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Systematic assessment of wastewater resource circularity and sustainable value creation

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ABSTRACT

The circular use of wastewater has attracted significant attention in recent years. However, there is a lack of universal definitions and measurement tools that are required to achieve the circular economy's full potential. Therefore, a methodology was developed using three indicator typologies, namely resource flow, circular action, and sustainability indicators, to facilitate a robust and holistic circularity assessment. The method uses value propositions to integrate the assessment of intrinsic circularity performance with consequential circularity impacts, by quantifying sustainable value creation (using techniques such as life cycle assessment or cost-benefit analysis). Assessment method capabilities were exhibited by applying the defined steps to a wastewater treatment plant, comparing conventional and novel photobioreactor technologies. The resource flow indicator taxonomy results highlight improved outflow circularity, renewable energy usage, and economic efficiency of the novel system. Action indicators revealed that the photobioreactor technology was successful at achieving its defined circular goals. Lastly, sustainability indicators quantified a reduction of carbon footprint by two thirds and eutrophication by 41%, a M€ 0.5 per year increase of economic value, and that disability adjusted life year impacts are 58% lower. This supports that improving wastewater system circularity using photobioreactor technology results in environmental, economic, and social value for stakeholders.

1. Introduction

The water sector is key to the circular economy (CE) transition due to the direct reliance industry and society has on clean water supply and adequate wastewater management (Smol et al., 2020). Recent efforts to develop specialised tools to facilitate circularity, such as KWR's dashboard for a circular water sector (KWR, 2021) and The World Bank's Water in Circular Economy and Resilience framework (The World Bank, 2021), highlights the CE's potential to improve water sector practices. Although this shows water utilities have a desire to enhance their circularity, it has not translated into the universal definitions and standardised measurement tools required for ubiquitous understanding of CE benefits for stakeholders (Ahmed et al., 2022).

It has been shown that engineering and technological aspects are no longer barriers that inhibit the circular transition, in fact it is a lack of planning and performance analysis (Smol and Koneczna, 2021), and hesitant company culture viewing circular investments as economically unfavourable in the short term (Kirchherr et al., 2018). Without a dedicated methodology for measuring the value creation of wastewater processes, it is difficult to build business cases and convince companies to invest in circular solutions (product, technology, process, service, or strategy) (Nika et al., 2021). This is compounded by the fact that there is limited research on how the CE provides this competitive advantage (Lahti et al., 2018), emphasising the need for assessments that can prove economic feasibility of circular solutions and quantify their multi-dimensional benefits.

CE monitoring frameworks focus on measuring material flows, where aligning resource focused indicators with triple bottom line (TBL) dimensions has been used as evidence for the assessment of sustainability (Harris et al., 2021). This results in patchy assessments, rebound effects, and impact leakage (Chen, 2021), leading to insufficient consideration of wider sustainability impacts and the attitude of *circularity for circularity's sake* (Harris et al., 2021). Concurrently, environmental impact indicators, including life cycle assessment (LCA) impacts,

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have been used to assess the circularity of products and services (Corona et al., 2019). Although these indicators validate CE effectiveness, they cannot quantify changes to resource circularity, even though this is needed to differentiate the CE from the vague goal of sustainable development. Therefore, a significant gap exists in CE assessments to systematically understand how changes in physical resource flows impact sustainability dimensions.

This is pertinent for the assessment of water systems as water utilities' strategic circular aims focus on societal-level sustainability issues such as carbon neutrality, water provision, and energy security, the majority of which are realised by exploiting the value of wastewater. Tapaninaho and Heikkinen (2022) found that sustainability value is created when societal-level sustainability aims are addressed by circular business models, and that the traditional focus of value creation on profitability is insufficient to capture the breath of CE benefits. Therefore, sustainable value creation should be used as a holistic indicator of circular performance for wastewater systems, which uses stakeholder collaboration to understand value creation across the TBL (Tapaninaho and Heikkinen, 2022). This is critical to showcase the validity and societal relevance of the CE, or else the concept is at risk of being thought of as unachievable or discredited as a new form of greenwashing (Friant et al., 2020).

In this work, an assessment method is constructed which combines a detailed understanding of wastewater process circularity with the support of explicit sustainability analysis. It shows how the actions of decision makers alter physical wastewater resource flows and the resultant impacts of this on sustainable value creation. Therefore, the method is able to distinguish between and assess intrinsic circularity, following the three CE principles of designing out negative externalities, regeneration of natural capital, and keeping products and materials in use (using resource flow and action indicator sets) (Ellen MacArthur Foundation, 2015), and consequential circularity impacting sustainability dimensions (using complementary analysis techniques). This requires systematic indicator selection and calculation, and it is hoped the methodology provided implements this to act as the basis for standardising holistic wastewater resource circularity assessments.

2. Methodology

2.1. Methodological principles

The CE concept serves as a key facilitator of sustainable development, therefore, the assessment method is based on five principles developed from relevant sustainability science, sustainability assessment, and CE literature (Sala et al., 2015; Superti et al., 2021; Tapaninaho and Heikkinen, 2022; Troullaki et al., 2021). The methodology developed provides solutions to the gaps identified in current circularity assessments (Section 1).

Principle 1: Circularity performance assessments should consider both intrinsic circularity and consequential circularity in line with the definitions provided by Saidani et al. (2019). As a result, the developed method is concept specific (assessment of circular performance without excessively opening scope), yet multi-dimensional (simultaneously highlights impacts of circularity on sustainability dimensions). This is achieved by selecting a taxonomy of indicators which demand a detailed assessment of resource circularity and efficiency, and are then used to identify relevant sustainability impacts. Thereby, circularity and sustainability indicators are used to support each other, validating outcomes to strengthen decision making capabilities, facilitating circularity assessments that are normative and valid. This mitigates the current approach of excessively opening the scope of indicator sets, in which circularity and sustainability assessments are used as fragmented pillars or as a substitute for the other (Troullaki et al., 2021), diluting analysis of both dimensions (Superti et al., 2021).

Principle 2: Circular actions are used as a foundation for the selection of relevant circularity performance indicators and to guide complementary sustainability analysis. Therefore, systematic selection of indicators considering the scenario of application has been integrated in the assessment methodology, using project specific data and models. This means indicator selection is flexible and dynamic, depending on individual project targets, directed by the proposed 'circular actions' of the investigated system (Coenen et al., 2020; Moraga et al., 2019). This facilitates a pertinent aspect of sustainability science, linking science to actions through solution-oriented assessments (Sala et al., 2015; Troullaki et al., 2021).

Principle 3: It is necessary to understand and quantify the impacts the investigated system has on sustainable value creation considering environmental, social, and economic dimensions. This enables users to holistically understand how the consequential circularity impacts of the investigated system contribute to sustainable development. For the assessment of wastewater processes this is particularly important, as in the CE, waste valorisation must be prioritised to transform these streams, previously considered as burdens in the linear economy, into valuable resources and products (Leder et al., 2020).

Principle 4*:* Resource traceability is a key element of circularity measurement and assessment as it provides an enhanced understanding of circularity by tracking the source and destinations of flows. Resource traceability of biotic/water resources is not commonly employed (Harder et al., 2021), but the developed methodology evidences its utility using the approach of Renfrew et al. (2023) to trace key wastewater resources, enabling robust circularity indicator calculation.

Principle 5: Stakeholder participation is vital for the assessment to increase CE acceptance and credibility by providing context specific insights. In the method developed, stakeholder perspectives are key for understanding the goals of circular actions, to select relevant performance indicators and assess sustainable value creation.

2.2. Methodological explanation

By combining the principles summarised in Section 2.1 a method was developed for the systematic assessment of wastewater resource circularity, as shown in Fig. 1. The steps in Fig. 1 result in a taxonomy of indicators that, when calculated using the resource classification approach of Renfrew et al. (2023), can act as the basis for standardising the circularity assessment of wastewater resources. The method provides i) a detailed analysis of inflow and outflow (materials/nutrients), energy, water, and economic resource circularity, ii) a performance evaluation of the circular actions implemented, as well as iii) analysis of the sustainability impacts and sustainable value generated by the targeted system of interest (SOI).

