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Citation for the original published paper (version of record):

Neth, M., Mattsson, A., Wilen, B. et al (2023). Weighted score ratios (WRS) give transparent weighting in multicriteria sustainability
assessments - A case study on removal of pharmaceutical residues from wastewater. Science of the Total Environment, 893. http://dx.doi.org/10.1016/j.scitotenv.2023.164792

Science of the Total Environment 893 (2023) 164792

Contents lists available at ScienceDirect

Science of the Total Environment

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

Weighted score ratios (WRS) give transparent weighting in multicriteria sustainability assessments - A case study on removal of pharmaceutical residues from wastewater

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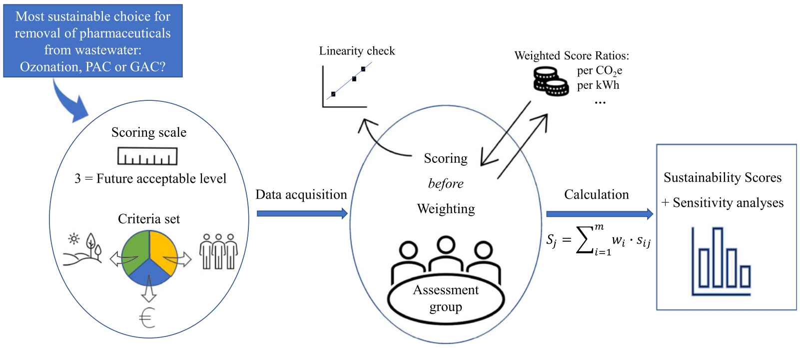
HIGHLIGHTS

- Often sustainability assessment methods lack transparency and objectivity.
- A more transparent and objective sustainability assessment method is suggested.
- Using weighted score ratios show how the criteria are valued, e.g., cost/CO_2e.
- The method was applied on a case study for removal of pharmaceutical residues.
- For the case study, ozone and GAC were more sustainable than PAC.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paola Verlicchi

Keywords:
Multicriteria analysis
Sustainable
Ozonation
Activated carbon
Pharmaceuticals
WWTP

ABSTRACT

Sustainability assessment using multicriteria analysis (MCA) is a structured way of including criteria from the three sustainability dimensions (environmental, economic, and social) when comparing different alternatives. A problem with the conventional MCA methods is that the consequences of the weights given to different criteria are not transparent. Here, we amend the simple additive weighting MCA method with weighted score ratios (WSRs), which are used during the sustainability assessment to show how the weights affect the valuation of the criteria (e.g., cost per kg CO_2e). This enables comparisons to other sustainability assessments and reference values from society, which increases the transparency and can make weighting more objective. We applied the method to a comparison of technologies for removal of pharmaceutical residues from wastewater. Due to growing concern about the effects that pharmaceutical residues can have on our environment, implementations of advanced technologies are increasing. However, they entail high requirements of energy and resources. Therefore, many aspects must be considered to make a sustainable choice of technology. In this study, a sustainability assessment was performed of ozonation, powdered activated carbon and granular activated carbon for removal of pharmaceutical residues at a large wastewater treatment plant (WWTP) in Sweden. The outcome showed that powdered activated carbon is the least sustainable choice for the studied WWTP. Whether ozonation or granular activated carbon is most sustainable depends on how climate impact and energy use are valued. The total sustainability of ozonation is affected by how the electricity is assumed to be produced, whereas for granular activated carbon it depends on whether the carbon source is of renewable or fossil origin. Using WSRs allowed the participants in the assessment to make conscious choices on how they weighted different criteria in relation to how these criteria are valued in society at large.

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http://dx.doi.org/10.1016/j.scitotenv.2023.164792
Received 22 February 2023; Received in revised form 30 May 2023; Accepted 8 June 2023
Available online 14 June 2023

1. Introduction

In the past century, wastewater management has become a central structure in modern societies, evolving from only diverting the wastewater to protect human health, to the removal of organics and nutrients to protect our waters. More recently, there are increasing concerns about emerging contaminants, often referred to as organic micropollutants (OMPs). OMPs are commonly detected in aquatic environments at low concentrations, but can still at these low concentrations be very toxic and persistent (Luo et al., 2014). Examples of OMPs include pharmaceutical residues, personal care products, pesticides, synthetic and natural hormones and industrial chemicals (Bui et al., 2016).

For pharmaceutical residues, effluents from wastewater treatment plants (WWTPs) are the main source of contamination (Bartelt-Hunt et al., 2009; Luo et al., 2014; Silva et al., 2011). Most conventional WWTPs today are designed for the removal of organic matter and nutrients (Clouzot et al., 2013), but they are not designed to remove OMPs, such as pharmaceutical residues. Therefore, many OMPs are to a high degree discharged with the effluents from WWTPs. If a high removal of a broad range of OMPs is to be obtained, the implementation of new advanced treatment is necessary, and for this several technologies have been studied (Bui et al., 2016; Luo et al., 2014; Wang et al., 2020). Two advanced treatment technologies were identified as having potential for large scale implementation, ozonation or adsorption onto activated carbon (Margot et al., 2013). Activated carbon can either be used as a filter medium of granular activated carbon (GAC), or as powdered activated carbon (PAC) added in activated sludge (Cimbritz et al., 2019) or coagulation tanks (Luo et al., 2014). Ozonation, PAC and GAC are the preferred technologies with full-scale implementations existing in Switzerland, Germany, and some other countries (Bui et al., 2016; Eggen et al., 2014).

Implementing ozonation, PAC or GAC, at a WWTP entails increased requirements of energy and other resources (Li et al., 2019) both from an economical and an environmental perspective. WWTPs are already large consumers of chemicals and energy and since constructions for wastewater treatment have a lifetime of decades (Lienert et al., 2015) the choices made today will impact the sustainability for a long time. To be able to make a sustainable choice of technology for advanced treatment, it is necessary to make a proper sustainability assessment regarding potential benefits, impacts and drawbacks (Neth et al., 2022).

Even though sustainability is a complex concept, seeing it as three integrated balanced dimensions, the environmental, social, and economic, is widely accepted. A possible method for comparing the sustainability of different alternatives is multi-criteria analysis (MCA), also referred to as multi-criteria decision analysis. MCA has been used for various decision problems in many fields, including the water sector (Malmqvist et al., 2006; Marques et al., 2015). Two strengths of MCA are that all three sustainability dimensions can be represented and that all aspects relevant to the question in mind can be included in the analysis (Marques et al., 2015). Another frequently applied method in the wastewater industry is Life-Cycle Assessment (LCA) (Corominas et al., 2013). LCAs specifically of advanced treatment technologies are presented by Pesqueira et al. (2020) and Li et al. (2019). From a holistic sustainability perspective, a disadvantage of LCA is that only the environmental dimension is included. Therefore, to assess the overall sustainability MCA is a better choice, or a combination of LCA and MCA. In a combination the LCA can provide the environmental data to the MCA. However, there are also weaknesses with MCA, such as lack of transparency of the results and lack of objective scoring and weighting (Kaliszewski and Podkopaev, 2016; Lai et al., 2008).

