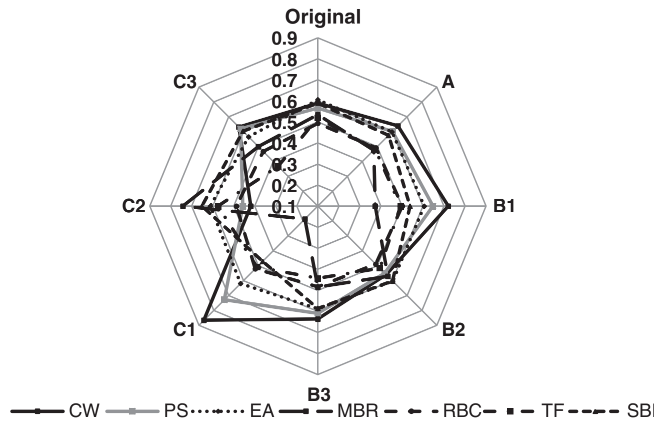

Fig. 3. Global sustainability composite indicator for the WWT technologies evaluated under eight scenarios.

for evaluating alternatives might be different for each group involved, competition and conflicts can be created in the decision-making process. In this context, our study was focused on the "standard stakeholders." Hence, in future studies, it would be interesting to compare the ranking of sustainable WWT technologies obtained based on the preferences of both groups: standard stakeholders and interest groups.

4. Conclusions

This paper presents an innovative methodology for the assessment of WWT solutions integrating the social dimension in the implementation of WWT technologies. Although the social component plays (or should play) a key role in project evaluations, the majority of studies do not address social issues. Thus, to capture fully the concept of sustainability, a set of indicators embracing economic, environmental and social issues is proposed to assess WWT technologies. Moreover, to overcome the limitation of assessing sustainability based on a set of separate indicators, the indicator system developed has been aggregated into a composite indicator which provides a multidimensional assessment of sustainability compiled into a single index. Therefore, for the first time, in the framework of the assessment of WWT technologies, a comparative analysis has been made possible using a global measure of the sustainability of seven different technologies for secondary treatment of waste water. Furthermore, the application of the AHP to assign weights to each indicator allows the incorporation of the preferences of experts and enhances the reliability of the comparative analysis.

Specifically, the WWT technologies assessed were two extensive technologies and five intensive technologies. Based on expert preferences, the results for the environmental dimension are opposite to those for the economic dimension. Intensive technologies are the cheapest but have the lowest environmental sustainability, whereas the membrane bioreactor exhibits the opposite trend. Interestingly, the global indicator of sustainability embracing the economic, environmental and social dimensions for all the seven WWT technologies was similar. Extended aeration was the most sustainable technology, whereas the rotating biological contactor was the least sustainable technology. Even the general perception that extensive technologies might be more environmentally friendly was contradicted.

Finally, a sensitivity analysis including a set of composite indicators corresponding to the prioritization of different dimensions (economical, environmental and social) was constructed (seven scenarios). The major findings from the scenario analysis show that for five of the seven scenarios, constructed wetlands comprise the most sustainable technology, whereas extended aeration and the membrane bioreactor are the most sustainable technologies when the environmental dimension is prioritized over the economic dimension. Moreover, extended aeration and the rotating biological contactor are identified as the technologies with the lowest variability in terms of sustainability. Hence, in an uncertain context, these might be considered the preferred options as their global indicator of sustainability does not depend on the weights assigned to the sustainability dimensions.

The proposed approach efficiently evaluates the global sustainability of WWT technologies from a holistic perspective. Therefore, it contributes to the ease of interpretation by decision makers in relation to a complex and multidimensional decision problem, such as the selection of the most sustainable WWT alternative from a set of possibilities. Moreover, the integration of a battery of sustainability indicators into a single component has the potential to improve the dissemination and understanding of sustainability information to the general public.

Table 7
Scenarios definition.

Scenario	Weights to criteria (%)		
	Economic	Environmental	Social
Experts/Original	30.8	47.1	22.1
A	33.3	33.3	33.3
B1	50.0	25.0	25.0
B2	25.0	50.0	25.0
B3	25.0	25.0	50.0
C1	80.0	10.0	10.0
C2	10.0	80.0	10.0
C3	10.0	10.0	80.0