2.2.1. Definition of wastewater system and boundaries

The first phase of the methodology involves defining assessment goal and scope. Overall it is recommended to align the goal and scope definition with both the intrinsic and consequential circularity following the requirements of standardised performance assessments such as ISO 14,040 guidelines (British Standards Institute, 2020). In line with ISO 14,040, the goal includes explaining the reason, intended application, and interested audience of the assessment, whilst assessment scope illustrates the system being studied, boundaries, and assumptions. This may also include the functional unit, allocation methods, limitations, and data requirements if necessary.

This phase of the methodology also includes the definition of SOI circularity goals. Strategic goals are commonly defined as quantitative targets that are calculated using key performance indicators (KPIs) which guides the selection of relevant circular action indicators and facilitates the assessment of sustainable value creation impacts and trade-offs. There are many sources in the literature defining the strategic goals of the CE transition for wastewater, such as the work of Smol et al. (2020) that developed a framework based on the six actions of reduction, reclamation, reuse, recycling, recovery, and rethink. Furthermore, the strategic goals of the European wastewater sector are mapped out in

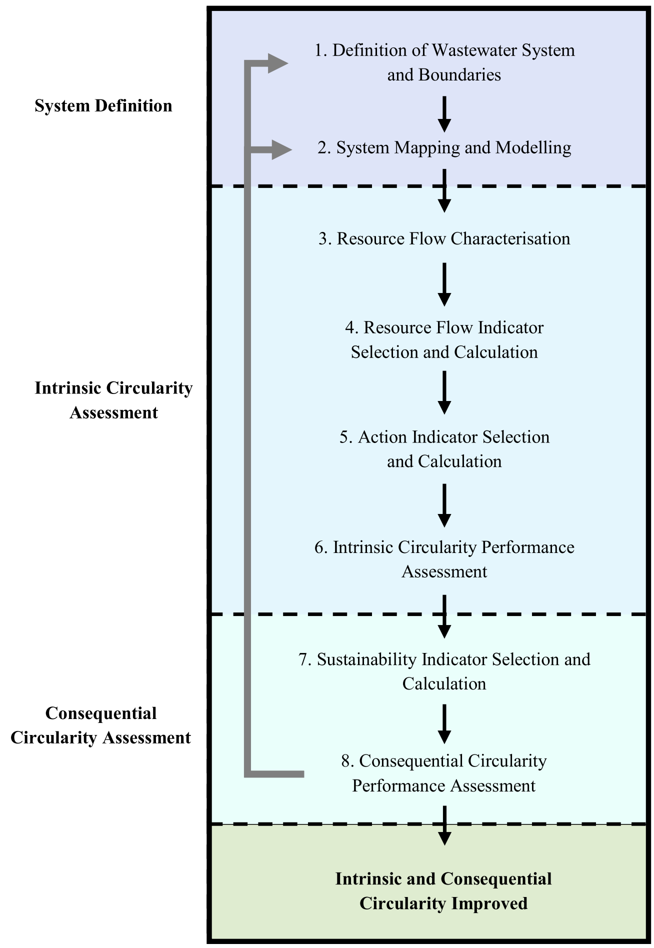

Fig. 1. Framework for the circularity assessment of wastewater systems.

the proposed update to the Urban Wastewater Treatment Directive, including net zero and resource recovery targets (European Commission, 2022). Additionally, it is recommended to use project publications (such as websites, deliverables, or industrial reports) to consider the specific goals for each targeted SOI and scenario of application.

Comprehensive understanding of the goal and scope facilitates the definition of the benchmark system, which acts as a baseline with which the targeted SOI can be compared against during the assessment. Establishing a representative benchmark is required for robust performance assessment and is dependent on the scenario of application. To develop a suitable benchmark, it is recommended to use either a real-world case study (such as the technology the SOI is replacing) or a model of a conventional industrial technology developed with process experts.

System boundaries are pertinent when assessing circular systems as they must be able to account for resource loops and the multiple life cycles of resources or products that can be recovered (Çapa et al., 2022). Furthermore, the temporal boundaries of circular systems may also require definition. An appropriate temporal scale is needed to account for the cascading uses of secondary resources captured from wastewater. Therefore, it is important to understand and define spatial and temporal boundaries in detail.

2.2.2. *System mapping and modelling*

Detailed description of the process(es) being investigated is required for modelling and data collection. Important aspects to describe are the location, loading, treatment process units, or operational constraints to establish necessary information about the wastewater system (Zawartka et al., 2020). Additionally, if temporal boundaries are established, the process data needs to be updated accordingly for each different resource cycle, including the variations of all flows described when prospective or forecast data is utilised (Beloin-Saint-Pierre et al., 2020).

The effectiveness of the circularity assessment is dependent on the accuracy of process modelling, for both the SOI and benchmark system. Creation of the process inventories requires modelling or simulation of wastewater treatment units of varying complexity, which can be physical, chemical, or biological processes (Zawartka et al., 2020). It is recommended to use primary data when available, and whilst secondary data or modelling can be used, the impact on result reliability must be considered.

The development of process models enables MFA and substance flow analysis (SFA) to understand how resources flow around the benchmark system and targeted SOI. These models are combined with a resource classification approach (Renfrew et al., 2023) that defines their source and destination, which improves resource traceability. This helps to assign circular characteristics to resource flows, which is required for robust calculation of assessment indicators.

2.2.3. *Resource flow classification*

To facilitate indicator calculation, circular properties must be assigned to all resource flows in the modelled systems. Defining the circularity of resource inputs and outputs enhances the traceability and transparency of indicator calculation, facilitating principle 4 of the methodology and more robust assessment of wastewater resources. This information enables the calculation of the resource flow and selected action indicators to complete the intrinsic circularity assessment.

However, according to Renfrew et al. (2023), current definitions of waste circularity are inadequate, resulting in errors during quantitative assessments. Therefore, it is recommended to use the framework presented by Renfrew et al. (2023) for wastewater resource classification. The approach uses an environmental science perspective to simply define a resource's circularity by considering a combination of its source and destination, and its ability to cause harm, to reason whether outflows to the environment (soil, water, and air) should be considered linear, utilising the principles of the Do No Significant Harm (DNSH) framework (Italia Domani, 2021). This facilitates the calculation of circularity indicators for key wastewater resources.

2.2.4. *Resource flow indicator selection and calculation*

Resource flow circularity indicators are the first indicator taxonomy which assess the intrinsic circularity performance of the SOI. They should cover the key areas of material inflow and outflow, water, energy, and economic resource circularity, following a similar structure to those utilised by the wbcsd (2022). This aims to provide a more standardised analysis of key resources during the assessment and is useful for activities such as hotspot analysis. It should also enable comparison of results across different wastewater systems (plant location, technology, or size) as the indicators are sourced and calculated using similar methods. The indicators recommended for resource circularity assessment are summarised in Table 1 and are taken from the framework proposed by Renfrew et al. (2023).

2.2.5. *Action indicator selection and calculation*

In order to identify the indicators required for the second intrinsic circularity indicator taxonomy, circular actions need to be defined. Circular actions are the measures implemented which contribute to CE goals, thereby facilitating the three CE principles. Utilising these indicators ensures that the performance of the SOI's circular actions can be assessed and verify that they achieve CE goals, as defined in principle 2. To do this stakeholder inputs are crucial for understanding how the SOI circular actions satisfy expectations compared with the benchmark system (facilitating principle 5) and meet strategic circularity goals. The strategic goals defined by the goal and scope are used to align stakeholder and project targets before indicators are selected, ensuring they are able to assess necessary aspects of circularity for decision making.