The standard method for MCA consists of (1) problem structuring, which includes establishing the decision context; (2) model building, which includes specifying alternatives, criteria, and values related to the criteria; (3) model use, which includes aggregating data and information about the criteria into sustainability scores for the alternatives; and (4) develop an action plan, where the outcome of the MCA is used to serve as a basis for decisions (Belton and Stewart, 2002). Many models for assigning scores and weights and aggregating information from multiple criteria are available. Examples include simple additive weighting; the analytical hierarchy process, where scores and weights are calculated from pairwise comparisons of both the criteria and the alternatives performance; outranking methods, which aims to assess if one alternative is at least as good as another alternative; and the dominance-based rough set approach, which infers decision rules based on an overall assessment of alternatives together with the performance on each criterion (Cinelli et al., 2014). In MCA used for sustainability analysis, assigning scores and weights that balance all sustainability dimensions in a reasonable way is difficult. In water and wastewater management, there is a myriad of decision problems that would benefit from a robust sustainability assessment. However, since different decision problems concern different parts of the system, it is unreasonable to use the same sustainability criteria and weights in all assessments. Examples of decision problems include how to remove organic micropollutants, how to treat and dispose of sludge, how to expand a plant, or how to collect wastewater. The system boundaries and the choice of sustainability criteria depend on the problem. For example, social aspects may be very important when evaluating whether to collect food waste using waste grinders or with trucks, but less important when choosing technology for a WWTP expansion. Thus, it is misleading to always distribute the weights to the criteria the same way, independent of the characteristics of the part of the system presently studied. Therefore, there is a need to develop the MCA sustainability assessment method in a different way that makes the scoring and weighting transparent, more objective, and comparable between different assessments.

In this study, we introduce weighted score ratios (WSRs), which quantify interrelations between different criteria. The WSRs are used iteratively in the assessment process to give the assessment group a possibility to understand how the criteria are valued as a consequence of the assigned weights. The WSRs also enable comparisons with reference values from society and to sustainability assessments of other systems. The method was applied to evaluate the sustainability of three technologies for removal of pharmaceutical residues at the Rya WWTP in Gothenburg, Sweden.

2. Methods

2.1. Sustainability assessment method

This sustainability assessment method is a modification of a general MCA methodology using simple additive weighting for aggregating the total sustainability score of different alternatives (Belton and Stewart, 2002; Dodgson et al., 2009; Hwang and Yoon, 1981). The assessment is carried out by an assessment group consisting of relevant stakeholders, led by a moderator. The assessment group may be divided into separate subgroups that respectively perform data acquisition, scoring, and weighting. It may be relevant to make the weighting group consist of more decision-makers. It is important to understand when the role of the group is as experts and when it is as decision-makers, where the experts own the scoring, and the decision-makers own the weighting. The nine steps of the method are (1) aim, (2) specification of alternatives, (3) scoring scale, (4) criteria set, (5) data acquisition, (6) scoring, (7) weighting, (8) calculation of results, and (9) analysis and reflection. The steps are further described below.

2.1.1. Aim

Formulation of the aim of the assessment. Examples of potential aims can be “What is the most/least sustainably way to treat the wastewater for a 90% removal of substance X in the future?” or “What is the most/least sustainable way to handle Y tonne sludge from the WWTP today?”. The aim should specify whether the assessment concerns the present or a future year or period.

2.1.2. Specification of alternatives

Specifying the included alternatives as precisely as possible means that all assumptions and conditions are declared. This should be clear, both to participants of the assessment and later to readers of the sustainability assessment report. Relevant conditions that can be equal or differ between the alternatives are stated, such as geographical location, size, type of energy, type of chemicals, flow, and removal efficiency. This specification of the basic conditions for the alternatives is called the base case. Other variants than the base case can be handled as sensitivity analyses.

2.1.3. Scoring scale

The scoring scale is decided upon, meaning that the number of steps of the scale and general interpretations of the scores are set. A recommendation is that the general interpretations of the scores are connected to present or future goals or regulations at organizational, local, or national authority level.

2.1.4. Criteria set

A relevant set of criteria for the actual assessment, representing the environmental, social, and economic sustainability dimensions is determined. Previously performed sustainability assessments can provide suggestions for criteria (Machado et al., 2020; Malmqvist et al., 2006; Marques et al., 2015; Rosén et al., 2015). For each included criterion it must be possible to gather data, information, and facts to be used as basis for scoring.

2.1.5. Data acquisition

The data basis, including numbers, facts, and relevant information needed for scoring of the criteria is gathered. The data basis should reflect the intended year or time period for the assessment. Reference data from present day operation might be useful to facilitate the scoring process.

2.1.6. Scoring

The participants of the scoring group together score one criterion at a time for all alternatives based on the data acquisition presented by the moderator. Scores can also be set for variants of the alternatives, given in sensitivity analyses. As an iterative process the scores for quantifiable criteria are used for:

- Linearity check of the scoring
- Calculation of value per score step

2.1.6.1. Linearity check of scoring. For criteria with quantifiable data basis, the linearity of the scoring is checked. For each criterion, the data basis versus the set scores are plotted as the scores are being set. Each alternative will be represented by a data point in the plot. With three or more data points, the linearity can be checked. If a linear relationship is considered logical for the actual criterion, R^2 should be ≥ 0.95.

2.1.6.2. Calculation of value per score step. When scoring, the data basis is transformed into scores. For quantifiable criteria with a linear scoring relationship, value per score step can be calculated, using Eq. (1). This will provide information about how a score step for each criterion is valued.

$$V_s = \frac{\Delta v}{\Delta s} \tag{1}$$

where V_s is value per score step, Δv is the range in values (e.g., cost in € or energy consumption in kWh) and Δs is the range in scores corresponding to those values.

2.1.7. Weighting

Participants of the weighting group set weighting coefficients on a scale 1–20. The weights are automatically recalculated to percentages. The purpose of the 1–20 scale is that the group can focus on whether to give a criterion a high or a low priority, instead of focusing on the exact percentage. The weighting coefficients should represent the importance that the weighting group gives to the differences in performance (i.e. score) between the alternatives, and not the importance of the criteria itself (Marques et al., 2015). The group is also encouraged to set minimum and maximum weights for the criteria that can be used for sensitivity analysis.

The following activities were performed to facilitate and evaluate weighting.

