



Methodological guide and roadmap to assess the compliance of wastewater treatment plants with sustainability and circularity criteria

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ABSTRACT

Environmental certification has come up as a voluntary action to demonstrate a minimum quality level when it comes to the introduction of ecological-friendly principles in decision-making. However, most of the work done so far has focused on the food and agroforestry sectors and on the production and processing stages of the value chain rather than end-of life strategies. The present study aims to provide a roadmap that facilitates the evaluation of the performance wastewater facilities from sustainable and circularity perspectives. A six-step framework has been proposed with the objective of serving as the basis for a future certification system for this sector. First, mandatory requirements were collected from European legislative documents to identify the targets to be met. Subsequently, the collected data have been classified into five levels ranging from the definition of pillars, principles, criteria, requirements to the compliance of indicators. The selection of indicators was carried out taking into account the existing literature to gather both sustainability (167) and circularity (32) indicators, which were then associated with the defined requirements. The final step is to consider the testing or validation of the methodology to case studies, in this case, the design and operation of two large-scale wastewater treatment plants. The results indicated that most of the indicators are qualitative and about 61 % of the quantitative requirements of the framework could be calculated with routine plant information. For those indicators for which estimation was not possible due to lack of data, an easily manageable, fact sheet-type template was created so that companies were aware of data required to address the framework. Moreover, the application of this assessment framework to wastewater treatment plants identified some gaps to consider: (1) thresholds could not be defined for many of the indicators, (2) there is a lack of guidelines for data collection, (3) legislation needs improvement regarding circularity metrics in this sector and (4) the requirements should be strengthened to account for the specific characteristics of facilities operating at different scales and using various technologies.

1. Introduction

The unstoppable increase in population and the accelerated development of industrialization has jeopardized the supply possibilities for future generations and has also led to an escalation of environmental risks (Wang and Azam, 2024). To avoid this, the manufacturing sector has driven a transformation of the actual value chains of production and distribution of products to achieve a greener, sustainable and decarbonized industry (Mehmood et al., 2024). Apart from this, society has become aware of how its consumption habits also influence the use and demand for resources, products and services, as well as the market and the willingness of companies to go green. Led by these changes, many companies have participated in and demanded environmental certification systems or voluntary sustainability standards to highlight

compliance with minimum environmental criteria (Gomes et al., 2023).

Any of these certification schemes require the development of a set of specifications or requirements to determine whether or not a product or process is in line with policies, standards or legislation throughout its life cycle (Pavlovskaia, 2014). Therefore, the requirements are the basic elements in the structure of any certification scheme (Poncibò, 2007). Subsequently, they can be categorized according to the objectives pursued and create a quantitative or qualitative framework (Lee, 2013). This set of hierarchical requirements is then tested through a conformity assessment based on the audit methodology, verification guide and/or test methods of the standard (Liepiņa et al., 2014).

In most known certification schemes (e.g. Forest Stewardship Council or FSC, International Sustainability and carbon certification or ISSC, Programme for the Endorsement of Forest Certification or PEFC and Better Biomass), the evaluation process is qualitative and requires

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Nomenclature

ASC	aquaculture stewardship council
AWS	alliance for water stewardship
BSCI	business social compliance initiative
EC	European commission
EEA	European environmental agency
EU	European union
EWS	European water stewardship
FSC	forest stewardship council
ISO	international organization for standardization
ISSC	international sustainability and carbon certification
MBBR	moving bed biofilm reactors
MSC	marine stewardship council
PEFC	programme for the endorsement of forest certification
RSB	roundtable on sustainable biomaterials
SBP	sustainable biomass program
UNE	Una Norma Española
WAVE	water stewardship verified

the use of checklists with yes or no questions or indicators whose answers must be confirmed by an auditor. Despite the experience of auditors, the use of qualitative indicators is still under a certain degree of subjectivity. It is therefore recommended that a rigorous and systematic tool be developed that can provide objective qualitative and quantitative information.

Over the past years, there has been a blooming in the proposal of indicators to measure the implementation of both sustainable and circular practices since they can be used as policy-making instruments (Nowaczek et al., 2023). Also, they are useful to assess criteria at different levels, allowing for a multi-criteria analysis (de Oliveira and Oliveira, 2023). When implemented in certification schemes, they can contribute to the reduction of bureaucracy, costs and greenwashing, and facilitate the digitalization of conformity assessments (Flagstad et al., 2022; Rossi et al., 2024).

In addition to being mostly qualitative, certification schemes today face new challenges, such as incorporating specifications for two other concepts that have recently gained attention: the circular economy and the bioeconomy. The European bioeconomy has been launched to promote strategies and initiatives focused on the depletion of non-renewable resources, the improvement of bio-based processes and technological diversification and innovation, as well as for promoting the implementation of new practices in the management of the production and value chain (Fischer et al., 2024). However, the promotion of these technologies must also go hand in hand with the acceptance and environmental awareness of social communities (Macht et al., 2023). By promoting a green transition, the European bioeconomy cooperates with circularity, which is based on promoting the creation of closed-loop systems by reusing, recycling and recovering resources throughout their life cycle (Alhawari et al., 2021; Cavender-Bares et al., 2013; D'Amato and Korhonen, 2021). This is why both concepts should be considered when certifying these technologies.

Thus, bio-waste materials could be used in valorization processes for the generation of marketable value-added products or as intermediates that can be used as raw materials for other industrial processes (Mahjoub and Domscheit, 2020). Wastewater, as part of the water value chain, is also an example of biological waste with a multitude of valorization possibilities (i.e., from organic fertilizer to energy and biopolymers) (Chispim et al., 2021; Ferreira et al., 2023; Lutz et al., 2021). In addition, reclaimed water could be one of their co-products, a resource of increasing concern in areas suffering water scarcity (Foglia et al., 2023). Although it is not a resource strongly concentrated (since it is liquid) in recoverable components, it is a waste produced

continuously from anthropogenic activities (supply is assured). However, the redesign of wastewater treatment plants to incorporate aspects of circular economy, sustainability and bioeconomy implies an extra effort as the facilities become multifunctional (Ruffi-Salís et al., 2022).

However, certification of end-of-life processes is not fully covered, which hampers the possibilities for certification of wastewater management (Majer et al., 2018). Although certification schemes exist for the water treatment sector—such as the Alliance for Water Stewardship (AWS), IAMPO R&T, European Water Stewardship (EWS), Smart Approved Watermark, and Water Stewardship Verified (WAVE)—the technologies, process stages, and operations of wastewater treatment plants differ significantly, which is essential for the development of the basis for voluntary certification in wastewater (Alliance for Water Stewardship, 2024; European Water Stewardship, 2024; International Association of Plumbing and Mechanical Officials, 2024; The Water Council, 2024).

On the other hand, while some certification schemes attempt to include water-related criteria, they do not address wastewater treatment and are instead more suited to the agroforestry sector. Examples of these criteria are identification of water rights, implementation of a water management plan, depletion of water resources, water quality and preventive measures for water pollution (Fehrenbach, 2011). However, the specifications were established for a potential direct impact without considering the indirect impacts along the entire value chain. It is therefore urgent to create and update the criteria that must be maintained by certification systems in the wastewater treatment sector for a company to be sustainable and circular.

Based on this context, the focus of this research article is to provide a methodological framework for evaluating wastewater treatment technologies. This framework has been developed by identifying appropriate indicators and requirements to be included in certification schemes and labels to effectively assess the wastewater sector. The idea is to provide useful initial guidance for stakeholders, researchers and policy-makers using information gathered from European legislation and other documents relevant to the sector. In the search of formulating a certification scheme, which would entail stakeholder consultation and the creation of a conformity assessment guide, this study is a first step in identifying gaps and possibilities for the future creation of an open access certification scheme. Regarding the audit methodology, an analysis of indicators from the literature was conducted and subsequently correlated with the requirements and criteria of the framework. Furthermore, to assess the suitability and effectiveness of the proposed methodological framework, the design and operation of two large-scale wastewater treatment plants were considered as case studies (European wastewater treatment plants with a design capacity of >100,000 population equivalent).

2. Selection of documents to be reviewed

A simultaneous two-step integrated process has been carried out for the selection of the documents from which the specifications or requirements to be met by wastewater treatment plants have been collected. First, a systematic review of the official online database of European Union law (EUR-Lex), which contains, among others, legal acts, consolidated texts and international agreements, was carried out in July 2024. European legal acts are subdivided into 15,8531 regulations, 7749 directives, 52,654 decisions, recommendations and opinions, which, with the exception of the last group, are legally binding (European Union, 2024). All of them have been categorized into 21 domains. Considering that the operation of wastewater treatment plants involves the compliance of very diverse aspects, the use of keywords was not considered, and the focus of the analysis was on European Directives.

The first draft of selected directives was conducted considering the EUR-lex entry “*Summaries of the European Regulations*”. Other types of documents were not considered for the systematic review. Using the

EUR-lex advanced search tool, the compilation of directives was performed by searching only for current legislation, excluding corrigendum and taking into account the relevant legislative authorities (the European Commission, the European Parliament and the EU Council). A total of 735 were exported from the database, of which only 45 applied to the wastewater sector.

The second step was the reading of the technical documentation of the two case studies used in this research and the compilation of the applicable legislation. The total number of directives included for analysis was 60, which means that 15 could not be found in the systematic literature review. The directives for which information has been included in the specification framework are shown in Table 1.

Additionally, other 9 documents were also evaluated despite not being the 60 directives previously mentioned. The first is a possible future legislative act, the proposal for a Directive of the European Parliament and of the Council concerning urban wastewater treatment (COM/2022/541). There is also one Regulation ((EU) 2020/741 on water reuse) and two Commission Delegated Regulations of the European Parliament and of the Council ((EU) 2021/2139 and (EU) 2023/2486 with the EU Taxonomy technical criteria). Finally, five ISO standards representative of a good management system were chosen for environment (ISO 14,001:2015), quality (ISO 9001:2015), energy (ISO 50,001:2018), economic (ISO 20,400:2017) and occupational health (45,001:2018) issues. The possible list of ISO directives and standards (with some others not selected for the criteria framework) can be found in **Supplementary Materials B**. It is important to emphasize that only the indicators most relevant to the operation of wastewater treatment plants are considered, without delving into specific details of the analysis (e.g., influent and effluent composition) or equipment specifications.

3. Definition of the certification framework

The framework proposed for this research is structured in different levels: pillars, principles, criteria and requirements. The first step was the definition of each of the aforementioned levels. This is because their meaning is nowadays subject to a certain degree of subjectivity among documents, as discussed in Colfer et al. (1995), BOPP (2012), Ritchie et al. (2000) and UNE-EN 16,751:2016.

The most detailed or specific level of the framework are the requirements, which are the specifications that organizations must meet in

order to comply with the requirements for accreditation or, if this is not possible, at least to comply with legislation. Thus, they define the type of action to be taken to perform well in terms of sustainability or circularity. These requirements were gathered from the documentation already presented in Section 2.

Supplementary Materials B show the relationship between each of the requirements with the articles or sections found within each directive or document. They have all been grouped according to the aspirational goal to be met and thus define objectives for the company. These groups are called criteria. Criteria can be further classified into principles, which are laws that provide a rationale for action or higher purposes (i.e., preservation of habitats or appropriate use of resources). Finally, principles are intended to give representation to different key thematic areas of interest (sustainability or circularity). Fig. 1 is a representation of the different levels of the framework, together within their definitions and the number found for each of them.

