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Tracing wastewater resources: Unravelling the circularity of waste using source, destination, and quality analysis

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ABSTRACT

Current circularity assessment terminology restricts application to wastewater processes due to the focus on technical systems. Waste stream and wastewater discharge circularity definitions lead to paradoxical assessments that generate results of little value for evidence-based decision making. Therefore, a classification approach was developed to measure inflow and outflow circularity of the main wastewater resource flows using the principle of traceability, adopting the attitude that not all waste is created equally. Applying it to a wastewater treatment plant (12,000 m^3/d load) showed how upstream agricultural, industrial, and human practices impact downstream treatment, and the effectiveness of resource cycling within the natural environment. Industrial actions increasing fossil carbon concentration (400 m^3/d effluent at 1000 mgC/l) reduced inflow and outflow circularity by 16 % and 10.6 % respectively, as secondary and sludge treatment fossil emissions increase significantly. Alternatively, changes to human and agricultural practices (50 % reduction of detergent and synthetic fertiliser usage) improved phosphorus inflow and nitrogen outflow circularity by 5.2 % and 20.1 % respectively. This approach can educate and assign responsibility to water users for developing robust circular economy policy, shifting the pattern from promoting circularity to discouraging linear actions, overcoming the shared economic and environmental burden of linear water use.

1. Introduction

Transitioning towards a circular economy (CE) means decoupling economic growth from the consumption of finite resources (Kjaer et al., 2019), providing a pathway to operationalise the sustainability of economic systems through specific activities that close and extend resource loops (Kirchherr et al., 2017). The attention given to the CE concept by industry in recent years has generated such momentum that it is becoming integrated within environmental policy (EU, China, US) (Moraga et al., 2019). However, it is argued the vagueness and uncontroversial nature of a CE has resulted in its popularity, by promising multiple benefits with few burdens (Corvellec et al., 2022). This ambiguity is signified by the lack of universal definitions (Moraga et al., 2019) and standardised metrics required for evidence-based decision making (Åkerman et al., 2020), meaning this trait now hinders the CE transition.

Currently, the most commonly exhibited circular strategies are more appropriate for technical processes (Kirchherr et al., 2017), which correlates to a lack of assessment methodologies for biological systems, as the terminology used and indicators selected cannot be directly utilised across both paradigms (Navare et al., 2021). This also applies to water systems as many technical CE strategies are not appropriate, including repairing, refurbishing, and remanufacturing actions (Morseletto et al., 2022), due to the nature of resources carried and biological treatment processes utilised. Subsequently, the assessment of biotic and water resource circularity must acknowledge the differences with technical materials, such as investigating the sustainability of their extraction (harvesting or abstraction) to validate resource circularity, as circular technical processes aim to mitigate natural resource extraction entirely (Navare et al., 2021). Additionally, these resources must be cascaded as they degrade in quality, until they are regenerated to their original state by the environment (Stegmann et al., 2020), whilst technical systems focus on reverse logistics to maintain resource value (Morseletto et al., 2022).

The recovery of value from wastewater is pertinent for realising a fully CE (Smol et al., 2020), however, in wastewater treatment plants

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(WWTP) the provision of service is dictated by upstream water user habits and the local climate, whereas most other production processes have choice of upstream materials and feedstocks. This leads to water asymmetry, where downstream users are dependent on upstream water use, whilst upstream users are mostly unaware or unimpacted by their own usage (Savenije and van der Zaag, 2020). Currently, it is difficult to pass responsibility on to water users to alter wastewater composition or production volumes, as this is a very sensitive area in terms of regulation and human rights protection (Gleick, 1998). Therefore, this is a pertinent area of development as it is currently difficult to define physical water resources as sustainable or unsustainable (Sauvé et al., 2021); it is how they are used along with the resultant impacts of usage. In technical systems, similar problems have been overcome by using the CE principle of traceability to enhance the sustainability of consumer practices. However, the technology is reliant on physically tagging products (Hoosain et al., 2023), thus this method is inappropriate for wastewater resources and requires an alternative strategy.

Wastewater production rate and composition is highly complex and case specific but it is ultimately dictated by water users (Sauvé et al., 2021), so generation that goes against CE principles should be penalised during circularity assessments. To address the resource imbalance caused by linear consumption, several methods have been trialled to facilitate the enhancement of circularity, including footprint calculators, material flow analysis (MFA), and life cycle assessments (LCA) (Metson et al., 2020). However, footprint calculations mitigate the spacio-temporal aspect needed to fully appreciate resource circularity (Metson et al., 2020; Sauvé et al., 2021), MFA neglects the resultant impacts of resources interacting with the natural environment, and LCA commonly assumes zero burden of waste streams utilised as feedstocks, ignoring the effect of upstream decision making on circularity (Pradel et al., 2016). Therefore, no currently available methodology can provide a holistic approach to mend water and nutrient balances, hindering evidence-based decision making for the CE.