- Calculation of WSRs and values per weighted score step
- Comparison of WSRs with reference values
- Calculation of total weight per sustainability dimension

2.1.7.1. Calculation of WSRs and values per weighted score step. When the weights have been set there is a relationship between the criteria, which shows the relative contribution of each criterion to the total sustainability score. Weighted score ratios between the criteria can then be calculated, using Eq. (2). The weighted score ratios can be in units such as €/CO_2e, €/kWh or kWh/CO_2e. To express all WSRs in relation to the criterion 'annual cost' it is recommended to start the weighting procedure by setting the weight for the criterion 'annual cost' and keep that weight constant.

$$\mathrm{WSR}\ [\mathrm{unit\ A/unit\ B}] = \frac{\mathrm{V_A}}{\mathrm{V_B}} \cdot \frac{\mathrm{w_B}}{\mathrm{w_A}} \tag{2}$$

where WSR is the weighted score ratio for criteria A and B, V_A and V_B are the values per score step, and w_B and w_A the weights of criterion A and B.

For non-quantifiable criteria, value per weighted score step can be expressed in any of the quantifiable criteria's units by using the relation between the weights of the criteria. For instance, work environment can be expressed as cost per weighted score step using Eq. (3), assuming annual cost is criterion C and work environment is criterion D. This describes the extra annual cost the organization could accept to improve the work environment by one score step. These values per weighted score for non-quantifiable criteria can also be used as guidance for weighting.

$$\begin{gathered}\mathit{Value\ per\ weighted score\ step}\\ [\mathit{unit\ C/weighted score\ step\ D}] = V_C \cdot \frac{w_D}{w_C}\end{gathered} \tag{3}$$

where V_C is the value per score step for criterion C and w_D and w_C the weights of criterion D and C.

2.1.7.2. Comparison with reference values. The WSRs can be compared to reference or standard values. The comparison can then be used as basis for adjusting the weights or to determine the plausibility of the combined scoring and weighting. By relating to external reference values, the assessment can be made more objective. This includes the set minimum and maximum weights. Potential sources for reference values for e.g. €/CO_2e, €/kWh, can be locally or nationally set goals, valuations from authorities and other sectors in society, and previous sustainability assessments. Weighting can also directly be adjusted to pre-determined reference values, such as a set cost per CO_2e.

2.1.8. Calculation of results

The total sustainability score for each alternative is calculated using Eq. (4).

$$S_j = \Sigma_{i=1}^{m} w_i \cdot s_{ij} \tag{4}$$

where S_j is the total sustainability score for alternative j, m is the number of criteria included in the analysis, w_i is the weight of criteria i and s_{ij} is the score of alternative j on criteria i.

2.1.8.1. Total given weight per sustainability dimension. Total weight in percentage for the criteria within each of the sustainability dimensions is summarized. This is done to show how the weight has been allocated between the sustainability dimensions.

2.1.8.2. Sensitivity analysis. Total sustainability scores for sensitivity analyses that change individual scores are also calculated using Eq. (4) with the changed scores.

Another type of sensitivity analysis is combined weighting, where the advantages of each alternative are favored one alternative at a time. This requires that minimum and maximum weights have been set for all criteria. In this automatic aggregated weighting calculation method, a "best for alternative X" scenario is created by giving maximum weights to all criteria with a grade in the higher end of the scale for alternative X. Likewise, minimum weights are given to all criteria for which alternative X has grades in the lower end of the scale. The new set of weights is then used to calculate new total sustainability scores for all alternatives. This type of sensitivity analysis can be very useful in showing how sustainable an alternative could be if the circumstances were all in favor for that alternative.

2.1.9. Analysis and reflection

The total sustainability scores for the alternatives are reflected upon in accordance with the aim of the assessment. Major and minor contributors to the total sustainability scores are analyzed for each alternative and sensitivity analyses are also evaluated. The alternatives are ranked from the highest to the lowest total sustainability score. All alternatives, including results from sensitivity analyses, can be included in an overall sustainability ranking.

2.2. The case study: removal of pharmaceutical residues at the Rya WWTP

The aim of the case study was to assess the sustainability of three potential alternatives for removal of pharmaceutical residues, integrated in the wastewater treatment process at the Rya WWTP in Gothenburg, Sweden. The Rya WWTP and the 130 km of tunnel sewer system is operated by the company Gryaab, which is co-owned by 8 municipalities in the Gothenburg region. The Rya WWTP treats an average flow of 390,000 m^3/d and serves a population of 800,000 persons, making it one of the largest WWTPs in Scandinavia. The treatment process includes screening, grit removal, primary settlers, high-loaded activated sludge for pre-denitrification and simultaneous precipitation, trickling filters for nitrification, secondary settlers, nitrifying, and denitrifying moving bed bioreactors (MBBRs), and disc filters. The effluent is discharged in the mouth of the Göta river. The sludge process consists of belt gravity thickeners, anaerobic digesters with biogas production and dewatering with sludge screw presses. For process schematic of the Rya WWTP, see Fig. S1, Supplementary material.

A pre-study on the potential implementation of a technology for removal of pharmaceutical residues was conducted at the Rya WWTP. The pre-study included suggested designs of ozonation, PAC and GAC integrated in the existing wastewater treatment process. Data from the pre-study was used as input to the sustainability assessment. This included data for: removal efficiency, average flow, location and size, investment and operational costs, chemical use, energy use, heat production, waste materials, climate impact from construction and operation, work conditions, risks, and security, reference facilities, operational robustness, maintenance need, and flexibility.

This sustainability assessment was conducted by a moderator (the first author of this paper) and a project group, consisting of 5 people with different competences at the Rya WWTP (operative manager, R&D manager, manager of project and planning, project leader and process specialist). The project group performed both scoring and weighting in this assessment but took on different roles in the scoring and weighting process. During the scoring step the role was as expert, performing scoring based on the data acquisition of the project. In the weighting step the role was as decision-maker, and three of the five group members also have positions in the management team of the WWTP. The moderator did not participate in the scoring and weighting.

All costs were originally in Swedish crowns (SEK) but are here converted to Euro using 10 SEK = 1 euro. Costs in American dollar ($) in references were converted to Euro using 1 $ = 1 euro.

3. Results

The results of applying the sustainability assessment method to the case study are presented for each step of the method, as described in Methods.

3.1. Method applied to case study

3.1.1. Aim

The aim was to assess the sustainability of three specified technologies for removal of pharmaceutical residues at the Rya WWTP. The assessment shall present the most and least sustainable alternative and for each alternative identify the criteria that affect the total sustainability score the most. The assessment concerns a present year, except for wastewater flow where an expected higher future flow was used.

3.1.2. Specification of alternatives

Three alternative technologies (ozonation, PAC and GAC) are included in the assessment as proposed full-scale implementations at the Rya WWTP (process schematics in Figs. S2-S4 in Supplementary material). With the proposed configurations of the technologies, they were assumed to treat the same flow of wastewater and give the same removal efficiency of pharmaceutical residues. Specification and assumptions for the base case are summarized in Table 1. Some variants were handled as sensitivity analyses and if so, they are specified in Table 1.