Tables 2 and 3 show the pillars, principles and criteria with the number of requirements and a code for each of them. The code has been defined in four levels, according to the framework structure levels. The first two or three letters refer to the pillar. ES is for environmental sustainability; SES is for socioeconomic sustainability and CI is for circularity. The numbers separated by dots are necessary to identify the principles, criteria and requirements. For example, the code ES 01.01.01 indicates that the first requirement of the first criterion and first principle as shown in Tables 2, 3 and **Supplementary Materials B** has been cited.

As shown in Tables 2 and 3, the specification framework has been built on a total of 102 requirements distributed between environmental sustainability (~49 %), socio-economic sustainability (~38 %) and circularity (~13 %). The number of principles is 9, while the number of criteria is 26. The criteria with the highest number of requirements are socio-economic and refer to the safety of the operation. In terms of criteria, the maximum number is in the environmental pillar and belongs to the principle referring to the conservation and management of ecosystems.

4. Dataset of available indicators

An audit methodology consists of procedures that result in the compilation of evidence about the organization's performance in relation to the requirements of the framework (shown in Section 3)

Table 1

Directives under consideration for the proposed framework of the methodology classified per decades and areas of protection.

Area of protection	Directive code				
	Before-1990	1990–2000	2000–2010	2010–2020	2020-Now
Air quality	–	92/62/EEC	2003/87/EC, 2008/50/EC 2010/75/EU	2015/1127/EU, 2015/1480/EU 2016/2284/EU	2024/299/EU
Energy	–	–	–	2018/2001/EU, 2018/2002/EU 2018/844/EU	2023/1791/EU, 2023/2413/EU 2024/1405/EU
Environmental Assessment	–	–	2001/42/EC, 2003/35/EC and 2009/147/EC	–	–
Nature conservation	–	92/43/EEC 97/62/EC	–	–	–
Noise	70/157/EEC, 81/334/EEC 84/424/EEC	92/97/EEC, 96/20/EC, 1999/101/EC 2000/14/EC	2002/49/EC 2007/34/EC	2015/996/EU 2020/367/EU	–
Prevention and control	–	–	2004/35/EC	–	–
Residues and contaminated soils	86/278/EEC	1999/31/EC	2008/98/EC	2018/851/EU	–
Safety	–	–	–	2012/18/EU 2014/34/EU	–
Technical aspects	89/491/EEC	–	–	2011/92/EU 2014/30/EU	–
Water and coast	–	91/271/EEC, 91/676/EEC 2000/60/EC	2006/7/EC, 2006/118/EC, 2007/60/EC, 2008/56/EC, 2008/105/EC 2009/90/EC	2013/39/EU, 2014/101/EU, 2014/80/EU 2020/2184/EU	–
Work conditions	89/391/EEC	91/322/EEC, 1999/92/EC 2000/39/EC	2006/54/EC	–	2022/2041/EU 2024/1500/EU

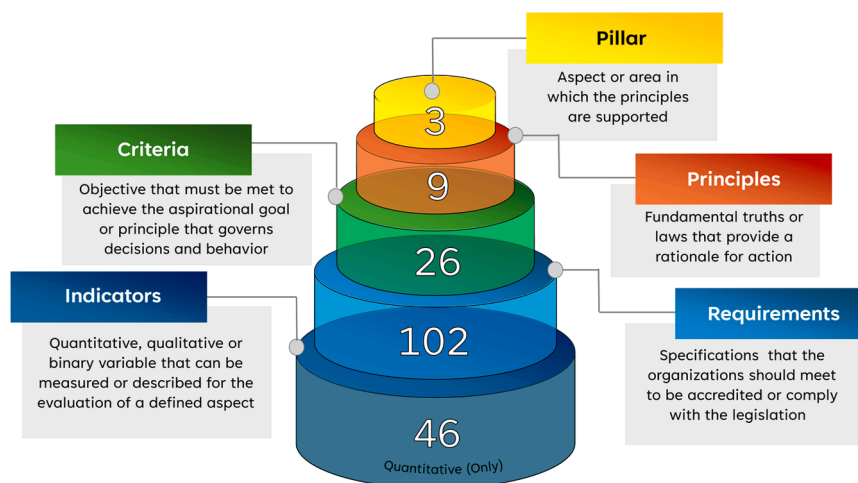


Fig. 1. Structure of the specification framework applicable to certification schemes in the wastewater sector.

Table 2

Presentation of the specification framework in terms of pillar, principles and criteria for the environmental pillar of sustainability.

Pillar	Principles	Description of the principles	Criteria	Code of the requirements	Number of requirements
ES: Environmental sustainability	Conservation and preservation of habitat diversity	This principle looks for the protection of habitats and diversity. It is considering both the conservation of biotic and abiotic factors.	The organization shall consider limitations regarding the operation in sensitive or protected areas	ES 01.01.01–06	6
			The organization shall preserve the biological diversity of species and restricts the use of genetically modified invasive species	ES 01.02.01–03	3
	Conservation and management of the functions of the ecosystem	This principle encompasses all the objectives of the company to preserve the functions of soil, water and air with the control of the contamination. Both direct and indirect impacts are considered.	The organization shall prevent indirect water contamination through soil quality preservation	ES 02.01.01–04	4
			The organization shall have control over its water-related discharges over the environment	ES 02.02.01–07	7
			The organization shall have strategies to minimize direct emissions causing climate change	ES 02.03.01–05	5
			The organization shall preserve the functions of the soil for future uses	ES 02.04.01–02	2
			The organization shall preserve the functions of the air for future uses	ES 02.05.01–02	2
			The organization shall provide surveillance of the ecosystem functions	ES 02.06.01–06	6
			The organization shall prevent the emissions or physical origin (i.e., noise, electromagnetism, odour...)	ES 02.07.01–05	5
	Sustainable use of resources to prevent depletion	Input flows should be measured to ensure that the current demand can be met through the time of operation	The organization shall have limitations on the use of energy	ES 03.01.01	1
			The organization shall have limitations on the use of chemicals	ES 03.02.01–02	2
			The organization shall have limitations on the use of water	ES 03.03.01–02	2
	Waste management	Non-product outputs should be traced to ensure that they are managed properly	The organization shall characterize the waste generated	ES 04.01.01–03	3
			The organization shall ensure the traceability of waste	ES 04.02.01–02	2

(Mironéasa and Codină, 2013). The nature of these procedures is based on analysis, inspection, observation, inquiry, calculation and reproduction. Normally, the auditor selects the most appropriate procedure to reduce the risk of error of judgment to an acceptable level (Xiao et al., 2020). Indicators, as quantitative, qualitative or binary metrics, can be used to verify the reliability and the accessibility to the information provided by organizations. In addition, they can be used by an external auditor to qualify compliance with requirements and criteria. Therefore,

it is of vital importance that the diagnosis is carried out with well selected indicators.

Therefore, once the specification framework has been defined, a subsequent step is to identify the most suitable indicators for each of the requirements. In order to know the possibilities of integrating indicators into the framework, it is first necessary to identify viable indicators that can be used for wastewater treatment plants. For this reason, a scientific and grey literature review was conducted. This type of review was

Table 3

Presentation of the specification framework in terms of pillar, principles and criteria for the socio-economic pillar of sustainability and circularity.

Pillar	Principles	Description of the principles	Criteria	Code of the requirements	Number of requirements
SES: Socio-economic sustainability	System thinking, value creation and business models	This principle indicates that efforts should be made to increase the functionality and performance of resources and a comprehension of the interaction of the different economic actors involved.	The organization shall obtain profits from the production of resources	SES 01.01.01–05	5
			The organization shall have good financial management	SES 01.02.01	1
			The organization shall estimate and register its operational and construction costs	SES 01.03.01–04	4
			The organization shall be aware of the social welfare provided	SES 01.04.01–02	2
			The organization shall ensure that the water is safe for human consumption	SES 02.01.01	1
	Safety and labour conditions	This principle aims at the safe and healthy operation of the facilities	The organization shall ensure minimum working conditions	SES 02.02.01–05	5
			The organization shall have plans to ensure that the facilities operate safely	SES 02.03.01–14	14
			The organization shall have restrictions to preserve human health	SES 02.04.01	1
			The organization shall ensure that the company makes documentation available	SES 03.01.01–06	6
			The organization shall produce circular products from residual materials	CI 01.01.01–03	3
CI: Circularity	Availability of resources by keeping them at the highest value	This principle tries to reduce the dependence on virgin resources and the input requirements	The organization shall make use of renewable materials	CI 01.02.01–07	7
			The organization shall apply the rules of the R _s in circular economy	CI 02.01.01–03	3
	Contribute to the resilience and regeneration	This principle promotes the resilience of materials through their recycling and reuse in the production process or value chain			

selected considering that this study has very open search fields (indicators and wastewater treatment) (Snyder, 2019). The compilation of the indicators found is shown in **Supplementary Materials A**, where they have been grouped into three data sets according to their primary goal.

- The first dataset includes 106 technical and sustainability indicators to describe quantitatively a wastewater treatment plant (process-based system boundaries).
- The second dataset compiles 61 technical and sustainability indicators for sewer construction, operation and maintenance.
- The third dataset has 32 indicators for circularity.

In addition to the name, formula and parameters for their calculation, each of the indicators was classified or organized by areas of protection. Fig. 2 shows the representativeness of each of the protection areas for each of the datasets. It should be noted that the figure is shown only for aspects within the economic, environmental and social pillars of sustainability and circularity. Technical performance indicators are not shown in the graph, but are described in **Supplementary Materials A**.

Considering that legislative actions seek the implementation of measures that society or industry must comply with, the third circularity dataset collects consistent circularity indicators specific to the sector. These types of indicators were selected to measure the environmental, economic and social performance of circular economy strategies implemented within the European Union that impact sustainability (Renfrew et al., 2024; Saidani et al., 2019). No intrinsic circularity indicators applicable to wastewater treatment that measure the success of the implementation of circularity principles were incorporated. This is because circularity principles and criteria are still at a non-sectoral level, as exemplified by the European Green Deal, the Catalogue of Best Practices in Circular Economy, the Categorisation system for the circular

economy and the EEA (European Environment Agency) Report 2/2016 (European Commission, 2020; European Environment Agency, 2016; Ministerio para la Transición Ecológica y el Reto Demográfico, 2021; The European Green Deal, 2019).

5. Screening of indicators

To ensure verification of the requirements, it is necessary, as a first step, to associate and select the database indicators described in Section 4 with the specification framework (shown in Table 4). For this purpose, all indicators were correlated with those aspects that could be quantified. Indicators for those aspects that were qualitative were also proposed, as shown in **Supplementary Materials B**. Since they could not be estimated, they were not verified in the framework of this research. Once chosen, a multivariate analysis was performed to impute missing values. In other words, each indicator was studied for the identification of the parameters on which data should be collected. Also, in connection with this analysis, system boundaries and case study processes were investigated. Important data were collected in terms of capacity, process units, operating limitations, and chemical and energy consumption.

6. Application to case studies

The creation of the process inventories for the calculation and testing of the indication was performed using two case studies, A and B, representative of centralized Spanish wastewater treatment plants. Primary data were taken mainly from facility operation and project construction reports, but secondary data from models or mass-energy balances were also used when primary data were not available. Figs. 3 and 4 show the process flow diagrams for case studies A and B.