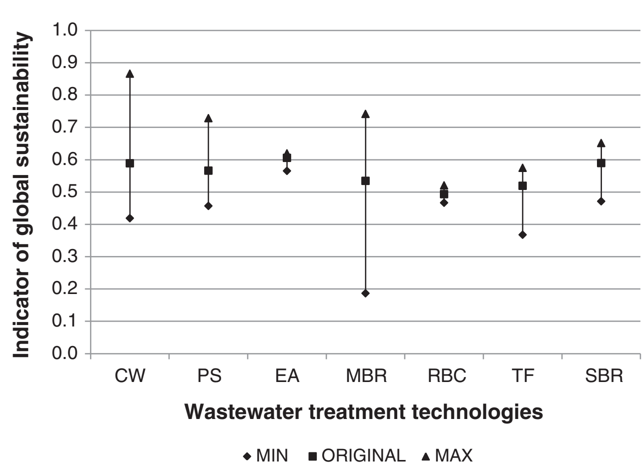

Fig. 4. Variability of the global sustainability for the scenarios evaluated.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.08.026.

References

Aull-Hyde R, Erdogan S, Duke JM. An experiment on the consistency of aggregated comparison matrices in AHP. Eur J Oper Res 2006;171(1):290–5.

Balaguer M, Puig M, Salgot M, Sànchez-Marrè M, Turon C. Gestió i tractament d'aigües residuals [In Catalan] Wastewater Treatment and management. Girona: Universitat de Girona, Servei de Publications; 2007.

Balkema A. Sustainable Wastewater Systems—Developing a Methodology and Selecting Promising Systems (PhD dissertation) Eindhoven, Netherlands: Technische Universiteit; 2003.

Balkema AJ, Preisig HA, Otterpohl R, Lambert AJD, Weijers SR. Developing a model based decision support tool for the identification of sustainable treatment options for domestic wastewater. Water Sci Technol 2001;47(7):265–70.

Balkema AJ, Preisig HA, Otterpohl R, Lambert FJD. Indicators for the sustainability assessment of wastewater treatment systems. Urban Water 2002;4(2):153–61.

Bao PN, Aramaki T, Hanaki K. Assessment of stakeholders' preferences towards sustainable sanitation scenarios. Water Environ J 2013;27(1):58–70.

Belton V. A comparison of the analytic hierarchy process and a simple multi-attribute value function. Eur J Oper Res 1986;26:7–21.

Bernasconi M, Choirat C, Seri R. Empirical properties of group preference aggregation methods employed in AHP: theory and evidence. Eur J Oper Res 2014;232(3):584–92.

Blancas FJ, Caballero R, González M, Lozano-Oyola M, Pérez F. Goal programming synthetic indicators: an application for sustainable tourism in Andalusian coastal counties. Ecol Econ 2010;69(11):2158–72.

Blancas FJ, Lozano-Oyola M, González M, Guerrero FM, Caballero R. How to use sustainability indicators for tourism planning: the case of rural tourism in Andalusia (Spain). Sci Total Environ 2011;412–413:28–45.

Bottero M, Comino E, Riggio V. Application of the analytic hierarchy process and the analytic network process for the assessment of different wastewater treatment systems. Environ Model Software 2011;26(10):1211–24.

CEDEX. La depuración de las aguas residuales en pequeñas poblaciones españolas [In Spanish]. The treatment of wastewater in small Spanish towns Center for New Water Technologies. Madrid: Spainish Ministry of Civil Works; 2008.

CENTA. Manual para la implantación de sistemas de depuración en pequeñas poblaciones [In Spanish]. Manual for the implementation of wastewater treatment systems in small towns. Madrid: Ministry of Environment and Rural and Marine, Center for Studies and Experimentation of Civil Works; 2010.

Comas J, Alemany J, Poch M, Torrens A, Salgot M, Bou J. Development of a knowledge-based decision support system for identifying adequate wastewater treatment for small communities. Water Sci Technol 2003;48(11):393–400.

Corominas L, Foley J, Guest JS, Hospido A, Larsen HF, Morera S, et al. Life cycle assessment applied to wastewater treatment: state of the art. Water Res 2013:5480–92.

Dixon A, Simon M, Burkitt T. Assessing the environmental impact of two options for small-scale wastewater treatment: comparing a reedbed and an aerated biological filter using a life cycle approach. Ecol Eng 2003;20(4):297–308.

EcoSanRes. Comparing sanitation systems using sustainability criteria. Stockholm Environment Institute; 2009 [Available from: http://www.ecosanres.org/pdf_files/ESR2009-1-ComparingSanitationSystems.pdf].

Eisenberg D, Soller J, Sakaji R, Olivieri A. A methodology to evaluate water and wastewater treatment plant reliability. Water Sci Technol 2001;43(10):91–9.

Ellis KV, Tang SL. Wastewater treatment optimization model for developing world. I: Model development. J Environ Eng ASCE 1991;117:501–18.