Table 1
Resource flow analysis indicator taxonomy.

Category	Indicator	Equation
Materials	Circular Inflow (as defined by classification approach) (%)	$\frac{\textit{Mass Circular Inflow}}{\textit{Total Mass of Inflow}}$
	Renewable Recirculation Outflow (%)	$\frac{\textit{Mass Renewable Ouflow}}{\textit{Total Mass of Outflow}}$
	Circular Outflow (as defined by classification approach) (%)	$\frac{\textit{Mass Circular Outflow}}{\textit{Total Mass of Outflow}}$
	Wastewater Nutrient Removal Efficiency (%)	$1 - \frac{\textit{Output Concentration}}{\textit{Input Concentration}}$
Water	Water Discharged in Accordance with CE Principles (%)	$\frac{\textit{Volume of Circular Discharge}}{\textit{Volume of Water Withdrawal}}$
	Water Use from Circular Sources (%)	$\frac{\textit{Volume Water Used from Circular Sources}}{\textit{Volume of Water Required by the Process}}$
Energy	Energy Consumed from Renewable Sources (%)	$\frac{\textit{Renewable Energy Consumption}}{\textit{Total Energy Consumption}}$
Economic	Circular Material Productivity (€/kg)	$\frac{\textit{Total Revenue}}{\textit{Mass of Linear Inflow}}$
	Product Value per Mass (€/kg)	$\frac{\textit{Product Revenue}}{\textit{Mass of Virgin Resources}}$

The development of VPCs with project stakeholders is recommended for this step, and the method of da Luz Peralta et al. (2020) is employed for the example in Section 3. This requires the views of stakeholders to understand the desires and obstacles for implementation, and linking them with 'gain creators' and 'pain relievers' to show how a technology aims achieve stakeholder expectations i.e., identifying SOI circular goals. To create the VPC, workshops with relevant stakeholders are required to create a Lean Canvas, revealing SOI circular actions that satisfy expectations, and an Empathy Map of what stakeholders wish to accomplish (da Luz Peralta et al., 2020).

To link the goals identified from VPCs with appropriate indicators, the first step is to group them based on strategic goals of the SOI. These are used to create generic CE actions that are initiated in the SOI, for example recycling or renewable energy generation. Simultaneously, VPC development recognises how the SOI aims to meet stakeholder expectations, by using 'gain creators' to highlight the technology goals. These are combined with the generic CE actions to develop circular actions of the specific SOI being assessed, in terms of stakeholder requirements. Lastly, the specific circular actions are used to select appropriate indicators from literature for the assessment of circular action performance, to understand if the defined goals are achieved. These steps are illustrated in Fig. 2 and an example is provided in Section 3.5.

These indicators reveal the success of SOI actions, as they will be tailored to each scenario considering technological, stakeholder, and local context aspects. The action indicators differ from those analysing resource flows, as they can communicate how the relationships between sustainability pillars and CE principles are impacted by the SOI using the VPC developed, instead of just reporting information on resource properties. For example, improving the renewability of resource flows only reveals information about physical materials, whereas an indicator such as the eco-efficiency shows how circular actions affect greenhouse gas (GHG) emissions and revenue. The identification of circular actions to select indicators follows a similar approach to that of Nika et al. (2022), however, this method goes a step further by using VPCs to understand the performance of the SOI's circular actions for more systematic and targeted indicator selection.

Circular action indicator calculation may require a combination of resource flow characterisation with additional analysis or modelling to quantify wider impacts, such as environmental and economic dimensions for eco-efficiency indicators. However, this is dependent on the indicators selected to assess circular actions. Thereby, the action indicator taxonomy can be combined with the resource flow indicator taxonomy to provide a complete assessment of intrinsic circularity performance.

2.2.6. *Intrinsic circularity performance assessment*

The results provided by the resource flow and circular action indicator taxonomies show whether the SOI has been successful at improving the circularity of physical resource loops in the defined system and whether the performance of SOI circular actions meets stakeholder expectations and CE goals. Improvements can be directly quantified by comparing SOI results with those of the benchmark system. This step of the methodology fulfils principle 1, facilitating decision making based on intrinsic system circularity, ensuring assessment validity.

2.2.7. *Sustainability indicator selection and calculation*

To investigate the impacts that result from the implementing SOI's intrinsic circularity (both resource flows alterations and circular actions), a third complementary sustainability indicator taxonomy must be selected to quantify the value created for stakeholders and understand the SOI's consequential circularity. If indicators have been selected with adequate scope, then all dimensions of the TBL should be represented; if not, then at least one indicator should be selected and calculated for the missing dimension(s) to ensure a holistic assessment of sustainable

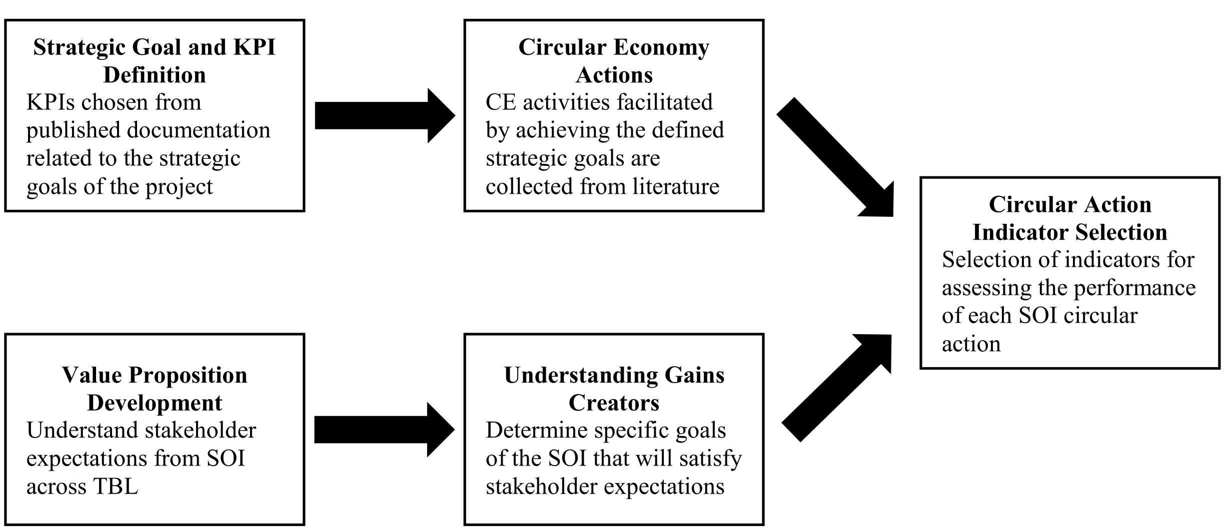

Fig. 2. Steps for selecting the circular action indicator taxonomy.

value. Strategic goals highlighted during goal and scope definition can be used to guide indicator selection for any missing TBL dimensions.

To understand the impacts of consequential circularity, it is recommended to use the data requirements of the circular action indicators for identification of the required areas for sustainability analysis. This avoids pre-selection of complementary analysis techniques, enhancing assessment flexibility, mitigating the omission of sustainability impacts which are pertinent to the assessment. For example, eco-efficiency indicator calculation requires both environmental and economic inputs, highlighting that more detailed LCA or life cycle costing would be suitable as complementary analysis. Process inventories derived from benchmark and SOI models can be used to complete the required complementary assessment techniques. This indicator taxonomy reveals wider impacts of SOI implementation not captured during the intrinsic circularity analysis. Once sustainability indicators have been calculated, the results are utilised to quantify the sustainable value creation that results from SOI implementation, to see if it is able to satisfy the value proposition for stakeholders.