Construction and installation are generally not included in sustainability assessments, thus only the operative phase is analyzed. However, for this assessment construction and installation were included to show this impact in relation to the impact of the operative phase. One reason

Table 1
Specification of the base case for ozonation, PAC and GAC, and variants handled in sensitivity analyses.

	Ozonation	PAC	GAC
Removal efficiency	Same removal efficiency for pharmaceutical residues assumed (80–90 %)[a]		
Location	Within existing site	Within existing site	In the adjacent Rya Forest
Construction and installation	Estimates of climate impact effect and annual cost from construction and installation are included.		
Treated wastewater flow	A yearly average flow of 4,08 m^3/s (129 Mm^3/year)		
Electricity mixture	Swedish electricity mixture[b]		
Origin of activated carbon	No activated carbon used	Fossil[c]	Fossil[c]
Dosage	10 mgO_3/l	15 mg PAC/l	20,000 bed volumes[d]
Heat production	11,400 MWh/year with local oxygen production	Estimated to 5400 MWh/year from incineration of PAC sludge	No heat production
Transports	All transports with trucks using diesel as fuel, unless otherwise specified.		
Conditions specific for each alternative	Local oxygen production	New separate handling of PAC sludge included	Carbon reactivation in Belgium[e]

[a] Potential effect on the removal of other substances is not included in the assessment.
[b] Sensitivity analysis for other electricity mixes.
[c] Sensitivity analysis for activated carbon with renewable origin.
[d] Sensitivity analysis for 30,000 bed volumes.
[e] Sensitivity analysis for activated carbon reactivation with a new reactivation plant at Rya WWTP.

being that the size of the installations differs greatly between the included alternatives. It should be noted that the impact from construction and installation are rough estimates on annual cost and climate impact. The estimates consider concrete, reinforcement bars, steel for machines, plumbing and transport during the construction phase. Examples of factors not included are excavation and excavation mass, electrical material, construction waste, and electricity consumption for the construction phase.

3.1.3. Scoring scale

A scoring scale from 1 to 5 was used and score 3 in general terms refers to the future acceptable level for each criterion. In this assessment the future refers to year 2050 and the future acceptable level, score 3, was specifically interpreted for each criterion.

- Score 1: Considerably worse than future acceptable level
- Score 2: Worse than future acceptable level
- Score 3: Future acceptable level
- Score 4: Better than future acceptable level
- Score 5: Considerable better than future acceptable level

3.1.4. Criteria set

The criteria set represent the criteria that the assessment group found most important in this specific sustainability assessment. The criteria are divided into environmental, economic, and social dimensions. The complete criteria set is presented in Table 2, including short explanations and units for quantifiable criteria.

3.1.5. Data acquisition

A summary of the data acquisition can be found in the Supplementary material, see Table S5. Most of the data and information for the assessment was provided by the project group of the case study. All data for quantifiable criteria were calculated per year. For non-quantifiable criteria, such as work environment or technical function and reliability, information was derived from reference facilities. One reference facility was the WWTP in Linköping, Sweden, with a full-scale ozonation process and another one was the Simrishamn WWTP, Sweden, that includes both an ozonation and a GAC process. For the criterion climate impact, different parts contribute to the total number. The contributing parts are provided in the Supplementary material, Table S6. For climate impact from activated carbon with fossil origin the numbers in literature vary greatly (Joseph et al., 2020) and for this assessment 13,16 kgCO_2e/kg carbon was used (CONTACTICA and EMIVASA, 2018).

3.1.6. Scoring

The group set the scores for one criterion at a time. The scores together with a short motivation of the scoring is presented in Table 3.

3.1.6.1. Linearity check of scoring. Linearity plots, shown to the assessment groups as the scores were being set, are presented in Fig. 1. These are the final linearity plots for the scoring. For climate impact, the group let score 1 correspond to approximately 15,000 t CO_2e/year. Since the lowest possible score is 1, the PAC alternative that had >15,000 t CO_2e/year still got score 1. This means that scoring of the criteria climate impact and scoring of chemical use was not completely linear, since for each of these criteria one alternative was outside the set scoring scale of 1 to 5. For the criteria sludge to agriculture, it should be noted that there were only two different data points since two alternatives had the same value for tonne of sludge to agriculture per year.

3.1.6.2. Calculation of value per score step. For all quantifiable criteria in this sustainability assessment the value per score step for each criterion was calculated according to Eq. (1) using the linearity plots in Fig. 1. The resulting values per score step for the quantifiable criteria are presented in Table 4.

3.1.7. Weighting of criteria

The final weights for all criteria set by the group are presented in Fig. 2. The largest weights were given to the criteria climate impact (18 %), annual cost (13 %), work environment (11 %) and security (11 %). The criteria with the lowest weights (all 3 % each) were heat production, chemical use, society's perception, and maintenance. For each criterion the assessment group also set a minimum and a maximum weight based on reasonable values for WSRs. Minimum and maximum weights were intended to be used for the sensitivity analyses with combined weighting.

3.1.7.1. Calculation of weighted score ratio and value per weighted score step. Weighted score ratios were calculated for the quantifiable criteria according to Eq. (2), with annual cost as criterion A. The weighted score ratios are presented in Table 4, and they are based on the values per score step, also in Table 4, and the criteria weights in Fig. 2.

For both quantifiable and non-quantifiable criteria, values per weighted score step were calculated using Eq. (3), with annual cost was used as

Table 2

Criteria set for the sustainability assessment of the case study, divided into sustainability dimensions. Each criterion is shortly explained, and units are given for quantifiable criteria.

Sustainability dimension	Criterion [unit]	Explanation
Environmental	1. Climate impact [t CO_2e/year]	Emissions of greenhouse gases to the atmosphere.
	2. Energy use [kWh/year]	Energy use, regarding energy as a resource. Climate impact from energy is included in criterion 1. Heat production is included in criterion 3.
	3. Heat production [kWh/year]	Produced heat that can be used to replace other heat production. Decreased climate impact from heat production is included in criterion 1.
	4. Chemical use [t/year]	Chemical use, regarding chemicals as a resource. Climate impact from chemicals is included in criterion 1.
	5. Sludge to agriculture [t/year]	Quantity of sludge possible to use as fertilizer on farmland.
Social	6. Organizational and legal work	Organizational changes or new legal work or issues.
	7. Society's perception	Society's perception regarding the alternatives and regarding land use.
	8. Work environment	Impact on the daily work environment at the plant, such as dirty, physically demanding, noise and increase of transports. Risks are included in criterion 9.
	9. Security risks	New security risks regarding persons and property of the company.
Economic	10. Annual cost [€/year]	Yearly cost for operation and investment.
	11. References	Reference facilities and how established the technology is.
	12. Technical function and reliability	How robust, reliable, and technically demanding the technology is.
	13. Maintenance	Extent of maintenance need. The cost for maintenance is included in criterion 10.
	14. Flexibility	How flexible, reversible, convertible the technology is.