Estrada JM, Kraakman NJRB, Muñoz R, Lebrero R. A comparative analysis of odour treatment technologies in wastewater treatment plants. Environ Sci Technol 2011;45(3):1100–6.

Fan Y, Chen W, Jiao W, Chang AC. Cost-benefit analysis of reclaimed wastewater reuses in Beijing. Desalin Water Treat 2014. [in press].

Flores-Alsina X, Gallego A, Feijoo G, Rodriguez-Roda I. Multiple-objective evaluation of wastewater treatment plant control alternatives. J Environ Manage 2010;91(5):1193–201.

Foley J, de Haas D, Yuan Z, Lant P. Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. Water Res 2010;44(3):831–44.

Gavasci R, Chiavola A, Spizzirri M. Technical-economical analysis of selected decentralized technologies for municipal wastewater treatment in the city of Rome. Water Sci Technol 2010;62(6):1371–8.

Guest JS, Skerlos SJ, Barnard JL, Beck MB, Daigger GT, Hilger H, et al. A new planning and design paradigm to achieve sustainable resource recovery from wastewater. Environ Sci Technol 2009;43(16):6126–30.

Hardisty PE, Sivapalan M, Humphries R. Determining a sustainable and economically optimal wastewater treatment and discharge strategy. J Environ Manage 2013;114:285–92.

Hoffmann B, Nielsen SB, Elle M, Gabriel S, Henze M, Mikkelsen PS. Assessing the sustainability of small wastewater systems: a context-oriented planning approach. Environ Impact Assess Rev 2000;20(3):347–57.

Høibye L, Clauson-Kaas J, Wenzel H, Larsen HF, Jacobsen BN, Dalgaard O. Sustainability assessment of advanced wastewater treatment technologies. Water Sci Technol 2008;58(5):963–8.

Kalbar PP, Karmakar S, Asolekar SR. Selection of an appropriate wastewater treatment technology: a scenario-based multiple-attribute decision-making approach. J Environ Manage 2012;113:158–69.

Lahdelma R, Salminen P, Hokkanen J. Using multicriteria methods in environmental planning and management. Environ Manage 2000;26(6):595–605.

Larsen HF, Hauschild MZ, Wenzel H, Almenmark M. Homogeneous LCA methodology agreed by NEPTUNE and INNOWATECH; 2007 [www.eu-neptune.org].

Lassaux S, Renzoni R, Germain A. Life cycle assessment of water from the pumping station to the wastewater treatment plant. Int J Life Cycle Assess 2007;12(2):118–26.

Loghmanpoor M, Vardanian Z, Elahi M. Evaluation the sustainability of two forest regions under both Participatory and Governmental Management system using AHP. Ecol Environ Conserv 2013;19(3):661–71.

Lozano-Oyola M, Blancas FJ, González M, Caballero R. Sustainable tourism indicators as planning tools in cultural destinations. Ecol Indic 2012;18:659–75.

Lundin M, Molander S, Morrison GM. A set of indicators for the assessment of temporal variations in the sustainability of sanitary systems. Water Sci Technol 1999;39(5):235–42.

Macharis C, Springael J, De Brucker K, Verbeke A. PROMETHEE and AHP: the design of operational synergies in multicriteria analysis - Strengthening PROMETHEE with ideas of AHP. Eur J Oper Res 2004;153(2):307–17.

Maggino F, Ruviglioni E. Obtaining weights: from objective to subjective approaches in view of more participative methods in the construction of composite indicators. Eurostat; 2009 [Available from: http://epp.eurostat.ec.europa.eu/portal/page/portal/research_methodology/documents/POSTER_1A_OBTAINING_WEIGHTS_MAGGINO_RUVIGLIONI.pdf].

Martinez-Alier J, Munda G, O'Neill J. Weak comparability of values as a foundation for ecological economics. Ecol Econ 1998;26:277–86.

Menikpura SNM, Gheewala SH, Bonnet S. Framework for life cycle sustainability assessment of municipal solid waste management systems with an application to a case study in Thailand. Waste Manage Res 2012;30(7):708–19.

Merz M, Hiete M, Comes T, Schultmann F. A composite indicator model to assess natural disaster risks in industry on a spatial level. J Risk Res 2013;16(9):1077–99.

Metcalf, Eddy. Wastewater engineering: treatment and reuse. 4th ed. New York: McGraw-Hill; 2004.

Molinos-Senante M, Hernández-Sancho F, Sala-Garrido R. Assessing disproportionate costs to achieve good ecological status of water bodies in a Mediterranean river basin. J Environ Monit 2011;13(8):2090–101.