Case study A is a facility that serves 260,000 inhabitants and treats domestic wastewater from five adjacent urban areas. As in any typical

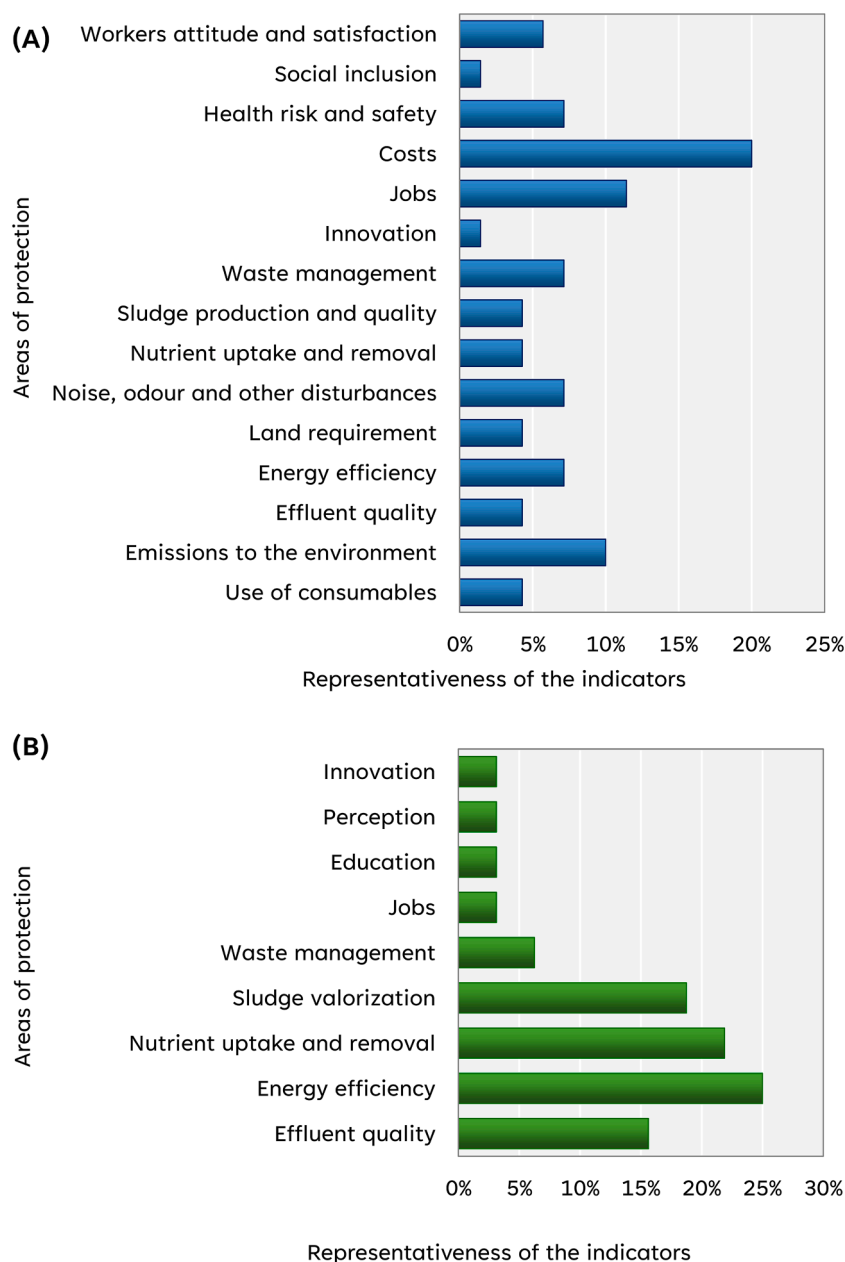


Fig. 2. Representativeness of the areas of protection for sustainability (a) and circularity (b) indicators of the datasets to be accounted for the certification framework.

large-scale wastewater treatment plant, the treatment scheme consists mainly of four stages (pretreatment, primary, secondary, tertiary and sludge treatment). Pretreatment focuses on the removal of fine and coarse solids, as well as grease and grit. A three-line gritting and degreasing process with the introduction of air with submersible aerators is used. The solid residues removed from the screens are compressed before being stored and exported off-site for treatment. The sands and grains are then pumped to a sand classifier and surface scrapers to reduce the water content before being stored.

During primary treatment, chemical coagulation-flocculation with iron chloride and polyelectrolyte is used, while a 4-line treatment train (one anoxic chamber and three sequential aerobic chambers) of moving bed biofilm reactors (MBBR) has been installed for organic matter degradation and nitrification-denitrification. After the MBBR, the effluent is fed to an Actiflo®Turbo clarifier that performs secondary coagulation, flocculation and laminar settling with microsands. Finally, there is a tertiary treatment with ultraviolet disinfection. After this

stage, the treated wastewater is discharged to the sea with a transmarine pumping station.

As for the sludge line, the solids removed with the water line technologies are subjected to thickening and/or stabilization processes (anaerobic digestion). The case study described here is characterized by a segregation of the sludge stream, since solids from primary and secondary treatment are not mixed together. Thus, all sludge from the primary treatment has been valorized as biogas under anaerobic conditions, but the secondary sludge is only partially treated within the digestion stage. The effluent from the anaerobic reactor is thickened (to at least 20 % dryness) and subsequently stored. The concentration of the secondary sludge is also a precondition for its transport to an authorized external manager (minimum dryness of 18 %). Subsequent dewatering and thickening of the sludge also takes place.

Case study B was designed for 800,000 inhabitants-equivalent. Pretreatment is based on large particle pits, automatic large particle screening, fine solids screening, waste transport and compaction,

Table 4

Correlation between the requirements of the specification framework and quantitative indicators from the wastewater treatment dataset. The equations for the indicators are shown in Supplementary Materials A.

Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
ES 02.01.01	I1. Sewage sludge quality indicator (Dimensionless)	F ₂ O ₃ mass in the sewage sludge ash	kg/d	There are no thresholds for the indicator or for the compounds used to estimate.	Preisner et al. (2022)
		Al ₂ O ₃ oxides mass in sewage sludge ash	kg/d		
		MgO mass in sewage sludge ash	kg/d		
		P ₂ O ₅ mass in sewage sludge ash	kg/d		
		Fe mass in sewage sludge ash	kg/d		
		Al mass in sewage sludge ash	kg/d		
ES 02.01.02	I2. Eutrophication net environmental impact (Dimensionless)	CaO mass in sewage sludge ash	kg/d	The indicator values below the unit mean that the WWTP is underperforming with respect to the theoretical removal capacity while values over the unit indicate a performance above the legislation standards.	Lorenzo-Toja et al. (2016)
		Potential of eutrophication produced by the discharge of wastewater without previous treatment	kg PO ₄ ³⁻ eq/d		
		Potential of eutrophication indirectly coming from the process treatment	kg PO ₄ ³⁻ eq/d		
		Potential of eutrophication caused by the discharge of the effluent	kg PO ₄ ³⁻ eq/d		
ES 02.01.04	I3. Sludge disposed (non-utilized) (%)	Potential of eutrophication caused by the discharge of the effluent determined by law	kg PO ₄ ³⁻ eq/d	The restrictions are variable and depend on the country and regions where the wastewater treatment plants are installed. There could be limitations for sludge disposal in landfills. In some cases, only the sludges that could not be valorised would be admissible for landfill disposal.	Matos et al. (2003)
		Volumetric flowrate of sludge disposed	m ³ /d		
ES 02.02.04	I4. Intermittent overflow discharge volume per capacity (%)	Volumetric flowrate of sludge produced	m ³ /d	An overflow reduction plan should be in place but there are no thresholds established.	Kang et al. (2020)
		Overflow discharge caused by events (i.e., heavy rains)	m ³ /d		
ES 02.02.06	I5. Organic matter removal efficiency (%)	Average operational treatment capacity by design	m ³ /d	The minimum percentage of reduction is 70–90 % for biological oxygen demand, 75 % for chemical oxygen demand, 90 % for total solids for facilities with >10,000 habitants equivalent, 70 % for total solids for facilities between 2000 and 10,000 habitants equivalent.	Preisner et al. (2022) Council directive 91/271/EEC
		Chemical oxygen demand concentration in the influent	mg/L		
		Chemical oxygen demand concentration in the effluent	mg/L		
ES 02.02.06	I6. Nitrogen removal efficiency (%)	Average operational treatment capacity	m ³ /d	The minimum percentage of reduction is 70–80 % for total nitrogen.	Preisner et al. (2022) Council directive 91/271/EEC
		Nitrogen concentration in the influent	mg/L		
		Nitrogen concentration in the effluent	mg/L		
ES 02.02.06	I7. Phosphorus removal efficiency (%)	Phosphorus concentration in the influent	mg/L	The minimum percentage of reduction is 80 % for total phosphorus.	Preisner et al. (2022) Council directive 91/271/EEC
		Phosphorus concentration in the effluent	mg/L		
ES 02.02.07	I8. Reduction of flow of wastewater generated (Dimensionless)	Concentration of total suspended solids in the effluent	mg/L	The contaminants of the wastewater effluents should have concentrations below 25 mg/L for biological oxygen demand, 125 mg/L for chemical oxygen demand, 35 mg/L for total solids in facilities with >10,000 habitants equivalent, 60 mg/L for total solids for facilities between 2000 and 10,000 habitants equivalent, 2 mg/L for total phosphorus in facilities between 10,000–100,000 and 1 mg/L for facilities larger than 100,000 habitants equivalent, 15 mg/L of total nitrogen for facilities between 10,000–100,000 and 10 mg/L	Kiselev et al. (2019) Council directive 91/271/EEC

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Table 4 (continued)

Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
				L for facilities >10,000 habitants equivalent. For the indicator, the result is 1 when the ratio between the measured and the legislative values of the previously cited parameter is lower to 1.	
ES 02.03.02	I9. Global warming potential (kg CO ₂ eq./m ³ kg CO ₂ eq./habitant)	<p>Concentration of biodegradable oxygen demand in the effluent</p> <p>Concentration of chemical oxygen demand in the effluent</p> <p>Concentration of Kjeldahl nitrogen in the effluent</p> <p>Concentration of phosphorus in the effluent</p> <p>Concentration of nitrates in the effluent</p> <p>This indicator needs mass balances around the system boundaries. For a wastewater treatment plant should include at least: composition and flowrate of the wastewater effluent, composition and flowrates of air direct emissions, mass and type of chemicals consumed, quantity of energy (both heat and electricity) and composition and flowrate of wastes, sludges and products.</p>	<p>mg/L</p> <p>mg/L</p> <p>mg/L</p> <p>mg/L</p> <p>mg/L</p> <p>kg CO₂eq./m³</p> <p>kg CO₂eq./habitant</p>	<p>Thresholds have still not been established by law. Examples of estimations for large scale centralized wastewater treatment plants: (1) Ranieri et al. (2024) calculated the greenhouse gases of 183 wastewater treatment plants with compensation measures. Their results indicated an average carbon footprint of 1.22 kg CO₂eq/m³. (2) Parravicini et al. (2022) proposed a range of emissions for WWTPs between 50 and 125 kg CO₂eq/person equivalent/y. (3) Lorenzo-Toja et al. (2015) studied 113 Spanish WWTPs. The average carbon footprint was 0.45 kg CO₂eq/m³.</p>	<p>Cossio et al. (2020)</p> <p>Ranieri et al. (2024)</p> <p>Parravicini et al. (2022)</p> <p>Lorenzo-Toja et al. (2015)</p>
Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
ES 02.03.03	I10. Spills and/or leakages of chemicals, by-products and wastewater (kg/10 ⁶ m ³)	<p>Gas chemicals accidentally released to the atmosphere</p> <p>Average operational treatment capacity</p>	<p>kg/d</p> <p>m³/d</p>	<p>Thresholds were not identified for this indicator. The expected result should indicate that any kind of spill of produced</p>	<p>Quadros et al. (2010)</p>
Es 02.04.01	I.11 Pollutant content indicator from sewage sludge (Dimensionless)	<p>Concentration of cadmium in the sludge</p> <p>Concentration of copper in the sludge</p> <p>Concentration of chromium in the sludge</p> <p>Concentration of phosphorus pentoxide in the sludge</p> <p>Concentration of mercury in the sludge</p> <p>Concentration of nickel in the sludge</p> <p>Concentration of lead in the sludge</p> <p>Concentration of zinc in the sludge</p>	<p>mg/kg</p> <p>mg/kg</p> <p>mg/kg</p> <p>mg/kg</p> <p>mg/kg</p> <p>mg/kg</p> <p>mg/kg</p> <p>mg/kg</p>	<p>The limiting values for heavy metals in sludge to be use in agriculture in mg/kg are: 20–40 for cadmium, 1000–1750 for copper, 300–400 for nickel, 750–1200 for lead, 2500–4000 for zinc and 16–25 for mercury.</p>	<p>Preisner et al. (2022)</p> <p>Council directive 86/278/EEC</p>
ES 02.04.02	I12. Current land valuation (€/m ³)	<p>Value of the land where the WWTP is located</p> <p>Average operational treatment capacity</p>	<p>€</p> <p>m³</p>	<p>These costs are dependent on the country and region. A market analysis is needed but there are not thresholds associated.</p>	<p>Quadros et al. (2010)</p>
ES 02.07.02	I13. Noise levels affecting the population (Dimensionless)	<p>Noise level during the day-time</p> <p>Noise level during the evening-time</p> <p>Noise level during the night-time</p>	<p>dBA</p> <p>dBA</p> <p>dBA</p>	<p>The permissible sound for each type equipment can be found on article 12 of Directive 2000/14/EC</p>	<p>Collivignarelli et al. (2022)</p> <p>Directive 2000/14/EC</p>
ES 02.07.05	I14. Odor emission potential (Dimensionless)	<p>Maximum chemical oxygen demand concentration</p> <p>Influent chemical oxygen demand concentration</p> <p>Odour emission rate per type of treatment unit</p>	<p>mg/L</p> <p>mg/L</p> <p>mg/L</p>	<p>Nowadays, there are no legislative thresholds for odor emissions.</p>	<p>van Schaik et al. (2021)</p>

Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
ES 03.01.01	I15. Energy consumption per flowrate (kWh/m ³ or kWh/habitant)	Energy consumed by the facility during its operation	kWh/d	For wastewater treatment infrastructure (according to legislation), the consumption should be below 35 kWh/habitants equivalent for facilities below 10,000; 25 kWh/habitants equivalent for facilities between 10,000 and 100,000 and 20 kWh/habitants equivalent for facilities above 100,000. He et al. (2019) provided a range for energy consumption in WWTPs of 0.1–1.2 kWh/m ³ which is comparable with the results of Toja et al. (2016) (0.185–0.785 kWh/m ³) COM/2022/541 indicates that energy neutrality in wastewater treatment plants should be achieved by 2040 for all facilities above 10,000 habitants equivalent.	Cassidy et al. (2020) Directive (EU) 2023/1791 COM/2022/541 Directive 2010/75/EU He et al. (2019) Toja et al. (2016)
ES 03.02.01	I16. Consumption of chemicals (% or kg/m ³)	Average operational treatment capacity Flowrate of acids and/or bases consumed during process operation	m ³ /d or habitant m ³ /d or kg/d	The consumption of chemicals should be progressively minimized but there are no legislative thresholds.	Quadros et al. (2010)
ES 03.03.02	I17. Freshwater consumption (%)	Average operational treatment capacity Flowrate of freshwater (or potable water) consumed during the process operation	m ³ /d	Temporary thresholds could be imposed by regional governments during water scarcity seasons based on the severity of the droughts. Therefore, the results of this indicator should be minimized.	Quadros et al. (2010)
ES 04.01.01	I18. Sediments from sewers and tanks (m ³ /habitant-d or kg/habitant-d)	Average operational treatment capacity Flowrate of sediments collected from sewers and tanks	m ³ /d m ³ /d or kg/d	Although the indicator makes reference to the production of grits, no threshold can be imposed. The indicator should be minimized.	Matos et al. (2003)
ES 04.01.01	I19. Solid waste from screenings and grit chambers (m ³ /habitant-d or kg/habitant-d)	Habitant equivalents served by the facility Flowrates from screenings and grit chambers	Dimensionless m ³ /d or kg/d	Same comment as described for the previous indicator (also related to requirement ES 04.01.01)	Matos et al. (2003)
ES 04.02.01	I20. Sludge destination (kg/d)	Habitant equivalents served by the facility Mass flowrate used in material recovery Mass flowrate used in energy recovery	Dimensionless kg/d kg/d	Same thresholds than for the indicator associated to the requirement ES 02.01.04	Collivignarelli et al. (2021)
Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
SES 01.01.01–02	I21. Revenues from the selling of fertilizers (€/d)	Mass flowrate of recovered phosphorus	kg/d	In terms of profitability the maximum ideal value is achieved when all the phosphorus and nitrogen of the wastewater influent has been recovered. Apart from the quality or market limitations that the company may find in the commercialization of the fertilizers, there are no thresholds for this indicator.	Smol and Koneczna (2021)
		Mass flowrate of recovered nitrogen	kg/d		
		Average selling price of phosphorus	€/kg		
		Average selling price of nitrogen	€/kg		
SES 01.01.03	I22. Revenues from the selling of produced electricity (€/d)	Electricity production from the digester	kWh/d	The limitation of the electricity production is theoretical methane yield (0.35 Nm ³ methane/kg chemical oxygen demand) and the efficiency of the heat and power unit (or other).	Smol and Koneczna (2021)
		Average country electricity price	€/kWh		
SES 01.01.05	I23. Reuse of wastewater (Dimensionless)	Mass flowrate of recovered phosphorus	kg/d	This indicator represents a ratio of avoided costs considering the management of nitrogen and phosphorus as fertilizers compared to their removal to prevent environmental impacts and damages. The maximum value is 1, result that indicates that all the removed nitrogen and phosphorus from the wastewater influent has been recovered. There are no minimum thresholds, but low (specially <0.5) values shows that the facility advocates more for the removal than for the recovery.	Kayal et al. (2019)
		Mass flowrate of removed phosphorus	kg/d		

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Table 4 (continued)

Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
SES 01.01.05	I24. Wastewater reclamation (Dimensionless)	Environmental costs of phosphorus	€/kg	No thresholds are imposed to the results of this indicator.	Kaya et al. (2019)
		Mass flowrate of recovered nitrogen	kg/d		
		Mass flowrate of removed nitrogen	kg/d		
		Environmental costs of nitrogen	€/kg		
		Volumetric flowrate of reclaimed water	m ³ /d		
SES 01.01.05	I25. Operating cost coverage (%)	Volumetric flowrate of reclaimed water that is not used	m ³ /d	There is no threshold for this indicator. The results should be compared for the same facility after modifications in the treatment process or company policies have been produced.	Smol and Koneczna (2021)
		Average price of reclaimed water	€/m ³		
		Annual operational revenues	€/y		
		Annual operational costs	€/y		
Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
SES 01.03.02	I26. Unit operational cost per flowrate (€/m ³)	Annual operational expenses	€/y	Although the annual operational expenses are dependent on the technologies selected, several examples are provided here as reference: (1) Garfi et al. (2017) found an average 0.79 €/m ³ for activated sludge, 0.40 €/m ³ for constructed wetlands and 0.42 €/m ³ for high rate algae ponds; (2) Lorenzo-Toja et al. (2016) indicated that those costs can be found between 0.344–0.70 €/m ³ ; (3) Molinos-Senante et al. (2010) showed values between 0.1158–0.7491 €/m ³ (average of 0.22 €/m ³)	OCDE (2022) Garfi et al. (2017) Lorenzo-Toja et al. (2016) Molinos-Senante et al. (2010)
SES 01.03.03	I27. Environmental costs (€/m ³)	Average operational treatment capacity This indicator needs the use of the results of a Life Cycle Assessment. The results will vary depending on the method (True Price, Delft or Wageningen) from which the weighting factors were taken for their estimation.	m ³ /y €/m ³	There is not threshold implicit. Looking for a minimization the company should evaluate continuously the indicator after process changes have been implemented.	Scheepens et al. (2016) Ponsioen et al. (2020) Korteland & de Bruyn (2010) True Price Foundation (2021) Kaya et al. (2019)
SES 01.03.04	I28. Efficiency in the production of waste (Dimensionless)	Volumetric flowrate of reclaimed water	m ³ /d	There is not yet a predefined threshold for this indicator. A comparison should be made between facilities, over time or with the average of the sector.	
SES 01.04.01	I29. Wastewater service coverage (%)	Average selling price of reclaimed water	€/m ³	The set-up of urban wastewater collecting systems is extended to all agglomerations with 1000 habitants equivalent or more	Nika et al. (2020) COM/2022/541
		Mass flowrate of removed phosphorus	kg/d		
		Environmental costs of phosphorus	€/kg		
		Mass flowrate of removed nitrogen	kg/d		
		Environmental costs of nitrogen	€/kg		
		Annual operational costs	€/y		
		Annualized capital costs	€/y		
Number of wastewater producers connected to the mains	Dimensionless				
SES 02.01.01	I30. Microbiological quality of reclaimed water at delivery points (%)	Number of potential wastewater producers living in region where the facility has been located	Dimensionless	The microbiological thresholds should be: 0 number of colonies per 100 mL of water for <i>Escherichia Coli</i> and <i>Enterococci</i>	Quadros et al. (2010) Directive 98/83/EC
		Average of the 10 % higher values recorded at the delivery point with higher microbiological counts	CFU/100 cm ³		
		Maximum allowable value	CFU/100 cm ³		
Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
SES 02.02.01	I31. On-the-job-training (%)	Annual training time dedicated	h/y	There is not a threshold for this indicator. The company should compare itself with other annual results and with other statistics of the sector.	Nam et al. (2019)

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Table 4 (continued)

Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
		Full time number of employees affiliated to the facility	Dimensionless		
SES 02.02.02	I32. Injuries and professional illnesses (d ¹)	Annual number of incidents at work registered	Dimensionless	The aspirational value for this indicator is zero.	Quadros et al. (2010)
		Full time number of employees affiliated to the facility	Dimensionless		
SES 02.02.03	I33. Overtime work (%)	Annual extra time dedicated by the workers	h/y	In accordance with Directive 2003/88/EC (article 5), the average working time for each seven-day period, including overtime, does not exceed 48 h. The maximum potential workload depends on the country.	Quadros et al. (2010) Directive 2003/88/EC
		Maximum potential workload by the workers	h/y		
SES 02.03.10	I34. Emergency response (min/event)	Average response time to emergency events	min	There is no regulation that establishes a standard for the response time and thus there are no thresholds for the indicator.	Quadros et al. (2010)
		Annual number of emergency events	Dimensionless		
SES 03.01.06 & CI 01.02.01	I35. Public perception indicator (Dimensionless)	Annual number of complaints received for all types of discomforts	Dimensionless	The indicators should be zero. The company should compare itself with others of the sector or with similar characteristics.	Popovic & Kraslawski (2017)
CI 01.01.01	I36. Reuse of reclaimed water for irrigation (%)	Volumetric flowrate of reclaimed water used in irrigation	m ³ /d	The quality requirements for irrigation are those of the urban wastewater directive 2020/741/EU. Class A is more restrictive compared to classes B and C. The thresholds for the reuse of the reclaimed water are <10 number/100 mL for <i>E.coli</i> , <10 mg/L for BOD ₅ , <10 mg/L for TSS and <5 mg/L for turbidity for class A. If there not limits in the quality of the reclaimed water, the effluent could be reuse up to environmental, applicability (i.e., no more land needs irrigation) or economic limits. The maximum of the indicator could be 100 %.	Preisner et al. (2022) directive 2020/741/EU
		Volumetric flowrate of the effluent	m ³ /d		
CI 01.02.03	I37. Energy-self sufficiency (%)	Recovered energy inside the facility	kWh/d	In accordance with the new wastewater treatment directive (COM/2022/541) the energy neutrality should be achieved by 2040 for all facilities above 10,000 habitants equivalent.	Nika et al. (2020) COM/2022/541
		Renewable energy consumed inside the facility	kWh/d		
		Energy consumption	kWh/d		
Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
CI 01.02.04	I38. Reuse of energetic flows (Dimensionless)	Renewable energy consumed inside the facility	kWh/d	There is not threshold for this indicator although it should be maximize.	Kiselev et al. (2019)
		Energy consumption	kWh/d		
CI 02.01.02	I39. Phosphorus recovery efficiency (%)	Mass flowrate of phosphorus in the influent	kg/d	There are not thresholds for this indicator but the current technologies of nutrient recovery from wastewater cannot still reach 100 % efficiency levels but recovery rates are ranging from 25 to 90 % or more.	Preisner et al. (2022) and Kiselev et al. (2019)
		Mass flowrate of phosphorus in the effluent	kg/d		
CI 02.01.02	I40. Nitrogen recovery efficiency (%)	Mass flowrate of nitrogen in the influent	kg/d	Nitrogen recovery efficiency may depend on the technologies implemented for product manufacturing and strategies for the recovery of waste (i.e., sludge). There is not a clear limit of recovery since it depends on the technologies used. Ammonia stripping may provide a recovery between 50 and 98 %, membrane technologies between 64 and 99.8 % and ammonium phosphate precipitation between 65 and 98 % (Zhou et al., 2023)	Preisner et al. (2022) and Kiselev et al. (2019) Zhou et al. (2023)
		Mass flowrate of nitrogen in the effluent	kg/d		
CI 02.01.02	I41. Biofertilization for phosphorus (%)	Concentration of phosphorus in the biofertilizer (or sludge) manufactured in the facility	mg/kg	The concentration of the biofertilizers of the facility has been compared with a commercial mineral fertilizer of diammonium phosphate (18 % of nitrogen and 46 % of phosphorus)	Preisner et al. (2022) and Kiselev et al. (2019)
		Concentration of phosphorus in a mineral fertilizer of reference	mg/kg		
Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.

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Table 4 (continued)

Code of the requirements	Indicator (unit)	Parameters used	Units of the parameter	Thresholds for the indicator	Refs.
CI 02.01.02	142. Biofertilization for nitrogen (%)	Concentration of nitrogen in the biofertilizer (or sludge) manufactured in the facility	mg/kg	The references mineral fertilizer for this indicator was also diammonium phosphate (as specified in the previous indicator)	Preisner et al. (2022) and Kiselev et al. (2019)
CI 02.01.02	143. Biofertilizer global efficiency (%)	Concentration of nitrogen in a mineral fertilizer of reference Mass flowrate of digestate produced in anaerobic digestion	mg/kg kg/d	The indicator associated to requirement CI 02.01.02 allows to identify quantitatively the percentage of biofertilizer manufactured from digested sludge. It is an informative indicator and there are, thus, no limits established.	Preisner et al. (2022) and Kiselev et al. (2019)
CI 02.01.02	144. Technological biofertilizer yield (kg/m ³)	Mass flowrate of biofertilizers manufactured in the facility Mass flowrate of biofertilizers manufactured in the facility	kg/d kg/d	In accordance with the results Lorenzo-Toja et al. (2016) the results of this indicator may be inside the range of 0.0838–1.685 kg/m ³ .	Preisner et al. (2022) and Kiselev et al. (2019)
CI 02.01.02 CI 01.02.06	145. Production of biogas from sludge (Dimensionless)	Average operational treatment capacity Volumetric flowrate of biogas	m ³ /d m ³ /d	The threshold for this indicator is the theoretical methane yield (0.35 Nm ³ methane/kg chemical oxygen demand).	Preisner et al. (2022) and Kiselev et al. (2019)
CI 02.01.02	146. Reuse of sludge flowrate (Dimensionless)	Volumetric flowrate of biodegradable waste generated in the facility Volumetric flowrate of digestate produced in anaerobic digestion Volumetric flowrate of dry sludge generated	m ³ /d m ³ /d m ³ /d	There are no thresholds. The indicator is informative.	Preisner et al. (2022) and Kiselev et al. (2019)

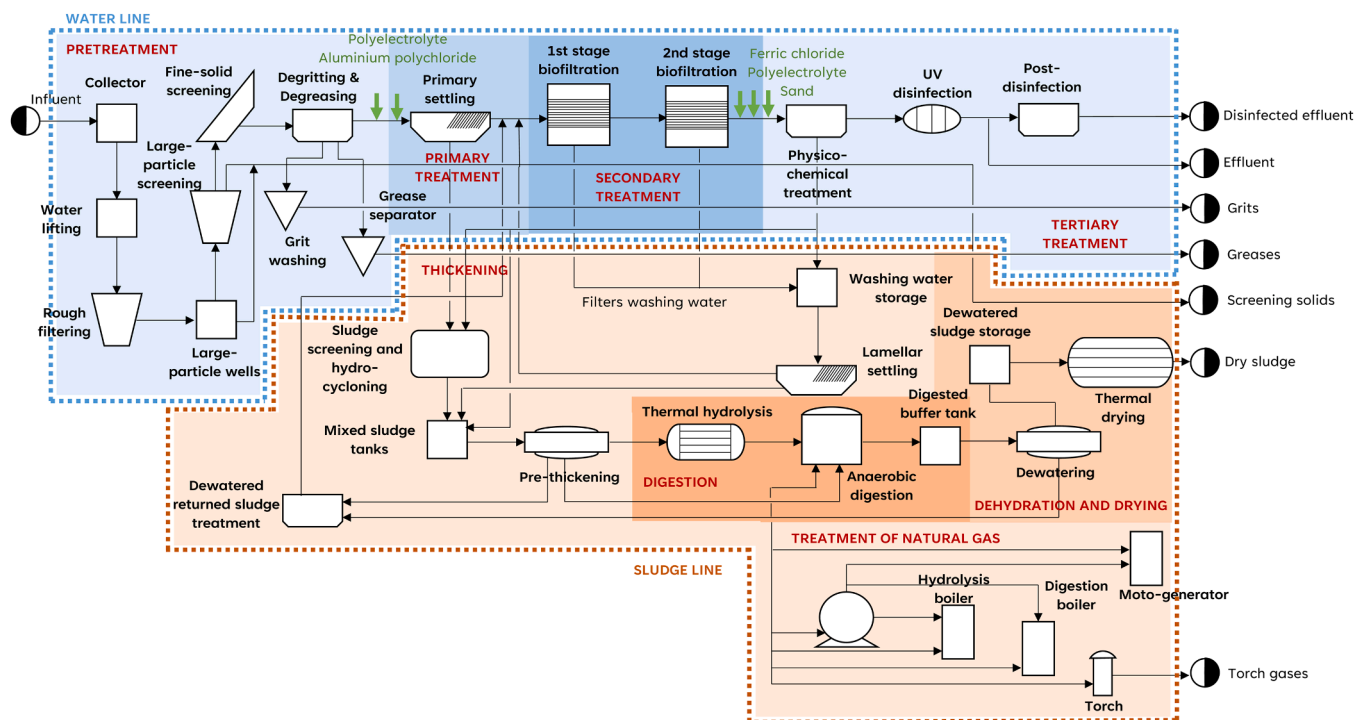


Fig. 3. Process diagram of the wastewater treatment plant corresponding to case study A.

degritting and degreasing, and grit washing. Primary settling is carried out in lamellar clarifiers that are supported by a physicochemical process in a humid climate to increase the efficiency of solids removal. For the biological process, a two-stage Biostyr® biofiltration with chemical nitrogen and phosphorus removal was installed. The plant's tertiary

treatment also includes a high-rate ballast clarification system (Actiflo), designed for both chemical phosphorus removal and stormwater treatment in peak flow situations. Effluent disinfection is performed by a modular ultraviolet (UV) radiation unit. The treated water is discharged to the sea through a submarine outfall.

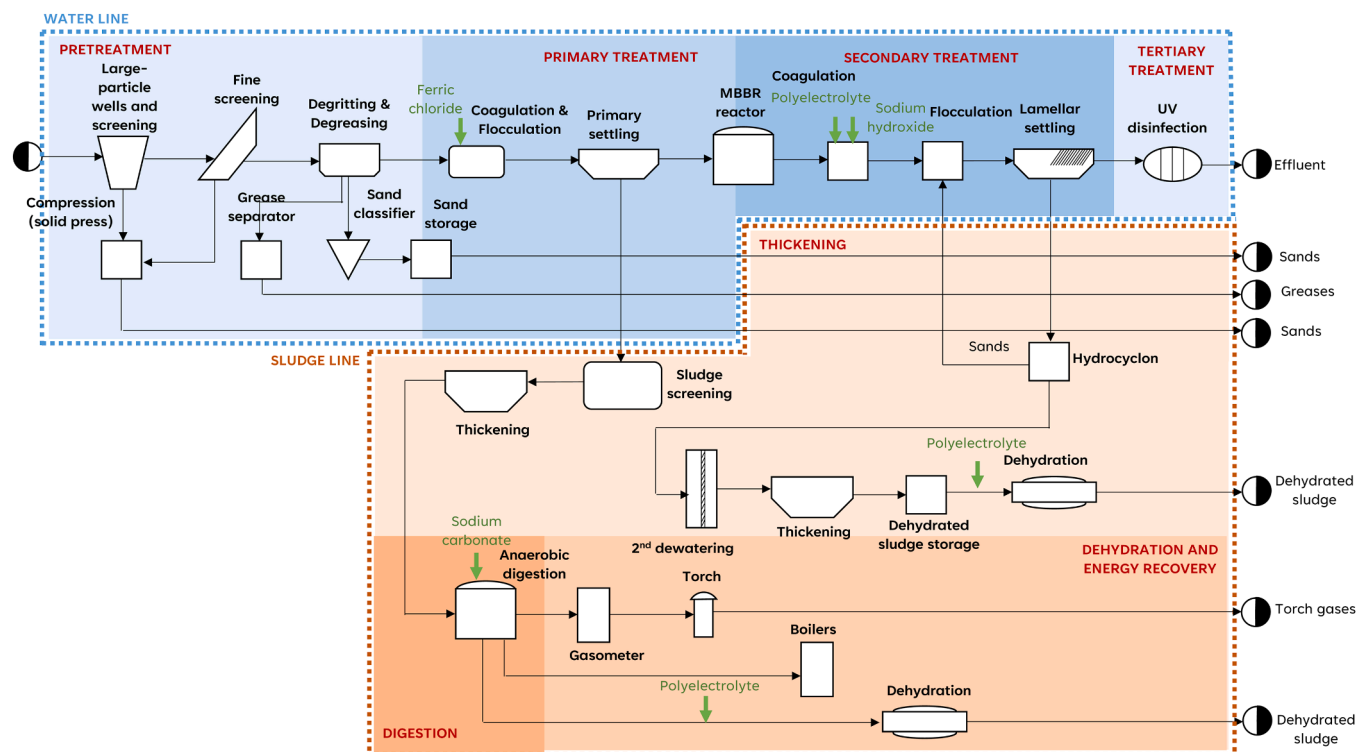


Fig. 4. Process diagram of the wastewater treatment plant corresponding to case study B.