2.2.8. Consequential circularity performance assessment

The final step of the method requires examination of the SOI sustainability indicator taxonomy results against the benchmark process. This facilitates direct measurement of the environmental, economic, and social sustainable value generated by the SOI, as required in principle 3, and shows whether the SOI satisfies the value proposition developed with stakeholders. Therefore, sustainable value creation is used to determine SOI consequential circularity performance. If the SOI improves both intrinsic and consequential circularity of the investigated wastewater system, then it can move to the next phase of design as it is able to generate value for stakeholders by improving system circularity. If not then the project goals, technology, or design can be iterated to update models and indicators until a suitable SOI is selected.

To enhance decision making capabilities and result communication, interpretation of results should consistent with the goal and scope of the assessment to make appropriate conclusions, explain limitations, and provide recommendations for wastewater system circularity performance (British Standards Institute, 2020). Results should be readily understandable and easily communicated to the intended audience, therefore, it is recommended that sustainable value creation is used to verify whether the defined circular goals of the system have been successfully achieved (as shown in Section 3).

3. Implementation – Spanish small scale WWTP

This section demonstrates implementation of the method developed in Section 2 for the assessment of a novel technology integrated within a WWTP. In this case, the SOI is an anaerobic purple phototrophic bacteria (PPB) photobioreactor (PBR) technology for wastewater treatment, known commercially as ANPHORA® (includes clarifiers, PBRs, sludge treatment), and was selected as it claims many benefits over conventional treatment processes.

3.1. Definition wastewater system and boundaries

The goal of the assessment is to quantify circularity improvements and the sustainable value created by implementing ANPHORA® technology for wastewater treatment. It will be used to evidence the advantages of this system compared with conventional technology and results will be shared with water sector stakeholders to expedite technology uptake.

Strategic goals of the project are mapped using publications and communications to define the expected advantages of the system (Deep Purple, 2019):

(1) Produce high value products from waste streams of sewage sludge
(2) Recover resources contaminated in wastewater
(3) Minimise waste
(4) Minimise energy demand of the plant trending towards self-sufficiency or energy positivity
(5) Reduce GHG emissions of value chains by 20 %
(6) Generate revenue from the recovery of waste resources
(7) Establish economic feasibility
(8) Evaluate environmental impacts

These statements clearly show that considered technologies wish to enhance value recovery from waste streams to facilitate the CE. From the statements, generic CE actions are identified and will be used as themes to categorise the technology gains creators. The terminology of minimising, maximising, and reducing several operational constraints such as economics, waste, GHG emissions, and energy demand are facilitated by developing disruptive technologies to *optimise process performance*. The emphasis on generating economic value from bioproducts and recovering energy from waste streams means that the technology must have the ability to *cascade biomaterials*. Lastly, recovering the organic and nutrient contaminants in wastewater and reducing waste production is achieved through the action of *recycling and waste minimisation* for wastewater resources.

As the SOI being assessed is known, a benchmark technology must be chosen to establish a baseline for results comparison. By consulting industrial experts, it was decided to use a conventional extended aeration system as a benchmark, which is an activated sludge process with high solid retention times between 20 and 40 days. Primary clarifiers are not required, therefore, the conventional process was assumed to operate with pretreatment of screenings and grit removal, aeration tank (nitrification) with clarifiers, and sludge is stabilised by liming. System boundaries are drawn from when wastewater leaves the water user and flows into the WWTP (meaning losses are accounted for), until wastewater effluent is discharged from the plant and biosolids are applied to land, as shown in Fig. 3. The ANPHORA® technology demonstration site is located in Spain, so processes were modelled considering local factors.

3.2. System mapping system and modelling

Advantages of the ANPHORA® technology are highlighted when used to treat wastewater for small, rural populations; thus a scale of 10,000 population equivalents (PE) (design load of 3000 m^3/d) was selected. Wastewater treatment on this scale in Spain regulates chemical oxygen demand (COD) removal and discharge limits. Due to limitations in data availability for a 10,000 PE WWTP case study, a model for the conventional process of prolonged aeration was constructed using parameters taken from literature for the physical and biological treatment units. The influent loadings were taken from literature for a wastewater treatment plant in the same area as the ANPHORA® demonstration facility (Rodríguez-Chueca et al., 2019). The data utilised is provided in Tables S1–S4 of the Supplementary Material.

The PBR was chosen for assessment as it operates anaerobically resulting in significant energy demand and emissions generation reduction compared with conventional aerobic treatment. The nutrient content of the PPB biomass means it can be used as a biofertiliser and sold to generate revenue. The biomass also has greater biomethane potential compared with conventional activated sludge, therefore it is economically viable to anaerobically digest sludge and produce biogas for energy recovery. The project is currently at the demonstration phase; however, these real-world scenarios have been agreed with experts for application of the circularity assessment method to a full-scale system.

Fig. 4 summarises the PBR process boundaries, which operates with screenings, grit, and fats, oils, grease (FOG) removal pretreatment, primary settling, anaerobic raceway PBRs, and clarifiers before wastewater discharge. Sludge is thickened, anaerobically digested, and dewatered before it can be sold as a high-quality biomass fertiliser for land application.

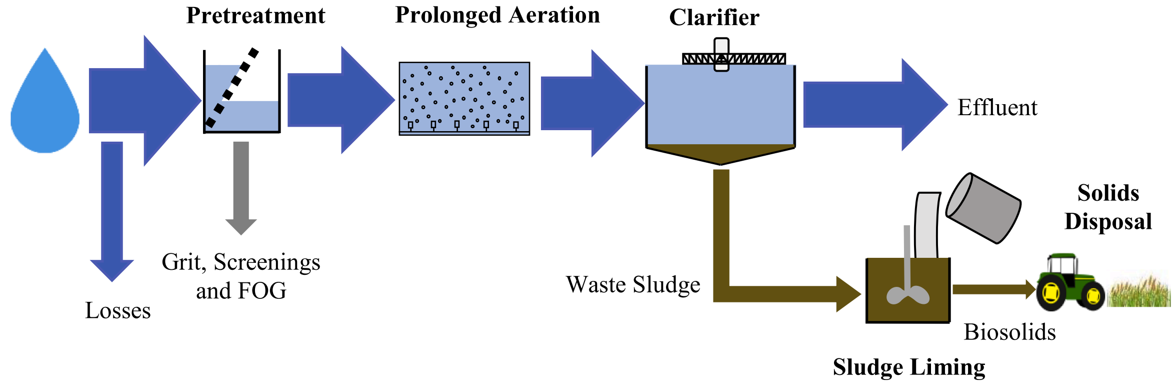

Fig. 3. Process stages of the benchmark system.

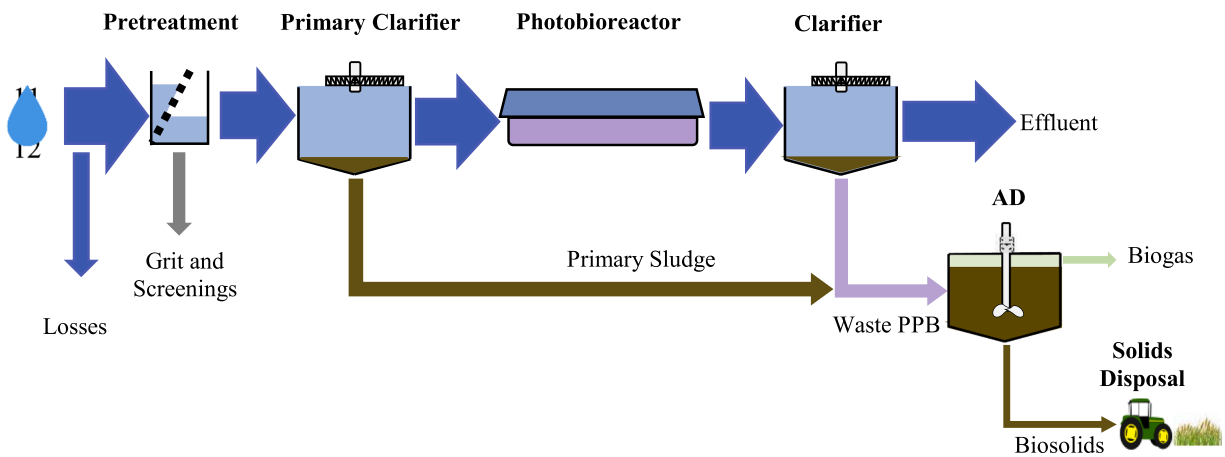

Fig. 4. Process stages of the photobioreactor system.