Table 3
Set scores and motivations for ozonation (Ozon), PAC and GAC for the 14 criteria.

Criterion	Score			Motivation for scoring
	Ozon	PAC	GAC	
1. Climate impact	5	1	2	Score 5 for ozonation since removal of pharmaceutical residues is achieved with almost no increased climate impact. The group decided not to use linear scoring[a]. Score 1 was set to ≥15 000 tonne CO_2e/yr and PAC obtained score 1, even though the climate impact was distinctly higher. Linear scoring[a] of GAC.
2. Energy use	1	5	4	Score 1 for ozonation due to very large energy consumption. Linear scoring[a] of PAC and GAC that both of which entail relatively low energy consumptions.
3. Heat production	5	4	3	All increases in heat production were considered >3 (acceptable level) and linear scoring[a] was applied.
4. Chemical use	5	1	3	Decreased chemical consumption is a present company goal, but +5% increase (GAC) was considered a future acceptable level (score 3). Non-linear scoring[a] was applied and score 1 set to ≥1000 tonne chemicals/yr and PAC got score 1. Score 5 for ozonation since it entails no increase in chemical use.
5. Sludge to agriculture	5	2	5	The decreased quantity of sludge possible to use as fertilizer for PAC was considered below future acceptable level (score <3). Score 5 to ozonation and GAC since they are not affected at all.
6. Organizational and legal work	4	4	1	Shift work is not needed for any alternative. The organizational work for an increased staff of 1-3 persons as for ozonation and PAC was considered score >3. Score 1 for GAC due to probable legal work necessary to build in the adjacent Rya Forest.
7. Society's perception	2	2	2	Score <3 for GAC due to proposed building in adjacent Rya Forest. Score <3 for ozonation because of high energy consumption and potential risks[b] which could be unpopular. Score <3 for PAC due to high chemical consumption and waste that needs to be incinerated.
8. Work environment	2	1	3	Score <3 for ozonation because of restrictions for certain people[c]. Low score for PAC because of dirt, dust, and increased number of transports. Score 3 for GAC since that work environment was considered acceptable.
9. Security risks	2	2	5	Scores for ozonation and PAC below future acceptable level (3) because they both entail new security risks[d]. Score 5 for GAC since no new security risks appear.
10. Annual cost	3	1	2	The annual cost for ozonation was considered acceptable (score 3) for achieving removal of pharmaceutical residues. Linear scoring[a] of PAC and GAC.
11. References	4	1	3	Many reference facilities exist for ozonation. Fewer for GAC than for ozonation. Reference facilities for this configuration of PAC were unknown to the project.
12. Technical function and reliability	3	1	4	Score 1 for PAC due to large uncertainties regarding the treatment of PAC sludge. GAC considered as a robust process therefore score 4. Ozonation score 3 because more systems than for GAC that need to work.
13. Maintenance	2	1	3	The maintenance work for GAC was considered acceptable. More is required for ozonation due to several different systems. Uncertainty regarding the maintenance need for PAC, both for the water process and the new PAC sludge treatment.
14. Flexibility	2	4	1	PAC was considered very flexible because it could quickly be stopped without much remaining investments. Score 1 for GAC due to large investments in construction. Score 2 for ozonation because of investments in construction but less than for GAC.

[a] Linear and non-linear scoring is explained in 3.1.6.1.
[b] Potential risks with ozonation regarding transformational- and byproducts formed, whose ecotoxicological effects are unclear (Sundin et al., 2017).
[c] Restrictions regarding staff with pacemaker.
[d] Ozonation entails fire risk and is harmful to health. PAC entails fire and explosion risk.

criterion C and the criteria weights given in Fig. 2. Resulting values per weighted score are included in Table 4.

3.1.7.2. Comparison with reference values. The weighted score ratios can be compared with reference values. Reference values for climate impact and energy use are included in Table 4 and the comparison will be brought up in the Discussion.

3.1.8. Calculation of results

The total sustainability score for each alternative is presented in Fig. 3, using the set scores in Table 3 and the weights in Fig. 2 for calculation according to Eq. (4). The height of the bar is the total sustainability score for each alternative, and the different criteria are visualized as separate blocks. A large block represents a positive sustainability aspect. A small block can mean that the criterion was not prioritized and assigned a small weight, resulting in all blocks for that criterion being small. Alternatively, a small block can be a negative sustainability aspect for that alternative and that it was scored low. The total sustainability scores for ozonation and GAC are significantly higher (3.2 and 2.9) than that for PAC (1.9). A table summarizing set scores, assigned weights, calculated weighted scores and the total sustainability scores is provided in the Supplementary material, Table S7.

3.1.8.1. Total given weight per sustainability dimension. The summarized weight for the criteria within each sustainability dimension is visualized in Fig. 2. The weight for the environmental dimension was 37 %, for the social dimension 29 % and, for the economic dimension 34 %.

Total sustainability scores for the base case and all sensitivity analyses are shown in Fig. 4. Sensitivity analyses that affected individual scores were changing from fossil to a renewable activated carbon in PAC and GAC, changing from Swedish electricity mix to European electricity mix, assuming 30,000 bed volumes for GAC instead of 20,000, and changing location for GAC from the Rya Forest to within the existing site of the WWTP. The other type of sensitivity analyses was combined weighting that favored one alternative at a time, and these are called *Best for ozonation*, *Best for PAC* and *Best for GAC*.

3.1.9. Analysis and reflection

Analysis and Reflection of the results from this sustainability assessment is placed in the Discussion part of this article.

4. Discussion

The aim of this paper was to present a structured sustainability assessment method that modifies the standard method and suggests new intermediate steps to improve the transparency and objectiveness in scoring and weighting. The method was applied to evaluate the sustainability of three technologies for removal of pharmaceutical residues at the Rya WWTP in Gothenburg, Sweden. The discussion is divided into two subsections, first discussing the suggested sustainability assessment method, and then discussing the results of applying the method.

4.1. The modified sustainability assessment method

Many sustainability assessments based on MCA have been performed within the water sector, but there is a need to improve the transparency and objectiveness in the development of the results (Lai et al., 2008). To address this, we used (i) a scoring scale related to future acceptable level, (ii) scoring before weighting, (iii) linearity checks when scoring quantifiable criteria, (iv) calculation of WSRs, comparison of WSRs with reference values, (v) calculation of value per weighted score step, and (vi) sensitivity analyses that separately favors each alternative.