On the other hand, the sludge line was designed to include sludge thickening with hydrocyclones, thermal hydrolysis pretreatment followed by anaerobic digestion, mechanical dewatering of the digested sludge, thermal drying of the dewatered sludge and treatment of the liquid returns before being incorporated back into the water line. The implementation of thermal hydrolysis prior to anaerobic digestion allows for a compact design while increasing the removal of organic matter and dry matter from the sludge to be treated by an external manager. However, the use of this technology also raised the ammonium concentration in the liquid sludge returns, resulting in the requirement of an ammonification process.

7. Estimation of indicators and verification of results

7.1. Feasibility of the estimation for the indicators

Of the dataset of 46 indicators (**Supplementary Materials A**, correlated with **Table 2** and **Supplementary Material B**), a total of 35 could be scored using primary data from the case studies. This implies that 23 of the 38 quantitative requirements, 61 %, of the framework can be addressed and analyzed with routine plant information. Of these 23 requirements, 57 % are environmental and 17 % circular, with the remainder being economic. With respect to the 11 indicators that could not be scored, these relate to safety (overflow discharges, chemical leaks, microbiological quality of reclaimed water, wastewater service coverage for the population, and emergency response times) and social (odor and noise complaints, public perception, prevention of over-exploitation of workers, and occupational injury coverage). More specifically, the indicators are coded as follows: I4, I10, I13, I14, I14, I29, I30, I31, I32, I33, I34 and I35 in **Table 4**.

The results and interpretation of each of the indicators calculated are presented in **Table 5**. From the screening and testing process, two types of indicators were identified:

- Indicators with measurable results: These 19 indicators have a reference point for comparison, such as legislative thresholds,

operational ranges reported in the literature, or optimum limits for the indicator. These are coded in **Table 5** using a color system to indicate compliance: green (met), orange (partially met), and red (not met).

- Indicators requiring benchmarking: These 16 indicators cannot be analyzed due to the lack of a baseline scenario for comparison. They are coded in **Table 5** with a gray color.

It should also be noted that most of the indicators can be calculated with simple and straightforward equations, the exceptions being I2, I9 and I27, which require the development of an LCA.

7.2. Data needed to implement the methodology

A fact sheet has been created as a guide for wastewater treatment companies to know the data needed to estimate feasible indicators for the specification framework. The form has been provided as online supplementary material. Two additional sections (also shown in the Excel sheet in **Supplementary Materials C**) have been incorporated into the datasheet as informative evidence of the additional data that should be necessary to estimate all the indicators available in **Supplementary Materials A**. **Fig. 5** shows the first page of the questionnaire in order to perform an analysis as shown in **Table 5**.

7.3. How indicators support the improvement of WWTPs

When calculating the indicators from **Table 5**, the datasheet (summarized in **Fig. 5** or **Supplementary Materials C**) sorts out the necessary data based on the nature of process inputs (wastewater influent, energy demand, chemical consumption) and outputs (sludge generated, other wastes, and products), being the exception some economic data (i. e., nutrient prices, operational and capital costs). Although the indicators from **Table 5** could be estimated with the previously mentioned data, not all of them can be assessed in terms of result interpretation. This limitation arises because some indicators lack reference values for comparison, even though they may still be useful for addressing specific

Table 5

Validation of the applicability of the indicators from Table 4 with the case studies. Indicators marked in grey highlight the absence of a benchmark for comparison (green: fulfilled, orange: partially fulfilled and red: not fulfilled).

Code of the requirement (indicator)	Indicators result		Result in line with thresholds?	
	Case study A	Case study B	Case study A	Case study B
ES 02.01.01 (I1)	1011.69 kg Fe/kg P ₂ O ₅	12.47 kg Fe/kg P ₂ O ₅	The sewage sludge quality indicator has been estimated only for iron because the remaining compounds have not been measured in the sludge of WWTPs. It is assumed that all of the mass of this compound comes from the iron chloride consumed during the treatment.	The amount of iron ending up in sludge is around 9,900 kg/d which is larger than for case study A (around 400 kg/d). However, the concentration of phosphorus oxide is also larger for case study B, which compensates for the concentration of iron as a heavy metal in the sludge.
ES 02.01.02 (I2)	1.12	1.35	The eutrophication net impact is above 1 and thus the facility performs above legislation standards.	Same comment as for case study A
ES 02.01.04 (I3)	0.0%	0.0%	All the sludge goes to an external manager and thus it is not disposed in landfills	Same comment as for case study A
ES 02.02.06 (I5, I6 and I7)	91.42% for organic matter 65.02% for nitrogen 84.94% for phosphorus	96.54% for organic matter 93.96% for nitrogen 81.87% for phosphorus	The removal of organic matter is above the minimum removals of 75% for COD, 70-90% for BOD, 70-80% for TN and 80% for TP according to the Directive 91/271/CEE	Same comment as for case study A
ES 02.02.07 (I8)	1.00	1.00	Since the result achieved is 1, the WWTP complies with the emission limits for the wastewater effluent.	Same comment as for case study A
ES 02.03.02 (I9)	1.08 kg CO ₂ eq./m ³ 78.31 kg CO ₂ eq./habitant	1.17 kg CO ₂ eq./m ³ 86.27 kg CO ₂ eq./habitant	The facility has similar carbon footprint results than other domestic wastewater treatment plants studied within the scientific literature.	Same comment as for case study A.
ES 02.04.01 (I11)	2.77·10 ⁻⁶	1.22·10 ⁻⁶	The lower this value, the better the quality of the sludge generated to be recovered in terms of pollutant heavy metals. The relative proportion of the heavy metals with respect with recovered phosphorus for a concentration of the metals equivalent to the indicated in the directive Council directive 86/278/EEC is 1.90·10 ⁻⁵	This scenario has a relative proportion of heavy metals with respect to phosphorus concentration in the sludge equivalent to 4.22·10 ⁻⁶
ES 02.04.02 (I12)	3.99·10 ⁻³ €/m ³	8.42·10 ⁻³ €/m ³	The land value per capacity needs to be compared with facilities from other regions and technologies. No bibliographic results were found to compare with.	Same comment as for case study A
ES 03.01.01 (I15)	0.55 kWh/m ³ 40.06 kWh/habitant	0.39 kWh/m ³ 28.51 kWh/habitant	The energy consumption per capacity of the plant is in line with the values from scientific literature. However, the facility has a capacity of 260,000 habitants. The plants with higher capacities than 100,000 should have consumptions of energy below 20 kWh/habitant. Moreover, the new wastewater treatment proposal looks for energy neutrality and, thus, in the coming years this case study will have to be updated to keep fulfilling the legislation.	The facility has a capacity of 800,000 habitants, which is above 100,000. This implies that the energy consumption should be below 20 kWh/habitants. The result obtained is very close to the 20 kWh/habitants but it is slightly above. This is because the facility has been sealed for odour removal and additional energy is needed for the filtration of the air before being expelled to the outside.
ES 03.02.01 (I16)	65.28 g/m ³	183.15 g/m ³	This indicator should be compared over time or when modifications are made to the treatment process.	Same comment as for case study A.
ES 03.03.02 (I17)	0.24%	4.34%	This indicator receives the same comment as indicator I14.	Same comment as for case study A.
ES 04.01.01 (I18 and I19)	3.27 g/habitant-d 16.48 g/m ³	9.05 g/habitant-d 44.63 g/m ³	The indicator was estimated considering the total production of grit and debris from the WWTP. There are no thresholds, the comparison should be made throughout time or after modifications are made in the process. Besides the production of grit and debris is also dependent on the characteristics of wastewater influent.	Same comment as for case study A.
	3.39·10 ⁻⁶ m ³ /habitant-d	9.13·10 ⁻⁶ m ³ /habitant-d	Apart from grit and debris this indicator incorporated the greases to its estimation (compared to the previous one). Also as indicated above, there are no thresholds.	Same comment as for case study A.
ES 04.02.01 (I20)	7,098.72 ton/y	12,085.17 ton/y	All the sludge is intended to be used for material recovery	The final destination of the sludge is agricultural application and thus, the goal of the valorization is material recovery.
SES 01.01.01-02 (I21)	130,244.69 €/y	207,556.78 €/y	If all the nitrogen and phosphorus was recovered from all the influent the maximum economic benefit achieved could be 438,531.11 €/y. The room for profits improvement, without a change of market prices, could be up to 3.36 times higher.	The maximum phosphorus benefit, as explained for case study A, could be for this case 963,528.29 €/y. The top benefits from the selling of fertilizer could not be bigger than 4.6 times the actual value with the current fertilizer prices.
SES 01.01.03 (I22)	0.0 €/y	880,880.50 €/y	Biogas valorization for electricity production is not considered. The facility has installed a boiler for the production of heat. Electricity production is also necessary in order to achieve energy neutrality.	This indicator should be evaluated over time when modifications are introduced into the process.

(continued on next page)

Table 5 (continued)