The PBR has only operated at a demo scale, and therefore required scale up calculations to ensure accuracy for the energy consumption and cost parameters. It was assumed that the removal efficiencies and nutrient content of the PPB biomass would be unaffected by scale up of the system. The circular PBR system was modelled using data provided in Tables S5–S8 of the Supplementary Material.

3.3. Resource flow characterisation

The circularity assessment was completed using the approach in Section 2 to characterise the water, nitrogen, phosphorus, and carbon resources from the benchmark and SOI process models. Tables S9–S16 in the Supplementary Material provide the circularity classifications of resource inflows and outflows.

3.4. Resource flow indicator selection and calculation

The taxonomy of resource flow indicators selected is provided in Table 1. Results of the outflow, nutrient extraction, and renewable energy indicators are provided in Fig. 5. WWTP removal efficiency was assessed and showed there was a reduction in carbon removal of 9.2%, however, COD discharge limits are still met. This results in lower carbon

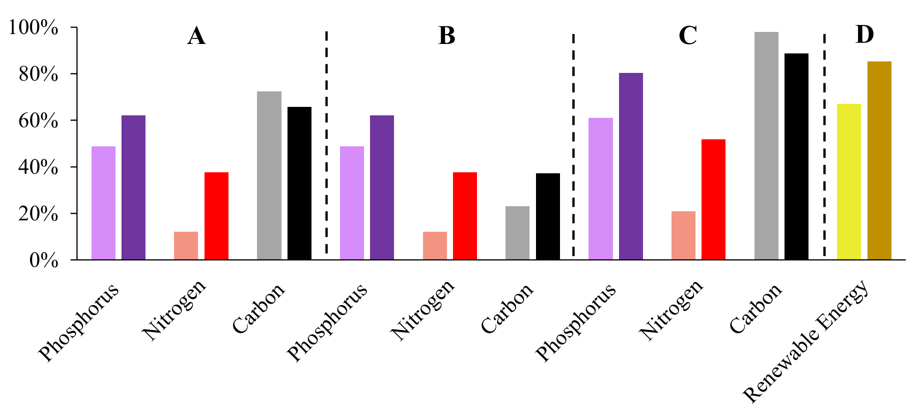

Fig. 5. Resource flow indicator results, where the lighter colour is the conventional process and darker colour is the Deep Purple PBR process. A: outflow circularity, B: outflow renewability, C: wastewater nutrient extraction, and D: renewable energy usage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

outflow circularity for the PBR process, but due to the composition of PPB biomass greater renewability is achieved. Nitrogen and phosphorus removal are improved by 148% and 32% respectively, due to the accumulation of nutrients by the PPB biomass meaning greater outflow circularity and renewability are achieved for NP by ANPHORA®. Whilst there are no NP consent limits for this type of small-scale treatment, performance is better in terms of both environmental protection and circularity. However, if this process was applied in an area with NP discharge limits, then tertiary treatment or polishing of the effluent would be required. Lastly, renewable energy usage grows from 67% to 85% due to the recovery of energy from biogas, which increases the renewable fraction above that of the Spanish electricity grid mix (including nuclear and biofuels) (IEA, 2021).

There was negligible change between conventional and PBR scenario influent resources, and therefore inflow and water indicators, when comparing systems so these results are not presented. Additionally, material productivity increased by approximately 300% as greater revenue from the sale of PPB biofertiliser is coupled with a reduction of linear inputs, namely lime for sludge treatment. Value per mass of the systems increased from 0 €/kg for the conventional system to 40.8 €/kg for the PBR, and this high value is achieved as the only virgin or primary material input is the polymer required for sludge thickening. The value of zero for the benchmark system occurs as only revenue from product sales is included in the calculation, excluding the service fee of wastewater treatment.

3.5. Action indicator selection and calculation

To ensure appropriate indicators are selected for evaluating the performance of PBR circular actions, the strategic goals must be understood and combined with the outcomes from sustainable VPC development. As explained in Section 2, the participatory method is utilised to link the generic, high level CE actions identified from the strategic goals of the project with the unique circular actions of the SOI for indicator selection. In this case study, the technology developers were used to generate the VPC, and the resultant Lean Canvas is presented in Fig. 6.

The 'gain creators' category identifies how the ANPHORA® technology is expected meet stakeholder expectations and the four gains

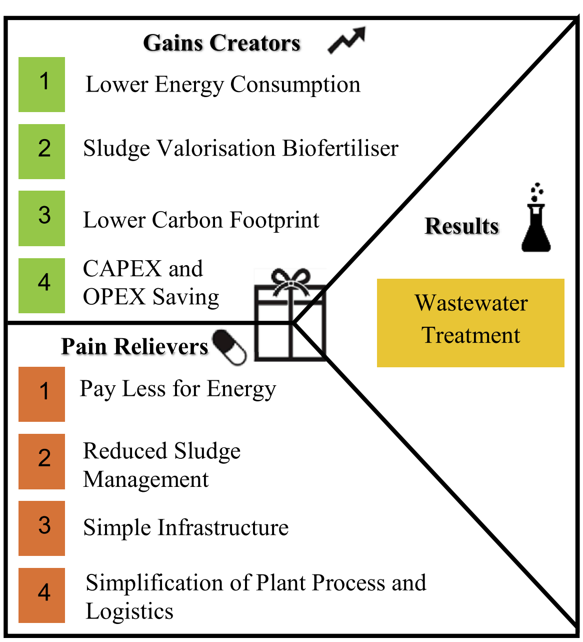

Fig. 6. Lean Canvas developed for the PBR technology based on that of da Luz Peralta et al. (2020).

creators were combined with CE actions identified in Section 3.1 to generate specific circular actions of the PBR process. The steps to select indicators for evaluating the circular actions are summarised in Table 2, starting with the gains creators in the left hand column. Indicator results show the performance of ANPHORA's® circular actions at meeting stakeholder expectations and project CE strategic goals, compared with the conventional extended aeration process. Table 2 summarises the second indicator taxonomy selected for the assessment of intrinsic circularity.

Results from the circularity assessment of project actions are summarised in Table 3 and are presented as the percentage change against the benchmark conventional process measurement, to reveal the performance of SOI circular actions.

The energy reduction indicators show that not only is the demand for electricity from the grid reduced, but self-sufficiency increases to almost 60% (from a baseline of 0) and circular energy intensity is more than halved. This trend can be attributed to the reduced energy requirement from mitigation of aeration processes, the amount of carbon available in waste sludge increasing, and energy recovery from combustion of biogas produced by AD. Carbon footprint reduction is achieved mostly through the mitigation of direct process emissions from anaerobic operation of ANPHORA®. Carbon footprint is a proxy for emissions to air and water, therefore, the emissions eco-efficiency result is almost doubled due to the decrease in the mass of emissions to air and nutrient concentration in the effluent, and increased revenue from biofertiliser sales. The yearly costs of the process, amortised CAPEX and OPEX, are also reduced due to the mitigation of aeration and chemicals required for sludge treatment.

Waste eco-efficiency is shown to decrease for the PBR process, as even though revenue is increased, there is greater removal of pretreatment solids that are landfilled. However, this has potential to be improved through addition of captured FOG to AD reactors. The largest increase is the value added per m^3 of wastewater treated, which can be attributed to a reduction in total costs and increased revenue from biofertiliser sales. The substitution factor of conventional biosolids compared with PPB biomass shows why this can be marketed as a higher quality fertiliser. Lastly, there was an increase in recovery for all nutrients analysed by the process, due the recovery of biogas and the high nutrient content of PPB biomass compared with conventional biosolids.