The scoring scale used in this study is related to future acceptable level for each criterion. There are other types of scoring scales being used, such as

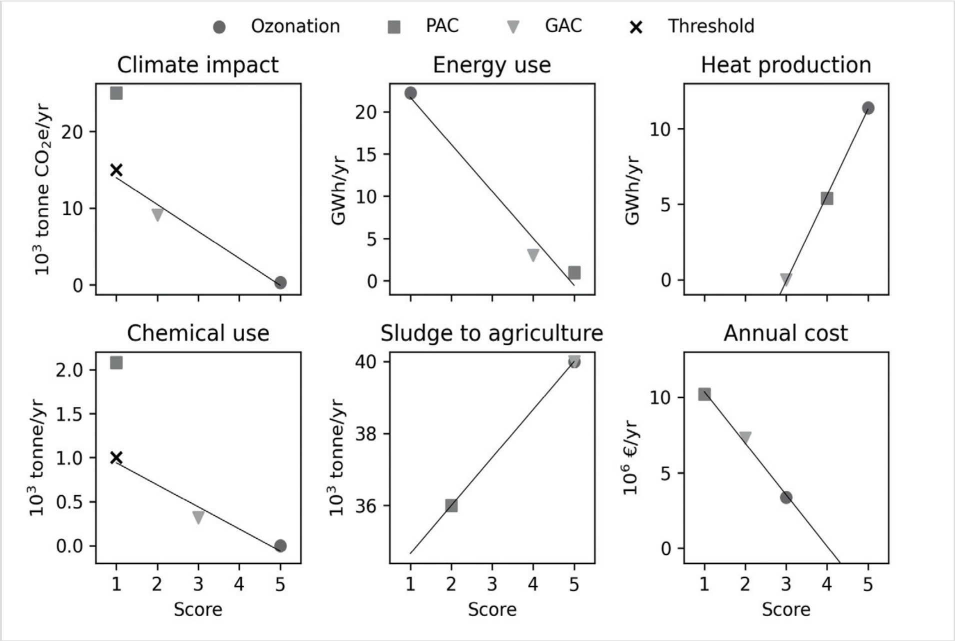

Fig. 1. Linearity plots for set scores versus data basis for the quantifiable criteria in the sustainability assessment. The circle, square and triangle correspond to ozonation, PAC and GAC respectably and the cross to the threshold value that the group decided corresponds to score 1 for climate impact and chemical use.

a scoring scale that is related to the current state or the results of a base case (Johannesdottir et al., 2021). However, a current state might not exist if the aim concerns an expansion or a complement to the existing WWTP. Also, this scoring scale is often used together with open ends, meaning that better or worse than x % from base case will not have any effect on the score. Another possible scoring scale is relative preference scales that are anchored at their ends by the most and least preferred options for each criterion (Dodgson et al., 2009). The remaining alternatives are assigned scores so that the differences in score represent differences in strength of preference. The use of the scale is maximized, but a small difference in data basis can lead to a large difference in score. This needs to be compensated for in the weighting procedure to avoid that small differences between the alternatives have a large impact on the final sustainability results. If the scores relate to future acceptable levels, scoring can be anchored to something external of the sustainability assessment, that increases the objectivity. Future acceptable level can for some criteria connect to future internal or external goals or future likely requirements. The set scores can be easier to understand when seeing them together with the interpretations of the score steps. Score 5 can be interpreted as the best available techniques. A limitation is that this scoring scale can also sometimes mean open ends of the scale.

Scoring before weighting is used in some studies (Johannesdottir et al., 2021; Marques et al., 2015) and the switched order is used by some (Masoud et al., 2022). Having weighting before scoring can be motivated since the weighting cannot be used to control the outcome of the assessment. On the other hand, when scoring is done before weighting, the weighting group can be informed of exactly what the scoring of the alternatives was based on for the different criteria. Marques et al. (2015) say that the assigned weights should represent the importance of a difference in performance. This information is only available for the weighting group if scoring is done before weighting. Furthermore, for weighting to be more transparent and objective the use of weighted score ratios together with reference values is one option. For that to be possible, scoring must be done before weighting.

Using linearity check when scoring guarantees that one score step always corresponds to the same value. Linear scoring could also provide the opportunity of giving the exact corresponding score to a certain data basis if decimal scores are allowed. Value per score step is given as a direct consequence of the linearity check. This value can also add transparency to the assessment by showing the actual difference between two scores. If full linearity is not applied, the data basis does not fully impact the set scores. This means that a better performance is not fully appreciated, and a worse performance is not penalized.

Calculation of WSRs between the criteria can increase the objectiveness of the combined scoring and weighting and connect the sustainability assessment to something outside the organization that is carrying out the assessment. WSRs is based on comparing what has the same impact on the total sustainability score and thereby valued the same for sustainability. If linear scoring has been applied for quantifiable criteria, all needed information to calculate WSRs is there. Although this is the case in many MCAs, WSRs are still not calculated. A WSR can, for instance, tell how much it is considered worth in annual cost to decrease the climate impact with x tonne CO_2e per year or to decrease the energy use with y MWh per year.

Comparison of WSRs with reference values can mean comparisons with other societal sectors where aspects such as climate impact and energy use are also relevant. Also, different sustainability assessments with criteria in common can be compared with each other. This does not necessarily always mean that WSRs must be equal in different studies, but it makes similarities and differences more visible. For instance, a higher WSR of €/CO_2e for the expansion of a WWTP that will stand for fifty years than a short-term solution for a food supplier can be both reasonable and motivated.

The calculated values per weighted score step for non-quantifiable criteria is useful to evaluate the combined scoring and weighting. To exemplify, if the difference between score 3 and 4 for work environment means an improvement in less physically demanding work. The WSR shows that this improvement is valued to x € as an annual cost. If this value seems too high, the weight for work environment should be lowered.

The type of sensitivity analysis that separately favors each alternative in different combined weighting scenarios can increase the objectivity in analyzing the overall results of the assessment. It shows how easily the sustainability ranking of the alternatives could be switched if the conditions were different. Using WSRs for guidance in setting the minimum and maximum weights for the combined weighting means achieving results based on a quantified value the weighting group have assigned to each criterion rather than a fixed percentage.

Some of the previous criticism of MCA regarding transparency and objectiveness can be addressed with these suggested modifications of the

Table 4

Value per score step for quantifiable criteria, value per weighted score step for all criteria, WSRs for quantifiable criteria and reference values for WSRs.