Molinos-Senante M, Garrido-Baserba M, Reif R, Hernández-Sancho F, Poch M. Assessment of wastewater treatment plant design for small communities: environmental and economic aspects. Sci Total Environ 2012;427–428:11–8.

Molinos-Senante M, Hernández-Sancho F, Sala-Garrido R, Cirelli G. Economic feasibility study for intensive and extensive wastewater treatment considering greenhouse gases emissions. J Environ Manage 2013;123:98–104.

Møller KA, Fryd O, de Neergaard A, Magid J. Economic, environmental and socio-cultural sustainability of three constructed wetlands in Thailand. Environ Urban 2012;24(1):305–23.

Monclus H, Puig S, Coma M, Bosch A, Balaguer MD, Colprim J. Nitrogen removal from landfill leachate using the SBR technology. Environ Technol 2009;30(3):283–90.

Muga HE, Mihelcic JR. Sustainability of wastewater treatment technologies. J Environ Manage 2008;88(3):437–47.

Murray A, Ray I, Nelson KL. An innovative sustainability assessment for urban wastewater infrastructure and its application in Chengdu, China. J Environ Manage 2009;90(11):3553–60.

Nardo M, Siasana M, Saltelli A, Tarantola S. Tools for composite indicators building. Institute for the Protection and Security of the Citizen, European Commision; 2005.

OECD. Handbook on constructing composite indicators. Methodology and user guide. Paris: OECD Publications; 2008.

OECD. Glossary of Statistical Terms. Available from http://stats.oecd.org/glossary/, 2014.

Ortega de Ferrer E, Ferrer Y, Salas JJ, Aragón C, Real A. Manual para la implementación de sistemas de depuración en pequeñas poblaciones. 1st ed. Madrid: CENTA; 2011.

Pérez V, Guerrero F, González M, Pérez F, Caballero R. Composite indicator for the assessment of sustainability: the case of Cuban nature-based tourism destinations. Ecol Indic 2013;29:316–24.

Peters M, Zelewski S. Pitfalls in the application of analytic hierarchy process to performance measurement. Manag Decis 2008;46(7):1039–51.

Poch Espallargas M. Les Qualitats de l'aigua. Barcelona: Rubes; 1999 [In Catalan].

Popovic T, Kraslawski A, Avramenko Y. Applicability of sustainability indicators to wastewater treatment processes. Comput Aided Chem Eng 2013;32:931–6.

Rodriguez-Garcia G, Molinos-Senante M, Hospido A, Hernández-Sancho F, Moreira MT, Feijoo G. Environmental and economic profile of six typologies of wastewater treatment plants. Water Res 2011;45(18):5997–6010.

Roy R, Chan NW, Rainis R. Rice farming sustainability assessment in Bangladesh. Sustain Sci 2014;9(1):31–44.

Saaty TL. The analytical hierarchy process. New York: McGraw-Hill; 1980.

Saaty TL. Decision making with dependence ad feedback: the analytic network process. Pittsburgh: RWS Publications; 1996.
Shmelev SE, Rodríguez-Labajos B. Dynamic multidimensional assessment of sustainability at the macro level: the case of Austria. Ecol Econ 2009;68(10):2560–73.
Tsagarakis KP, Mara DD, Angelakis AN. Application of cost criteria for selection of municipal wastewater treatment systems. Water Air Soil Pollut 2003;142(1–4):187–210.
UNICEF, WHO. Progress on drinking water and sanitation: 2012 update; 2012 [Available from: http://www.unicef.org/media/files/JMPreport2012.pdf].
Voces R, Diaz-Balteiro L, Romero C. Characterization and explanation of the sustainability of the European wood manufacturing industries: a quantitative approach. Expert Syst Appl 2012;39(7):6618–27.
Wang X, Liu J, Ren N-Q, Yu HQ, Lee D-J, Guo X. Assessment of multiple sustainability demands for wastewater treatment alternatives: a refined evaluation scheme and case study. Environ Sci Technol 2012;46(10):5542–9.
WCED (World Commission on Environment and Development). Report of the World Commission on Environment and Development: Our Common Future; 1987.
Wu CFJ, Hamada MS. Experiments: planning, analysis, and optimization. Wiley; 2011.
Yildirim M, Topkaya B. Assessing environmental impacts of wastewater treatment alternatives for small-scale communities. Clean – Soil Air Water 2012;40(2):171–8.
Zeng G, Jiang R, Huang G, Xu M, Li J. Optimization of wastewater treatment alternative selection by hierarchy grey relational analysis. J Environ Manage 2007;82(2):250–9.