3.6. Intrinsic circularity performance assessment

Resource flow indicators showed that the PBR system had negligible impact on resource inflow circularity, but was successful as improving the outflow circularity and removal efficiency of nitrogen and phosphorous. Action indicator results highlighted an improvement in performance of the PBR process versus conventional treatment (except waste eco-efficiency), ranging from 13% to greater than 1000%. Therefore, the ANPHORA® technology improves intrinsic circularity of the WWTP system as it achieves the circular action performance requirements and enhances the circularity of wastewater resource loops.

3.7. Sustainability indicator selection and calculation

One of the key outcomes of this assessment is to understand the sustainable value generated by, or consequential circularity of, SOI circular actions. The indicators selected to evaluate circular actions are used as a guide for directing sustainability indicator taxonomy selection. The circular action indicators utilised, including eco-efficiency, carbon footprint, and value added per mass, highlight the expected environmental and economic impacts of the SOI. Therefore, LCA and more detailed analysis of carbon footprint are required to understand environmental value creation, as well as total value-added inspection for economic impact investigation. Although the circular action indicators do not directly reveal which social indicators are needed to investigate the PBR process impacts, it is important that all TBL dimensions are considered. Due to the ANPHORA's® potential to reduce emissions and

Table 2
Steps to select the indicator taxonomy for assessing PBR technology circular action performance.

Gains Creators	CE Action	PBR Circular Actions	Indicators Associated	Equation
Lower Energy Consumption	Development of New Processes for Value Chain Optimisation	Reduction of Energy Intensity	Circular Process Energy Intensity Lokesh et al. (2020)	$\frac{Energy\ Demand - Internally\ Derived\ Energy}{Mass\ of\ Products\ (incl.\ co\ and\ recovered)}$
			Self-sufficiency Agudelo-Vera et al. (2012)	$\frac{Total\ Energy\ Produced}{Total\ Energy\ Demand}$
			Electricity Grid Demand Minimisation Agudelo-Vera et al. (2012)	$\frac{Benchmark\ Demand - Minimised\ Demand}{Benchmark\ Demand}$
Lower Carbon Footprint		Achieving Decarbonisation	Carbon Emissions Reduction	$\frac{Benchmark\ Emissions - SOI\ Emissions}{Benchmark\ Emissions}$
			Emissions Eco-efficiency Walker et al. (2009)	$\frac{Value\ Gained\ (Revneue)}{Mass\ of\ Emissions\ (Air\ and\ Water)}$
Savings on Logistics and Infrastructure		Reducing Capital Costs (CAPEX) and Operating Costs (OPEX)	Yearly Reduction in Cost vs Conventional Treatment	
Valorisation of Sludge	Cascading of Biomaterials	Extraction/Generation of Value Added Bioproducts	Waste Eco-efficiency Walker et al. (2009)	$\frac{Value\ Gained\ (Revneue)}{Mass\ of\ Waste\ (Solid)}$
			Value Added per Functional Unit Medina-Mijangos and Seguí-Amórtegui, (2021)	$\frac{Total\ Value\ Created}{Volume\ Wastewater\ Treated}$
		Renewable Resource Use (nutrients from fertilisation)	Substitution Factor of Virgin Materials Jander and Grundmann (2019) – Biosolids N	$\frac{Function\ per\ kg\ of\ Recovered\ Material}{Function\ per\ kg\ of\ Conventional\ Material}$
	Recycling and Waste Minimisation	Retain Nutrients in Wastewater for Fertiliser Production and Safe Return to Soil	Recovery Rate of WWTP - Nutrients NPC Institut de la statistique du Québec (2020)	$\frac{Mass\ of\ Nutrient\ (NPC)\ in\ Recovered\ Products}{Total\ Mass\ of\ Nutrient\ Inflow\ to\ WWTP}$

Table 3
Results from circular action indicator taxonomy, presented as the percentage change between conventional and PBR processes. Self-sufficiency, electricity demand minimisation, and carbon emissions reduction are provided as absolute percentages as self-sufficiency of the benchmark process was zero, whilst minimisation and reduction indicator results are intrinsically comparative calculations.

Action	Indicator	% Change
Reduce Energy Intensity	Circular Energy Intensity (kWh/kg Carbon)	- 67.6%
	Self-Sufficiency (%)	58.5% (vs 0)
	Electricity Grid Demand Minimisation (kWh/d)	13.4%
Achieving Decarbonisation	Carbon Emissions Reduction (%)	66.3%
	Emissions Eco-efficiency (€/kg)	+ 97.7%
Reduce CAPEX/OPEX	Yearly Cost (€)	- 44.6%
Extraction/Generation of Value-Added Products	Waste Eco-efficiency (€/kg)	- 34.5%
	Value added per m^3 WW Treated (€/ m^3)	+ 1152.6%
Renewable Resource Use	Substitution Factor N fertiliser (kg/kg)	+ 345.0%
Retain Nutrients	C Recovery Rate (%)	+ 165.3%
	N Recovery Rate (%)	+ 195.0%
	P Recovery Rate (%)	+ 15.5%

pollution, and generate revenue from waste streams, social indicators were selected to reflect these impacts. Those chosen were endpoint impacts, including disability-adjusted life years (DALY), employment, and economic contribution to the local community indicators.

3.7.1. Carbon footprint

Carbon footprint analysis was completed following the method defined by the IPCC for wastewater treatment facilities (Doorn et al., 2019). Emission factors for wastewater treatment were taken from the IPCC method, whilst those for other resources such as electricity and chemicals were extracted from ecoinvent databases. A description of the method and parameters used is found in Section 5.1 of the Supplementary Material.

3.7.2. Life cycle assessment

The LCA was completed using the same boundaries as the MFA and a functional unit of 1 m^3 of wastewater treated, following ISO 14,040 and 14,044 (British Standards Institute, 2020). The inventory used to complete the analysis is the same as that constructed for MFA and indicator calculation. SimaPro v9.4 was used to conduct the calculation of seven Environmental Product Declaration (2018) impact indicators; acidification, eutrophication, photochemical oxidation, abiotic depletion (elements), abiotic depletion (fossil fuels), water consumption, and ozone layer depletion.

3.7.3. Economic value added

Determining the operational and economic profitability of the investment in ANPHORA® was achieved by assessing the economic value added of the system. Fig. 7 explains the economic relationship between the water user and wastewater utility (Faragò et al., 2021). The water user pays an expected fee for the provision of the wastewater treatment services by the wastewater utility, however, investment in technologies can disrupt this flow by creating a surplus (revenue greater than expenditure) or deficit of value (revenue lower than expenditure), resulting in savings or increasing fees. Therefore, to understand the economic value generated by the water utility, the expected difference between WWTP operator revenue and costs were calculated for the conventional and biorefinery processes.

A method was followed similar to that of Medina-Mijangos and Seguí-Amórtegui (2021) for the assessment and is calculated using Eq.