Code of the requirement (indicator)	Indicators result		Result in line with thresholds?	
	Case study A	Case study B	Case study A	Case study B
SES 01.01.05 (I23, I24 and I25)	0.41	0.23	The reuse of wastewater indicator has a value below 0.5 (from the maximum of 1), which implies that the facility advocates for the removal of nutrients (nitrogen and phosphorus) than for their recovery.	As for case study A, the indicator result is below 0.5 and the facility is not characterized by an active recovery of nitrogen and phosphorus.
	0.00	0.00	Under normal operation, the value of the wastewater reclamation indicator is zero since the effluent is emitted directly to the sea and the water is not reclaimed. The facility considers, though, the reclamation in water scarcity periods for industrial applications.	Also as commented for case study A, the effluent is currently emitted to the sea and the water has not been reclaimed.
	4.61	2.30	The operating coverage indicator may reach a maximum of 11.94 for this WWTP considering the benefits from the recovery of nutrients through the sludge, wastewater reclamation and the service of treatment. It was assumed that nowadays the facility only receives benefits from the treatment service and thus there is room for 61% improvement.	The maximum for this indicator is 6.03 with the same assumptions shown in the description of the results of case study A. Therefore, the maximum enhancement of the facility is almost 62%.
SES 01.03.02 (I26)	0.055 €/m ³	0.017 €/m ³	The unit operational cost per flowrate indicator results shows that the operational costs of the facility per capacity are below those of the literature. The value is much lower than the Spanish average of 0.22 €/m ³ .	Same comment as for case study A.
SES 01.03.03 (I27)	31.10 €/m ³ (with the True Price factors) 106.67 €/m ³ (with the Delft factors) 1.12 €/m ³ (with the Wageningen factors)	0.8 €/m ³ (with the True Price factors) 9.54 €/m ³ (with the Delft factors) 0.22 €/m ³ (with the Wageningen factors)	No bibliographic values were found to compare with. The analysis should be repeated over time to monitor the continuous performance of the facility.	Same comment as for case study A.
SES 01.03.04 (I28)	Not available	0.30	The efficiency in the production of waste was an indicator that could not be estimated for case study A because the documentation did not provide the construction costs.	This indicator represents a monetary balance between the resources consumed to treat the wastewater and the avoided environmental costs because of the removal of contaminants. The higher the removal efficiency of pollutants and water reclamation rate, the bigger the value of the indicator. This indicator should be compared when technological changes are implemented in the facility.
CI 01.01.01 (I36)	0.0%	0.0%	The reuse of the reclaimed water for irrigation has not been considered for this facility. The WWTP is embedded in the middle of an urban and industrial area. If reclaimed, the water has been considered for industrial applications.	The facility is not reclaiming the wastewater effluent. However, the opportunities for wastewater reclamation for this WWTP are limited since it is located in a dense urban area. The regional government has restricted the flowrates for irrigation and street cleaning and thus the maximum value of this indicator could only be 0.15% for such a purpose.
CI 01.02.03 (I37)	27.81%	63.59%	The energy self-sufficiency indicator reached around 28% because of the use of heat produced in boilers from the burning of biogas produced in the anaerobic digestion of the primary sludge. In accordance with the new directive proposal for wastewater treatment, WWTP should reach energy neutrality for 2040. This implies that the facility should be updated in the coming years.	The facility uses boilers to burn the biogas and produce heat for sludge hydrolysis and anaerobic digestion. It also has motogenerators to produce electricity which allows the offsetting of electricity from the national grid. Both primary and secondary sludges are being fed to anaerobic digestion units. Although the performance of Case study B is better than A the energy neutrality has still not been reached.
CI 01.02.04 (I38)	0.07	0.54	The value reach for this indicator considers the ratio between the useful energy of the generated biogas (renewable self-produced energy) and the total consumption. If the combustion yield of the biogas was ideally 100% and the energy consumption of the facility was 0.1 kWh/m ³ , the value reached by this indicator could be 0.41. The phosphorus recovery efficiency has a value above 25% because of the external management of sludge and valorization as agricultural fertilizer.	This indicator may increase over time with modifications in the process that lead to minimization of the energy demand during operation or rise in biogas yields.
CI 02.01.02 (I39, I40, I41, I42, I43, I44, I45 and I46)	84.95% for phosphorus 13.66% for nitrogen	81.88% for phosphorus 9.25% for nitrogen	The nitrogen recovery efficiency also has an efficiency below what is expected for nitrogen recovery technologies. The explanation is comparable to the previous one for the phosphorus recovery indicator.	The reasoning of the indicator for case study B is similar to the one for case study A since the results achieved are similar.
	9.67% for phosphorus 27.22% for nitrogen	32.85% for phosphorus 22.22% for nitrogen	The concentration in phosphorus of the sludge is not comparable to mineral fertilizer. If compared the concentration of the sludge with struvite (12.62% of P or 28.92% of P ₂ O ₅) the result of the indicator would be 6.71%. The manufacturing of struvite may increase the value of this indicator up to 27.43%. The facility needs technology for phosphorus recovery to improve the circularity of such important agricultural nutrients like phosphorus. Although the concentration of nitrogen in the sludge is still under the value achieved for a mineral fertilizer, the results are much better than for phosphorus.	Although the concentration is still much better for the mineral fertilizer, the sewage sludge has a quality comparable to the one of struvite (22.82%).
CI 02.01.02 (I39, I40, I41, I42, I43, I44, I45 and I46)	317.55%	100%	The biofertilizer global efficiency is over 100% because not all the sludge has been used in anaerobic digestion. The results of this indicator cannot be conclusive.	All the sludge (primary and secondary) has been hydrolyzed and fed to anaerobic digestion.
	0.13 kg/m ³	0.07 kg/m ³	Since the bibliographic expected range for the indicator of technological biofertilizer yield is 0.0838-1.685 kg/m ³ , the facility performed according to literature.	The amount of dry matter sludge has been compared with the treatment capacity. This WWTP produces less sludge because of the use of thermal hydrolysis, which improves its degradation. The reduction of the indication cannot be considered negative if the quality increases (higher concentration in nutrients). This indicator should be analyzed altogether with I41 and I42.
	73.36	192.57	This indicator should be evaluated over time or when changes are introduced to the treatment process.	Same comment as for case study A
CI 02.01.02 (I39, I40, I41, I42, I43, I44, I45 and I46)	0.74	53.44	The indicator is informative and shows that not all the wet sludge is stabilized through an anaerobic digestion process before being dried. The wet primary sludge digested is a very small quantity compared to the total amount of dry sludge produced.	All the sludge passes through anaerobic digestion and thus the indicator represents the wet sludge digested compared to the dry sludge sent to an external manager. In this regard, the dry sludge is a 1.87% of the wet sludge digested.

DATA COLLECTION DATASHEET



CRETUS Cross-disciplinary Research in
Environmental Technologies

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Data collection for tested indicators inside the especification framework

Company and wastewater treatment plant identification

Company name	<input type="text"/>	Company address	<input type="text"/>
Facility name	<input type="text"/>	Facility street address	<input type="text"/>
Number of the street	<input type="text"/>	Postal code	<input type="text"/>
Telephone of contact	<input type="text"/>	City/Town	<input type="text"/>
Previous certifications	<input type="text"/>		
	email of contact <input type="text"/>		

Generic data

Data of collection of information (month/year)

Average design capacity (m³/d)

Process description and block diagram

Wastewater influent characterization

Average influent flowrate (m ³ /d) <input style="width: 100%;" type="text"/>	Average TN of operation (mg/L) <input style="width: 100%;" type="text"/>
Average COD of operation (mg/L) <input style="width: 100%;" type="text"/>	Average TP of operation (mg/L) <input style="width: 100%;" type="text"/>

Wastewater effluent characterization

Average effluent flowrate (m ³ /d) <input style="width: 100%;" type="text"/>	Average Kjeldahl N of operation (mg/L) <input style="width: 100%;" type="text"/>
Average COD of operation (mg/L) <input style="width: 100%;" type="text"/>	Average nitrates of operation (mg/L) <input style="width: 100%;" type="text"/>
Average BOD of operation (mg/L) <input style="width: 100%;" type="text"/>	Average TP of operation (mg/L) <input style="width: 100%;" type="text"/>
Average TSS of operation (mg/L) <input style="width: 100%;" type="text"/>	

Consumables and energy characterization

Identify and quantify the type (and purity) of chemicals used for the process and the in-process location

1.-
2.-
3.-
4.-

Quantify electricity and heat used for the process and the in-process location

1.- Electricity (kWh/d):
2.- Heat (kWh/d):
3.- Renewable energy (kWh/d):
4.- Fossil energy (kWh/d):

Fig. 5. First page of the request form for data collection to perform a circularity and sustainability analysis with indicators.

requirements of the framework.

To better understand their applicability, the indicators calculated in the case studies were classified according to their objectives and the type of information they provide for improving wastewater treatment plants. Table 6 organizes these indicators based on their usefulness—whether they contribute to the overall enhancement of the facility or support the monitoring of process inputs and outputs. Furthermore, the indicators were categorized by the nature and timeframe of the information they provide.

On one hand, some indicators need to be analyzed before the construction of the facility (referred to as *ex-ante* indicators in Table 6), while others are relevant during operation. Among the latter, certain indicators are static, whereas others require continuous evaluation over time. Static indicators can also be subdivided into those considering legislative thresholds and those providing information on the facility. The classification of indicators in Table 6 highlights a critical finding: the need to develop thresholds and validation tools to ensure the suitability of the facility during the planning and construction phases.

7.4. Moving towards a more comprehensive wastewater treatment system

7.4.1. Improvement of the certification framework: a comparison

Voluntary standardization aims to provide unified and logical procedures or specifications to facilitate the implementation of actions that result in improvements compared to common practices. Depending on its nature, this standardization can be classified into standards, certification, accreditation, and labels. While standards communicate documented agreements for technical specifications on products (not necessarily following mandatory regulations), management systems, and processes, certification involves procedures to ensure conformity with multiple standards along the supply chain.

Based on the previous definitions, the framework presented in Section 3 could be considered a guideline for wastewater sector assessment, considering the requirements of European legislation while following a structure commonly used in certification schemes. In this regard, analogous terminology has been considered (e.g., for analyzing the degree of compliance with certification schemes such as the Roundtable on Sustainable Biomaterials or RSB, which uses terms like "shall" to define mandatory requirements, "should" for recommendations, "may" for optional implementations, and "can" for possibilities and capabilities). Specifically, the term "shall" is used, as all the requirements in the proposed framework stem from legislation and, therefore, must be strictly complied with.

Moreover, the framework has been designed to potentially cover, in the future and with the necessary adaptations, all six stages of the entire water cycle: (1) water capture to supply different actors (e.g., communities or industries) and treatment, (2) water storage and distribution (already covered by some certification schemes such as AWS), (3) wastewater collection and sewage networks, (4) wastewater treatment, (5) by-products commercialization, and (6) solid waste treatment and recovery. Although the final stages are not part of the urban water cycle, they should be included under a circular economy approach, focusing on the recovery of resources from wastewater and the valorization of the wastes produced.

Regarding the structure of the proposed framework for the operation of wastewater treatment facilities, its construction was inspired by existing certification schemes from other bio-based sectors (i.e., forestry, agriculture and fisheries), but increasing the robustness by defining more than two or three levels of classification. For example, FSC is constituted by 10 principles (defined as essential rule or element) and related 57 criteria (a means of judging) (Matias et al., 2024); RSB has 12 principles that describe the best legal, social, environmental and management practices, 40 criteria and 165 explicit criteria (RSB, 2023); SBP is constituted by 2 principles, 16 criteria and 38 indicators (SBP, 2015); MSC standard has 28 performance indicators, under the three principles (Pierucci et al., 2022); ASC Salmon standards have 8 principles and a set

of 32 criteria (ASC, 2024). The Better Biomass certification scheme is constituted of 9 principles, 25 criteria and 14 indicators, and it is highlighted that for this scheme the definition of the principle and indicator is aligned with the ISO 13,065. Amfori BSCI is a two-layer certification scheme which is not structured into principles and criteria but rather in performance areas (a total of 13) and requirements (amfori BSCI, 2022). PEFC, on the other hand, is defined by objectives and requirements (known as quantitative or qualitative parameters describing the different subjects to be evaluated) (PEFC, 2021).

Compared to the previously presented certification schemes, the proposed framework in this manuscript represents a significant advancement by integrating five distinct layers, as well as defining thresholds (available in Supplementary Material B): pillars, principles, criteria, requirements, and indicators. In this way, the principles were classified based on their ability to fulfill the sustainability pillars and circularity. Additionally, there is a clear distinction between criteria, requirements, indicators, and thresholds, which enhances usability and comprehension. Moreover, the proposed framework also considers the assessment of quantitative indicators, rather than focusing solely on qualitative ones, which is the most common approach in the aforementioned certification schemes. This is considered a significant step toward achieving greater accuracy and transparency in the development of auditing processes (Halalisan et al., 2023).

7.4.2. Data gaps and routes for research on indicators

Some gaps were identified through the creation and study of the framework. First, there are not sufficient quantitative legislative thresholds (also as shown in Table 6) for all environmental, economic or social aspects listed in the requirements. Therefore, measuring the performance of wastewater treatment plants should be done primarily by comparison with predefined baselines to evaluate the potential and willingness of facilities to improve. For such a reason, rather than imposing immediate compliance, future legislation and standards should set dynamic targets to be met over time. The proposal and use of thresholds will allow the monitoring of targets and the identification of planned ad hoc government investments in wastewater treatment plants to avoid deviations. Moreover, the development of policies should focus on defining good practices and establishing appropriate operational ranges for facilities based on different scales and technologies. Finally, there should also be specific legislation for the manufactured products, taking into account their quality, safety of use, and permissible applications.

In addition to proposing broader thresholds for the sector, there should be an update in the development of sustainability indicators. Currently, there is a gap between the extensive list of indicators in the literature and the data that can be regularly collected in wastewater treatment plants. Some examples could be energy consumption per equipment, wastewater treatment characterization of the region adjacent to the facility, sewer sizing, and recording different aspects related to emergency events (i.e., medical care needed, maintenance, safety audit, blockages and flooding, among others).

In addition to the diversity of data and the difficulties encountered in collecting it, the legislation monitors the behavior of companies and individuals without using specific quantitative specifications. On the other hand, current certification schemes look for documents or records to ensure compliance with the predefined criteria and guarantee the quality of the services provided. Therefore, the current assessment procedures make it difficult to implement digitized data systems and other actions to integrate company monitoring with artificial intelligence.