Criterion	Value per score step [unit/score step, yr]	Value per weighted score step [€/weighted score step, yr]	WSR [€/unit]	Reference value for WSR [€/unit]
1. Climate impact	3515 t CO_2e	4.8 million	1360 €/t CO_2e	700 €/t CO_2e[a]
2. Energy use	5554 MWh	2.0 million	0.4 €/kWh	Electricity price: 0.08 €/kWh[b]
3. Heat production	5715 MWh	0.7 million	0.1 €/kWh	–
4. Chemical use	250 t chemicals	0.7 million	2730 €/t chemicals	–
5. Sludge to agriculture	1333 t sludge	1.4 million	1020 €/t sludge	–
6. Organizational and legal work		1.4 million	–	–
7. Society's perception		0.7 million	–	–
8. Work environment		2.7 million	–	–
9. Security risks		2.7 million	–	–
10. Annual cost	3.4 million €	3.4 million	1	–
11. References		1.4 million	–	–
12. Technical function and reliability		2.0 million	–	–
13. Maintenance		0.7 million	–	–
14. Flexibility		1.4 million	–	–

[a] Trafikverket (2020).

[b] Total electricity price per kWh at the Rya WWTP year 2019.

method. However, the method could still be further improved. The objectiveness and comparability of scoring and weighting of non-quantifiable criteria being one thing, although calculating value per weighted score step helps. The most useful results are obtained if the participants of the assessment are objective and understand and accept how to use the WSRs and values per score step.

4.2. Sustainability assessment of three technologies for removal of pharmaceutical residues

Technologies for removal of pharmaceutical residues have been evaluated in LCAs concerning their environmental impacts (Li et al., 2019; Pesqueira et al., 2020). Some studies include economic consequences (Margot et al., 2013), but few include all three sustainability dimensions. For this case study, the aim was to perform a sustainability assessment that includes all three sustainability dimensions in assessing three technologies for removal of pharmaceutical residues. The result should present the most and least sustainable alternative and for each alternative technology identify what affects the overall sustainability the most.

The results of this case study show that ozonation and GAC are comparable in terms of sustainability. Ozonation is marginally better than GAC while PAC clearly is the least sustainable alternative. Not even when the conditions are favoring PAC it can reach the same sustainability level as ozonation and GAC. One reason for this is that PAC in this configuration continuously consumes carbon that cannot be regenerated, in contrast to most of the carbon in the GAC filter (Bui et al., 2016). The carbon is fossil in the base scenario causing both the criteria climate impact and chemical use to be negative aspects for PAC. It also causes an unpleasant work environment, and the PAC sludge requires a new separate sludge process and cannot be used for agriculture. The suggested configuration with PAC dosed to an MBBR process is new in full-scale but has been demonstrated in pilot-scale (Cimbritz et al., 2019). In most reference facilities, PAC is dosed to an activated sludge process. For instance, in Germany all sludge is often incinerated (Schnell et al., 2020) and then the PAC sludge requires no separate treatment, but does entail an extra sludge volume to treat (Margot et al., 2013). In the study by Margot et al. (2013) PAC combined with ultrafiltration comes out as slightly better than ozonation with sand filter, when criteria such as local constraints (e.g., safety, sludge, disposal, disinfection), operational feasibility, cost and sensitive of receiving waters were considered.

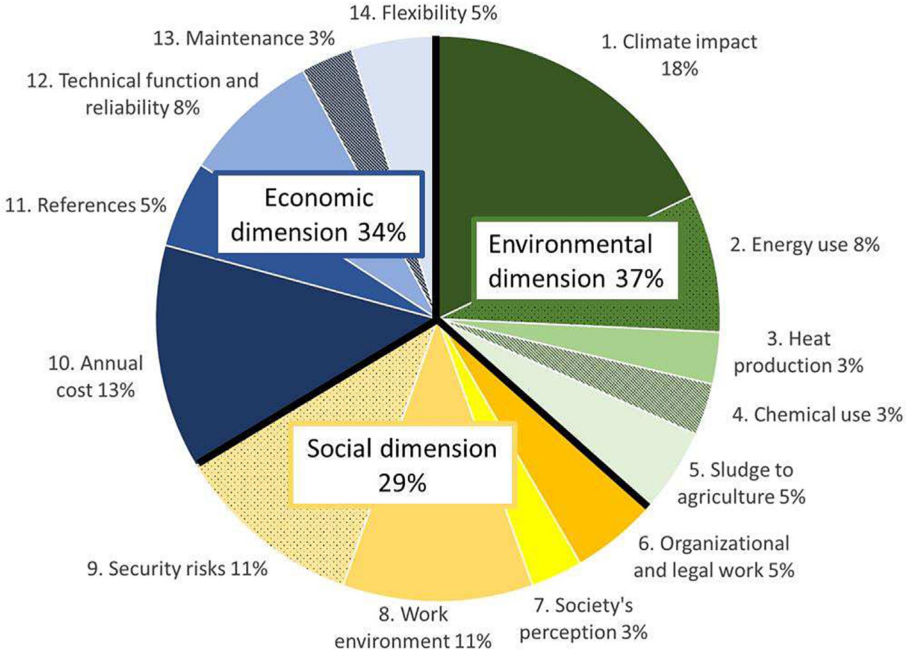

Fig. 2. The final weights (%) that the assessment group assigned to the included criteria. The total weights for the environmental, social, and economic dimensions are displayed inside the pie chart.

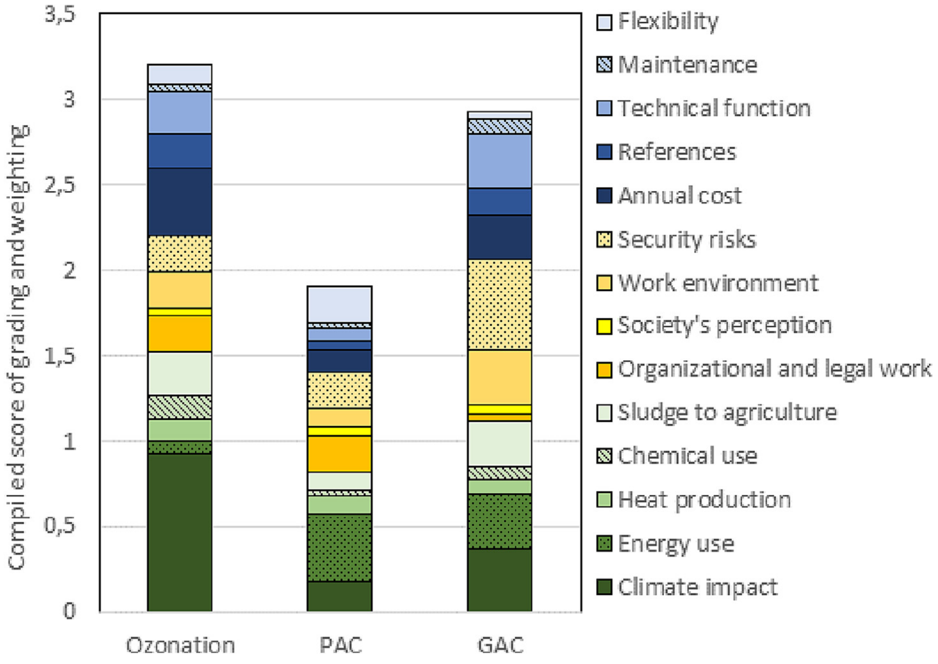

Fig. 3. The total sustainability score for ozonation, PAC and GAC in the sustainability assessment. The higher the score the more sustainable according to the assessment. Each criterion is visualized as a specific block.