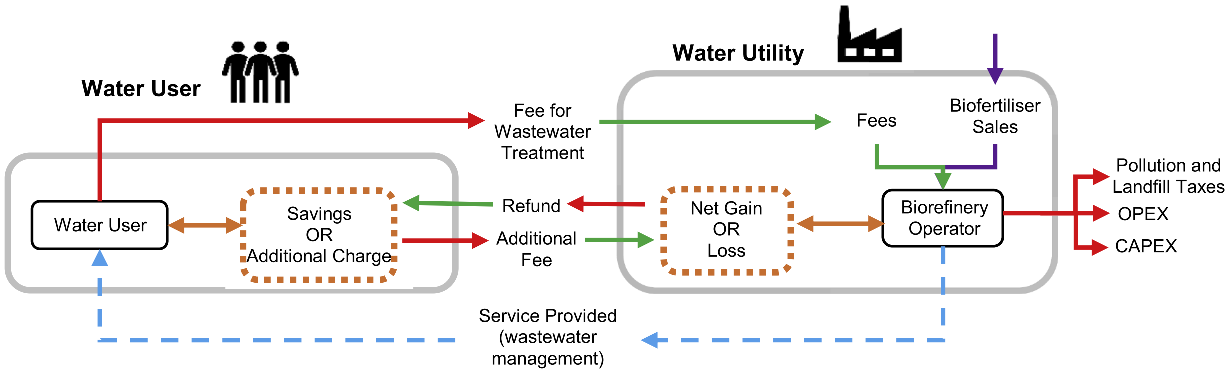

Fig. 7. Economic relationship between stakeholders in wastewater systems (adapted from Faragò et al. (2021)).

(1):

$$VC = (WWT_V \times GF) - (CAPEX + OPEX + ST) + In \quad (1)$$

Where, WWT_V is the volume of wastewater treated (m^3), GF are the gate fees of the WWTP (€/m^3), ST are state taxes for landfill and discharge (€), In is income from sales of products (€), and CAPEX is amortised. The steps and data used for economic value-added analysis are summarised Section 5.2 of the Supplementary Material.

3.7.4. *Social value analysis*

The social assessment comprises of three indicator groups targeting endpoint impacts, employment, and economic development of the local community. The damage to human health, ecosystems, and resources indicators were calculated using the ReCiPe Endpoint (H) model (Huijbregts et al., 2017), and included the production of chemicals and electricity consumed, direct emissions, and emissions from application of generated sludge to soil as fertiliser (European Commission, 2018). The inventory of material and energy flows, as well as environmental releases can be found in Tables S21 and S22 of Supplementary Material.

Employment and economic development indicators were calculated using information for the municipality of Soria. This area has a population of 10,445, which is similar to the 10,000 PE WWTP example, therefore it was used to investigate the social impacts that a WWTP of this size can have on a community (INE, 2022). Employment growth

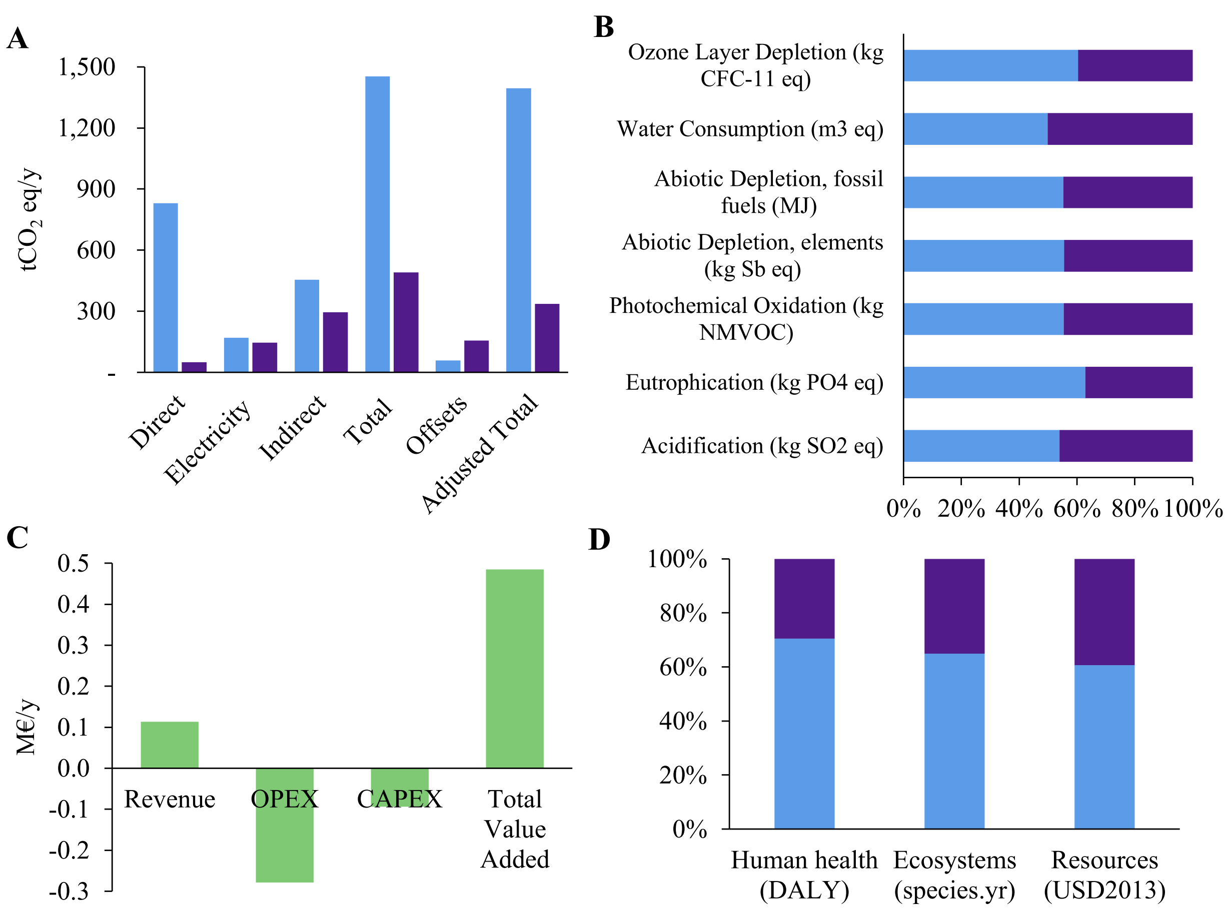

Fig. 8. Conventional extended aeration process results in blue, and PBR process results in purple. A: Carbon footprint results divided into direct, electricity, and indirect emissions, and offsets, B: LCA impact indicator results, C: economic value added visualised as the difference between revenue and costs of the PBR and conventional systems, and D: social endpoint (H) impact indicator results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resulting from investment in ANPHORA® technology was calculated based on discussions with local experts regarding expectations compared to conventional technologies. Employment of the conventional plant was estimated based on the total employees that work in the wastewater treatment sector in the autonomous community Castile and León (where Soria is located), to calculate an employment factor of workers per population (Santos et al., 2021). Then the population of Soria was used to calculate the number of workers in an urban WWTP of a similar size. Lastly, the effect on the economic development of the local community was calculated according to the expected economic value generated by both WWTPs. The impact on economic development was calculated based on the economic value added relative to the gross domestic product of the municipality (INE, 2022). Revenues and costs of suppliers were excluded because consumables were assumed not to be locally sourced.

3.8. Consequential circularity performance assessment

Fig. 8 summarises the results of the complementary sustainability analysis required to quantify the sustainable value creation of the PBR process. LCA results in Fig. 8B show that PBR operation performs better in six out of the seven impact categories investigated, ranging from 15% to 41% reduction. Eutrophication sees the largest decrease of 41%, attributed to the reduction of NP emissions in wastewater effluents. Ozone depletion, photochemical oxidation and acidification decrease by 34%, 20% and 15% respectively which occurs due to the reduction of emissions to air during wastewater and sludge treatment. The cost-benefit analysis of Fig. 8C shows that as the gate fees are constant the increase in revenue for the PBR system is a result of biofertiliser sales, adding approximately 0.1 M€/y. There is also reduction in OPEX due to the lower energy demand associated with the mitigation of aeration during biological treatment and energy recovery from biogas, as well as the removal of lime requirements for sludge treatment. Combining this results in an economic value added of almost M€ 0.5 per year for water the utility. Therefore, the PBR system facilitates better environmental and economic performance which are key for establishing project viability (a more detailed description of results is provided in Section 6 of the Supplementary Material).