Finally, there is a lack of guidelines or a common standardized methodology applicable to plant operators and sustainability (or circularity) assessment professionals for data collection that can be understood simultaneously by both. This is especially important when a multi-criteria analysis is needed since different departments of the company might be involved during data gathering and time can be saved.

Table 6

Classification of the calculated (in the case studies) indicators of the framework considering its objectives, timeframes and nature of information.

Classification groups		Indicators with legislative thresholds	Indicators to be evaluated over time	Informative indicators of quality	Indicators for ex-ante implementation
Related to inputs	Influents	–	–	–	–
	Chemicals	–	I16: The progressive reduction of the consumption of chemicals is a symptom of novel technology implementation and process optimization. I17: Freshwater decrease shows how the facility reclaims more effluent wastewater for its activities, and it is also related to a lower need of chemical dilution.	–	–
	Energy	I15: EU Taxonomy imputes thresholds for energy demand based on process capacity	I15: Energy neutrality must be achieved by 2040. I37: The goal of any WWTP should be to achieve energy-self-sufficiency. I38: The facility should look for the maximization of energy demand that is renewable.	I38: When the energy is taken from the country grid, the indicator informs how the WWTP renewability is dependent from the progress in terms of sustainability of the country of operation.	–
Related to outputs	Wastes and sludge	I11: The sludge should be of good quality in terms of heavy metals.	I18 and I19: The residues generated by the facility should be reduced through the implementation of in-situ technologies for valorization.	I1: The sludge should be of a good quality (in terms of composition) compared to its fertilizer power to be able to be used in agriculture. I3: The indicator shows whether the sludge is valorized. I20: The valorization options of the sludge should be traceable and indicated by the facility. I44: The sludge quantity can be maximized (if there are recovery options available) or minimized (if treated for an external manager) in accordance with the priorities and technologies of the facility. I46: This indicator informs about the share of sludge coming from anaerobic digestion.	–
	Products	–	I21 and I22: To measure the revenues from the production of fertilizers and electricity is important in WWTPs looking for a transition to a circular economy. I45: An improvement in the production of biogas from sludge is a consequence of a technology modification, reactor and process optimization.	I41 and I42: The quality of the fertilizers obtained in the WWTP should be compared with conventional mineral fertilizers. I43: This indicator informs about the amount of biofertilizers produced from sewage sludge. It is not a transitory indicator because the sludge can be valorized by other options.	–
	Effluents	I5, I6 and I7: The organic matter, nitrogen and phosphorus removal efficiency should be below the thresholds indicated by the Council directive 91/271/EEC	I24: To measure the benefits from the reclamation of wastewater is important in a transition to circular economy. I39 and I40: The phosphorus and nitrogen recovery efficiencies should be increased to align with circular economy strategies.	I8: The indicator shows if the facility complies with the Council directive 91/271/EEC in terms of effluent emissions. I24: The benefits from the reclamation of wastewater are quantitative information to incorporate in economic reports. I36: This indicator informs about the use in agriculture of reclaimed water.	–
Classification groups	Indicators with legislative thresholds	Indicators to be evaluated over time	Informative indicators of quality	Indicators for ex-ante implementation	
Related to overall monitoring	–	I9: There are still no thresholds for global warming potential in wastewater treatment plants and thus an initial baseline scenario should be defined. I25: This information informs about the minimization of costs and maximization of benefits (from the implementation of valorization or recovery measures). The value of the indicator can be increased up to the results achieved under optimal theoretical operation. I26: The costs of the facility should be minimized over time. I27: The WWTP operation should reduce the environmental costs throughout the implementation of continuous measures in the process. I28: There should be a transitional increment of the removal of pollutants from the influent and the reclamation of the effluent.	I2: The indicator shows the normalized eutrophication potential of the facility considering indirect impacts. I23: The indicator informs about the degree of recovery of the facility compared to the removal of nutrients.	I12: The price of the land for the construction of the WWTP should be considered in the selection of the location.	

7.4.3. Uncertainties of scale in wastewater treatment plants

The framework is broadly applicable to wastewater treatment plants of all scales, with exceptions pertaining to specific environmental and socio-economic sustainability requirements that are unique to certain facility capacities.

The socio-economic pillar is generally less affected than the environmental pillar. Among the socio-economic criteria, SES 02.03 (“*The organization has plans to ensure that the facilities operate safely*”) is the only one with specific remarks for small-scale plants. Approximately 10 of the 14 requirements under this criterion are influenced by Directive 2012/18/EU (Seveso III), which addresses the control of major-accident hazards involving dangerous substances. This European regulation applies to facilities that store at least one of the 48 substances listed in Annex I, and only when the quantity of a substance exceeds the defined threshold that categorizes the facility as an upper-tier establishment. Consequently, small-scale facilities are often not classified as upper-tier establishments, and requirements related to this directive may not be applicable. Further details about the specific requirements can be found in **Supplementary Materials B**.

Regarding the environmental pillar, three principles are applied differently depending on the scale of the facility. One such principle is ES 02 or “*Conservation and management of the functions of the ecosystem*”. Half of its six requirements are influenced by Directive 2000/14/EC, which pertains to noise emissions in the environment caused by outdoor equipment. Specifically, compliance with the CE label and the indication of the guaranteed sound power level depend on equipment size, which in turn is linked to the capacity of the facility. Beyond noise control, the “*identification of measures or the performance of an environmental impact assessment to achieve and maintain a good environmental status*” (ES 02.06.04) also differs between small and large facilities. According to Annex I of Directive (EU) 2011/92, an environmental impact assessment is mandatory only for wastewater treatment plants with a capacity exceeding 150,000 population equivalents.

Regarding energy demand, criteria ES 03.01 (“*The organization has limitations on the use of energy*”), three documents specify limitations of scale: Directive (EU) 2018/2021, COM/2022/541 and EU Taxonomy. Directive (EU) 2018/2001 promotes the use of energy from renewable sources, emphasizing the possibility for governments to provide feed-in tariffs to small facilities producing electricity. While Directive (EU) 2018/2001 does not specify a threshold, COM/2022/541 offers more detailed guidance, highlighting the requirement for wastewater treatment plants (WWTPs) serving populations of >10,000 equivalent inhabitants to achieve carbon neutrality by 2040. Additionally, the EU taxonomy defines energy consumption thresholds based on facility capacities: 35 kWh per inhabitant equivalent for facilities serving fewer than 10,000 inhabitants, 25 kWh per inhabitant equivalent for capacities between 10,000 and 100,000, and 20 kWh per inhabitant equivalent for capacities above 100,000.

On the other hand, with respect to the level of treatment, COM/2022/541 identifies the following requirements: (1) all urban wastewater treatment plants with a capacity of 100,000 population equivalents or more must provide quaternary treatment (ES 02.02.06), (2) agglomerations of between 10,000–100,000 population equivalent should apply quaternary treatment in areas identified as sensitive to pollution from micro-pollutants (ES 02.02.06), (3) integrated urban management plans are mandatory for agglomerations with 100,000 or more (ES 02.06.05), (4) such plans are also required for agglomerations between 10,000 and 100,000 population equivalents if stormwater overflow and urban runoff pose risks to the environment or human health (ES 02.06.05) and (5) a minimum annual number of samples for all the levels of treatment should be developed.

It is also worth mentioning the Council Directive 91/271/EEC, the oldest regulation concerning urban wastewater treatment, as it establishes standards for effluent composition and the minimum technologies to be implemented based on treatment capacity requirements. Article 4 specifies the minimum capacity of plants to incorporate secondary

treatment, while Annex I outlines the number of samples required based on plant capacity and the concentration of total suspended solids. The minimum percentage of reduction for this compound is 90 % in facilities serving >10,000 population equivalents and 70 % in facilities serving between 2000 and 10,000 population equivalents. Considering these aspects, the directive addresses requirements related to discharge points (ES 02.02.03), sensitive areas (ES 01.01.04), and effluent compositions (ES 02.02.06 and ES 02.02.07).

7.4.4. The circular economy: the uprising needs in wastewater treatment certification

An important topic to address in the discussion of the framework is circularity. A review of the wastewater-related directives suggests that current regulations primarily focus on reducing dependence on virgin resources and promoting resource resilience (e.g., extending resource life). However, they do not comprehensively address circular economy principles. This approach aligns with the practices observed in most recognized certification standards. For instance, certifications such as ISCC, ASC, Better Biomass, BSCI, and UEBT emphasize proper waste management practices, including waste segregation by type, minimizing the use of non-renewable energy and water, and implementing documented plans for waste reduction, reuse, and recycling. The notable exception is the Cradle-to-Cradle® certification scheme, which incorporates circular economy principles but only at the product level. This narrow focus can provide an incomplete perspective on circularity. Therefore, there is a pressing need to advance both quantitative and qualitative analyses of life cycle and circularity approaches. Such advancements aim to enhance the validity and transparency of assessments across value chains.

In this context, integrating the ISO 59,004 standard into certification schemes and legislative frameworks could offer a preliminary solution. This integration would support industrial symbiosis and promote the closure of resource loops, all while maintaining product quality and improving social indicators. It is essential, therefore, to consider this broader context when developing strategies for integrating circular actions into wastewater treatment plants, across all scales and technologies. Doing so could contribute to creating a more robust and cohesive wastewater treatment sector, supported by guidelines similar to those of Best Available Techniques.

8. Conclusions and future outlook

While environmental product certification has a strong background for sectors such as agriculture, forestry, textiles and construction, this is not the case for the wastewater sector. Therefore, a step forward was taken in this research with the objective of laying the groundwork for an end-of-life certification scheme for this sector. Systematic and comprehensive-critical literature reviews were conducted to gather information from directives and scientific and other documents with the objective of creating a framework of requirements and data sets with sustainability and circularity indicators. Each piece of information was combined to determine whether the quantitative indicators collected were sufficient to indicate whether the requirements were met. Since the indicators require data for their estimation, two case studies were used to verify the feasibility of using them to validate the framework and provide guidelines to improve the operation of any wastewater treatment plant. Considering that the data needed to estimate the indicators do not match the data that can be provided by the wastewater treatment facilities, a fact sheet was provided to support companies in data collection.

As described in this manuscript, the presented framework can be used as a prelude for quantitative verification of compliance with legislation, improving communication between wastewater treatment operators and methodology developers, and establishing a baseline for gap identification. In addition to this, the proposed framework could also be useful to advance the digitization of the certification process with

the incorporation of indicators that can be automatically estimated and verified.

The results of this research demonstrated that the current framework for the wastewater framework is not capable of addressing with a complete quantitative conformity assessment model. Therefore, future work should focus on creating quantitative thresholds and indicators for some of the requirements that are now addressed qualitatively. In addition to this, more effort and money should be invested for the transformation of the presented legislation-based framework into an operational certification scheme with features comparable to those already existing in the market. Examples of actions could be the creation of a verification guide for qualitative requirements that can be used by auditors; incorporation of requirements that go beyond legislation with the use of initiatives, reports and scientific literature; alignment of wastewater sector requirements with other bio-based sectors; strengthening traceability criteria, as wastewater treatment plants will also have to certify their products; stakeholder involvement; and the creation of a reliable score for the indicator system that accounts for digitalization, keeping the economic costs related to certification low.

CRedit authorship contribution statement

Sofía Estévez: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Ana Arias:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Gumer-sindo Feijoo:** Writing – review & editing, Validation, Supervision. **María Teresa Moreira:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Sofía Estevez Rivadulla reports financial support was provided by Spanish Ministry of Science, Innovation and Universities. Ana Arias Calvo reports financial support was provided by Galician Government. Sofia Estevez Rivadulla reports financial support was provided by HORIZON—CL6—2021-ZEROPOLLUTION-01. Sofia Estevez Rivadulla reports financial support was provided by Galicia Government. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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