In this study, the total sustainability scores for ozonation and GAC are almost equal. Both ozonation and GAC have several advantages for removal of pharmaceutical residues (Bui et al., 2016) and depending on if these advantages are weighted the most sustainable alternative can shift in the sensitivity analyses. If energy consumption is less important for sustainability and climate impact more important, ozonation is favored and is considered more sustainable than GAC. On the other hand, if energy consumption and technical function are important and climate impact not as prioritized, GAC will be the most sustainable choice. This is in line with the results of a LCA performed by Pesqueira et al. (2020) who found that the sustainability of ozonation is highly dependent on the energy source and that the activated carbon should be regenerated. They also note that adsorption to activated carbon removes transformation products, but that treatment of the sorbent is necessary to keep up the removal efficiency of the process.

The sustainability assessment did not consider differences in removal efficiency between the alternatives or the potential of improved removal of other pollutants from the wastewater. Also, there were uncertainties affecting the results, such as regarding maintenance work and treatment of PAC sludge and ecotoxicological effects from transformation products formed by ozonation. These aspects could affect the sustainability of the alternatives.

Regarding the WSRs, these were iteratively shown to the assessment group during the weighting process together with relevant references. It can be noted that the ratio for €/CO_2e is remarkably high (1360 €/t CO_2e). The given reference in Table 4 was at 700 €/t CO_2e and generally in society it is clearly lower, e.g. 51–185 €/t CO_2e (Rennert et al., 2022). However, we also calculated WSRs of annual cost and global warming for the two case studies on resource recovery by Johannesdottir et al. (2021). They were 1086 €/t CO_2e and 5572 €/t CO_2e respectively.

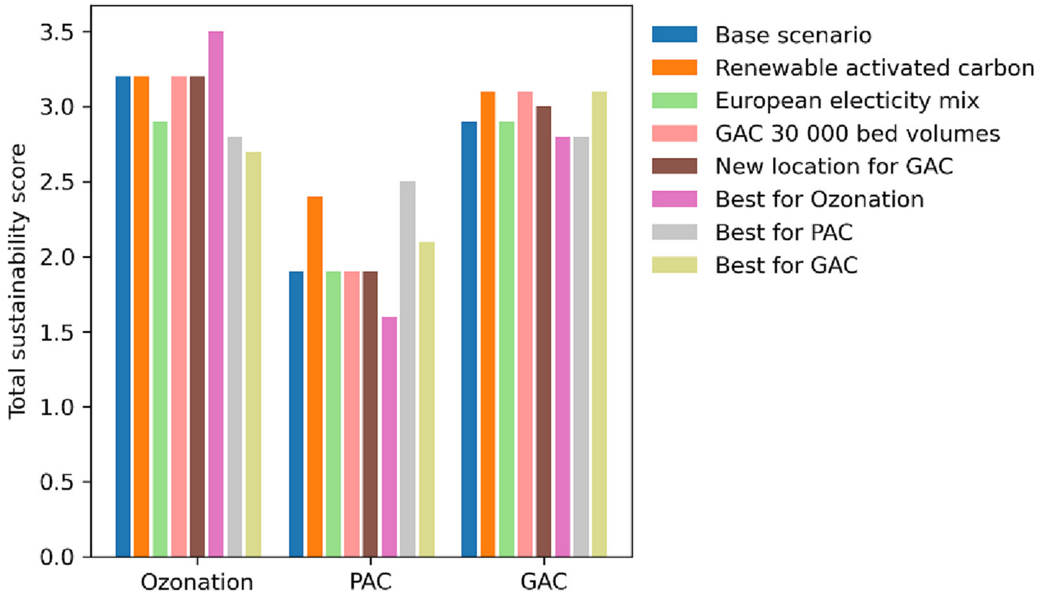

Fig. 4. Total sustainability scores for ozonation, PAC and GAC for the base case and for all sensitivity analyses included in the assessment.

If a completely linear scoring had been used for climate impact, that is including the climate impact of PAC in the linearity the WSR for €/CO_2e would have been lower. The assessment group was hesitating on how to handle the linearity for climate impact but decided to give score 1 to all alternatives having a climate impact above 15,000 t CO_2e per year, thus all emissions above this level are not included in the evaluation. This can be the result of having a scoring scale with open ends. This is also the case in the study by Johannesdottir et al. (2021). The difference in the WSRs for energy use and for heat production show that electricity and heat are not valued as equal energy sources and that electricity is seen as more valuable than heat. When the WSR for energy use is compared to the actual electricity price, the WSR shows that electricity as a resource is valued four times higher than the electricity price. This means the assessment group is prepared to pay four times the actual energy price per kWh to save energy.

Performing a sustainability assessment is valuable even if a clear “winner” is not found. Excluding exceptionally unsustainable solutions from further investigation can be just as valuable and makes it much easier to find the pathways to a future sustainable wastewater treatment.

5. Conclusions

A sustainability assessment method was developed that introduced WSRs and several other modifications to the simple additive weighting MCA method.

- WSRs show how the different criteria are valued and related to each other (e.g., cost per t CO_2e or cost per kWh).
- WSRs can be compared to reference values from society and sustainability assessments of other systems, which improves the transparency of the assessment and allows for the assessment group to make conscious choices during the weighting step. Objectivity can be improved by using reference values for guidance in weighting.
- This method also includes the use of a scoring scale related to future acceptable levels, performing scoring before weighting, the use of linearity checks when scoring quantifiable criteria and the calculation of value per weighted score step. Together with sensitivity analyses that separately favors each alternative these improvements lead to better transparency and objectivity of the sustainability assessment.

This modified method for sustainability assessment was carried out to evaluate three technologies for removal of pharmaceutical residues at a large WWTP in Sweden.

- Ozonation and GAC received higher total sustainability scores than PAC in the studied configurations.
- The sensitivity analysis showed that a high weight on the climate impact criterion favored ozonation while high weights on the criteria energy use and technical function favored GAC.
- PAC had the lowest total sustainability score mainly due to the inability to recycle the activated carbon which led to high a climate impact as well as a high cost.

CRediT authorship contribution statement

Maria Neth: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Ann Mattsson:** Conceptualization, Methodology, Data curation, Writing – review & editing, Funding acquisition. **Britt-Marie Wilén:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Oskar Modin:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing, Visualization, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We want to send a special thanks to the participants of the project group and in the sustainability assessment of the case study at the Rya WWTP, Gryaab.

Funding sources

This work was supported by Gryaab AB, VA-teknik Södra and Naturvårdsverket (case number NV-03644-19).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164792.

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