To realise this, traceability principles are needed to develop assessments that go beyond the current blanket definitions of waste, to show how water usage impacts circularity. However, understanding and standardising waste circularity becomes challenging when reviewing the definitions currently available in literature. Strategy- (Moraga et al., 2019), functionality-, and value-based (Iacovidou et al., 2017) classifications have been developed, but these consider technical manufacturing systems, meaning they cannot be applied to wastewater resources as wastes are deemed to have no value to the holder. More worryingly, a prominent industrial CE advocate defines an incoming waste stream as being non-virgin and therefore circular (wbcsd, 2022). This creates a paradox during the assessment of waste and wastewater treatment facilities, as intentional or preventable generation of waste is against many CE principles, yet it would be considered a circular inflow within these system boundaries, leading to errors during quantitative circularity assessments.

To overcome this, traceability principles should be applied to adopt the attitude that not all waste is created equally (Girard, 2022). The actions of wastewater producers across different sectors must be used to assign responsibility for linear utilisation of resources, shifting the current paradigm of policy instruments that only promote circularity to actively discourage linear practices (Corvellec et al., 2022). This is needed as it is currently difficult to construct economically feasible circular business models as disposal of materials to environmental sinks is relatively cheap (Åkerman et al., 2020). This means an approach is needed to assign responsibility for unsustainable water usage and wastewater production. Therefore, the aim of this work is to develop a method that measures and assesses the circularity of the main inflow and outflow wastewater resources (i.e. water, carbon, nitrogen, and phosphorus) based on CE principles for biobased systems (specifically traceability), to understand the consequences of upstream actions on downstream treatment processes. This characterisation will act as the foundation for developing holistic circularity assessments, enabling the incorporation of wider impacts such as environmental and human health dimensions.

2. Methodology

2.1. Overview

The framework developed by Harder et al. (2021b, 2021a) is one of the only examples in literature analysing the traceability of nutrients in biological systems, aiming for nutrient circularity '*disentanglement*'. However, it presents a simplified nutrient end-of-life scenario, ignoring nutrient interactions with the atmosphere and water bodies for resource cycling. Therefore, this work builds upon the Harder et al. (2021b, 2021a) framework by considering nutrient and water resources, to understand how they are cycled to supplement air, water, and soil in biological systems or as materials in technical systems, and lost to the environment in a harmful, dissipative manner during wastewater treatment. This model is illustrated in Fig. 1, highlighting the interconnectivity of wastewater resources with other sectors and how they disrupt natural water cycles through unsustainable water usage. This is needed as the economic and environmental burden of treatment is usually shared by stakeholders regardless of their individual consumption, making it challenging to develop policy that discourages unsustainable water use. Traceability of wastewater resources using this model enables assessors to understand the purpose behind water use, its alignment with CE principles, and the subsequent impact on water quality. Therefore, the approach can be used to assign responsibility to water users, helping to guide policy and regulatory frameworks that address sector-specific goals.

Utilising resource disentanglement, the current work aims to detail the origin and nature of wastewater resources to ensure they are not mistakenly labelled as circular during assessments. Firstly, influent water is classified based on source and recoverability from Kakwani and Kalbar (2022), whilst outflow circularity is defined by water quality and intended use to supplement fresh water abstraction. Nitrogen and phosphorus inflow circularity is based on nutrient sources from the work of Comber et al. (2013), whereas outflows must contribute to natural nutrient cycling or substitute virgin nutrient consumption to be classed as circular. Lastly, properties of biogenic or fossil carbon are used to differentiate circularity according to Law et al. (2013), as the former is part of natural cycling and release of the latter has detrimental impacts on the environment. Adding the interactions of wastewater treatment with environmental and human systems in this way will shed light on the previously neglected elements of waste resource circularity, by establishing which practices facilitate resource renewability, restoration, and substitution, as well as those that impede natural cycling.

2.2. Resource flow characterisation

The characteristics of waste streams cause confusion when defining and assigning circular properties. Terms such as raw material, virgin, biogenic, by-product, and renewable are often used in CE literature to describe resources, some of which reveal intrinsic circular properties whilst others require further investigation of resource characteristics. Korhonen et al. (2018) discusses the problem of distinguishing between wastes and by-products, concluding that without proper definition of materials it is *difficult to intentionally support their utilisation*. Using the principle of traceability, it is possible to assume that a waste feedstock may not be circular or contains non-circular components. This may not align with the common 'zero burden' burden assumption but without this classification it is easy to assume that as long as a WWTP operates as expected (meeting discharge permit limits), 100 % of wastewater inflows and 100 % of wastewater outflows are circular, meaning the assessment is of little value to decision makers.