This methodology aims to quantify the sustainable value creation that is generated from circular actions implemented by the SOI that change physical resource flows. Therefore, once analysis is complete it is important to relate the sustainability analysis results with the gains creators identified during VPC construction. Lowering energy consumption creates value across all TBL dimensions as it reduces the harmful emissions produced during electricity generation, reducing electricity emissions by 13.4% and other related LCA impacts categories, such as acidification and abiotic depletion of fossil fuels by 15% and 19% respectively, to create value for the environment. Reducing harmful emissions also provides social value by decreasing DALY by 58% and lower electricity demand contributes to the reduction in OPEX, creating economic value for utilities. Lowering the carbon footprint creates significant environmental value by mitigating two thirds of emissions, increasing to 75% when considering offsets of chemical fertilisers. Economic value added is the main indicator of the value created from savings on logistics and infrastructure, shown by the reduction of OPEX and CAPEX of 0.28 M€/y and 0.09 M€/y respectively which results in savings for the water utility. Valorisation of sludge creates economic value as shown by the increase in revenue of 0.11 M€/y, but also impacts social value by increasing the contribution to the local economy by almost 12 times. Lastly, the result of improved wastewater treatment performance has a strong influence on carbon footprint and other LCA categories by decreasing direct emissions by more than 90%, and related LCA impacts such as eutrophication by 41%, to generate significant value for the environment. Additionally, greater reduction of emissions to air, water, and soil as a result of wastewater treatment reflects the lessening of DALY (by 58%), thereby generating social value through enhanced WWTP performance from the ANPHORA® technology. Therefore, the SOI results in consequential circularity improvements for stakeholders across economic, environmental, and social TBL dimensions.

This example highlights the main benefit of the developed method, namely the systematic selection and calculation of indicators to determine how changes in the circularity of physical resources impact sustainability dimensions. This development is critical to the success of the CE transition as recent policy relies on enhanced resource circularity to meet many sustainability targets. For example, the new CE Action Plan is one of the main building blocks of the European Green Deal, which targets a 55% reduction of GHG emissions by 2030 (compared with 1990) (European Commission, 2021). However, it has been shown that the water sector is unable to implement circular strategies as decision makers cannot assess how their investments will facilitate sustainability objectives (Renfrew et al., 2022). Therefore, this method provides an integrated approach to support decision making by using pertinent, well-established metrics, including LCA and cost benefit analysis, to validate that investments which improve resource circularity also enhance sustainability performance. Assessment of the PBR provides a detailed example of how impacts can be directly quantified across the TBL including carbon footprint reduction to satisfy Green Deal targets, economic prosperity to justify the investment to businesses, and societal health and wealth benefits to reassure citizens about changes to the local area. Therefore, this method presents an important step in CE science, enabling industry decision makers to quantify how their circular actions leads to progress towards sustainability targets and business objectives, accelerating CE progress.

4. Discussion

4.1. Systematic assessment for decision making

Current assessment methodologies mainly rely on providing a list of preselected indicators from which users can choose, however, this runs the risk of facilitating cherry-picking to highlight specific interests of decision makers (Harris et al., 2021; Superti et al., 2021). Here a participatory approach to select a tailored set of indicators in a flexible yet replicable way, to ensure holistic assessment of the impacts that circular actions have on sustainable development. Papageorgiou et al. (2021) showed that CE assessment frameworks lack indicators which measure reduction of emissions, value creation, and social dimensions. Therefore, these aspects which are heavily relied upon for policy related decisions and industrial investment are often neglected during assessments. Here, an emphasis is placed on understanding the value added by circular interventions compared with conventional technologies, as this is one of the key metrics for evidencing business investment

This methodology provides decision makers with the information to satisfy a range of activities including performance comparison of their process with other WWTPs, selecting circular technologies that fulfil desired circularity and sustainability goals, and selecting indicators for optimising of process operation and sustainability. Selecting technologies can be a challenge for wastewater decision makers, due to trade-offs that must be considered for each technological option. Many multi-criteria decision making (MCDM) tools have been developed specifically for wastewater systems, that can rationalise options according to the user's priorities (Renfrew et al., 2022; Sucu et al., 2021). This assessment methodology can investigate and validate the outcomes from MCDM analysis for selecting circular technologies, as evidence for investment by water utility companies. Alternatively, the resource flow and circular action indicators selected could facilitate WWTP optimisation, whether it be hotspot analysis of a static system or integration of indicators within the control strategy of a process, to ensure more sustainable and circular operational performance. Therefore, this method can be used for multiple levels of decision making from plant optimisation to strategic planning.

4.2. Future work

Many circular intervention technologies are still being developed at low technology readiness level (TRL). To elucidate the advantages of these technologies, circularity assessments, and other sustainability analysis techniques (LCA, technoeconomic assessment, or social LCA) need to be completed. However, low TRL technologies (pilot scale) cannot compete in terms of economics, often due to higher energy and material consumption, with industrial scale processes. Therefore, technologies should be modelled at the full scale of implementation, requiring scale up calculations to build the models necessary for circularity assessments. Although, caution must be taken when building models and inventories of scaled up or future systems, as this introduces possibilities for high levels of uncertainty during the assessment.

To overcome the issues of uncertainty when modelling scaled-up technologies, the principles of prospective LCAs can be utilised. van der Giesen et al. (2020) recommends the use of responsive evaluations by technology designers and other relevant stakeholders to provide insights on the design choices and contextual factors which have larger influences on the outcomes of assessments, and therefore require greater attention when being modelled. The insights from technology designers can be combined with learning curves and upscaling analysis from experts in the fields of chemical and process engineering to create representative and realistic models of full-scale technologies. For example, Tecchio et al. (2016) provides a systematic method for the scale up of biorefinery processes, utilising primary data from pilot scale systems and combining it with knowledge of thermo-chemical processes, to estimate the environmental impact at an industrial scale.

Ex-ante and prospective LCA approaches provide many insights required for developing accurate models for full scale processes. This is pertinent, as to elucidate the advantages of circular technologies they must be modelled and compared at an industrial scale, even though many are still at low TRL. Therefore, the next developments to the proposed circularity assessment method must focus on the integration of a systematic process for developing full scale models for low TRL circular technologies, and investigation of uncertainty to mitigate calculation errors and improve assessment transparency.

5. Conclusions

The proposed method overcomes a significant gap between current circularity and sustainability assessments by systematically linking changes in physical resource circularity with resultant sustainable value creation, to harmonise the assessment of wastewater treatment processes. The indicator taxonomy facilitates a robust assessment using three typologies, namely resource flow, circular action, and sustainability indicators. This enables a normative circularity assessment that is directed by participatory identification of circular actions to identify sustainability analysis required to support the circularity assessment. These advancements were exhibited by applying the assessment to a wastewater treatment example by comparing PBR and conventional technologies at a scale of 10,000 PE. It showed how strategic project goals were combined with goals of the circular technology to select relevant action indicators, with the data requirements feeding complementary sustainability indicator selection. Resource flow indicator results highlighted improved outflow circularity (specifically for NP nutrients), renewable energy usage, and economic efficiency of the PBR system. Action indicators revealed that the PBR technology was successful at satisfying stakeholder expectations and achieving the defined strategic goals. Lastly, sustainability indicators enabled the direct quantification of environmental, economic, and social value creation, confirming the benefits of PBR wastewater treatment technology for stakeholders. Future work must focus on the use of ex-ante and prospective assessments to facilitate the scale-up and adoption of circular technologies currently at low TRL, and the systematic analysis of how data uncertainty impacts the use of indicator results for decision making.

CRediT authorship contribution statement

D. Renfrew: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **V. Vasilaki:** Writing – review & editing, Conceptualization. **E. Nika:** Writing – review & editing, Conceptualization. **G.A. Tsalidis:** Writing – review & editing, Formal analysis. **E. Marin:** Data curation. **E. Katsou:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.121141.

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