The developed method utilises the principles of the Do No Significant Harm (DNSH) framework (Italia Domani, 2021), to reason whether

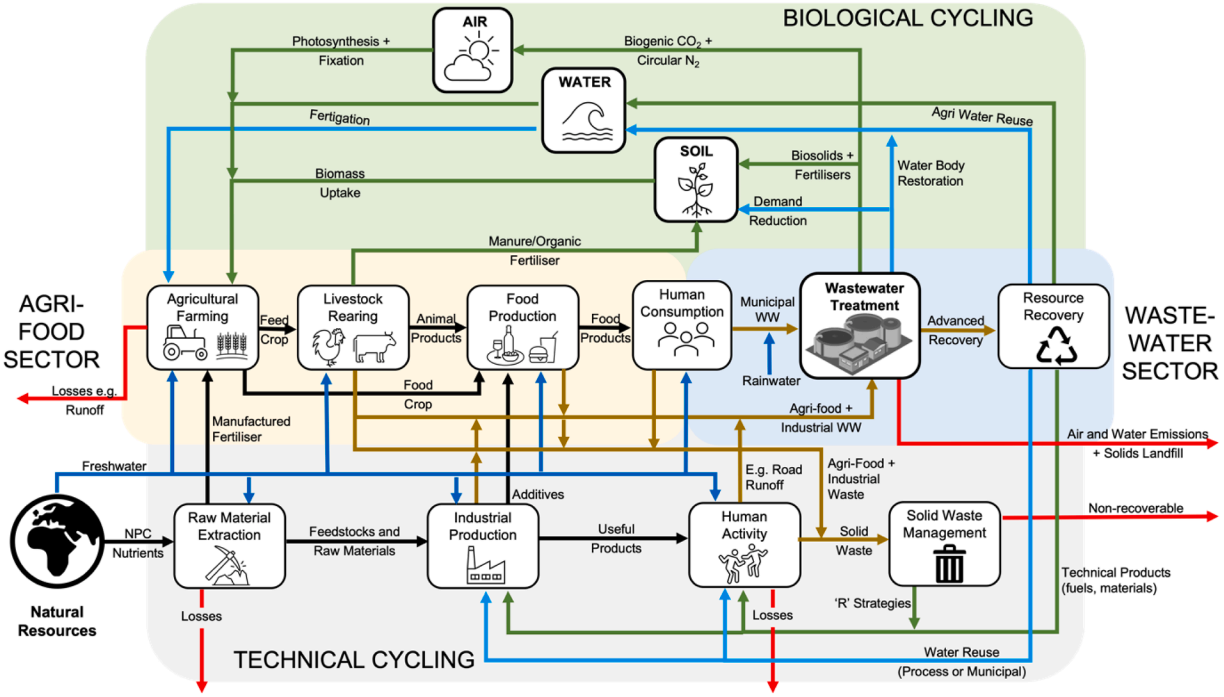

Fig. 1. Expansion of the work by Harder et al. (2021b) to show resource flows related to wastewater treatment through the human system. Flows are divided into technical (black), virgin water (dark blue), circular nutrient (green), circular water (light blue), losses (red), and waste treatment (brown) resources.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resource flows that interact with environmental (soil, water, and air) and human systems should be considered linear, and combines it with an understanding of resource source and destination. By applying this method to critically analyse wastewater, the different resources that make up this complex stream can be disentangled. Therefore, not only can all resource inputs and outputs be characterised, but also the different fractions and components of each nutrient considering their individual properties using the selected criteria and developed definitions from Sections 2.2.1 to 2.2.3. This is necessary due to the complexity of wastewater so definitions for the circularity classification of water, carbon, nitrogen, and phosphorus resources are provided, along with common wastewater treatment examples in Tables 1–7 to facilitate indicator calculation.

2.2.1. *Water*

According to Kakwani and Kalbar (2022) improving water circularity should focus on distinct water collection for water restoration, recycling, reuse, and reclamation. Whereas the definition of outflow circularity requires understanding of water flow quality and its destination.

2.2.1.1. Inflow circularity. This starts by defining a WWTP's primary aim, which is to collect wastewater and treat contaminants so that it can be discharged to restore a water body, recognising the potential of WWTPs to possess advanced technologies for water recycling, reuse, or reclamation. Next, the circular inflow fraction is defined as the *recoverable water that flows into a WWTP which has the potential to be upgraded for restoration of a water body or other recycling, reuse, and reclamation purposes*. Then the non-circular inflow requires an estimation of the quantity of water that is lost upstream, which is defined as the *unrecoverable water that is lost between water provision and WWTP, such as human consumption losses, distribution losses, spillages, or evaporation*, all of which reduce the amount of water a facility can treat. Lastly, a final category of water inflows is defined, for the water fraction in materials required for WWTP operation, such as ferric chloride ($FeCl_3$) solution. These fractions are usually recoverable but from virgin sources, so are considered linear (although the scale of wastewater treatment means they can usually be neglected). The values used in this study are summarised in Table 1 and are taken from Kakwani and Kalbar (2022).

Table 1
Circularity fractionation of water inflows.

Stream	Input fractions	Status
WWTP inlet	80 %	Circular (recoverable)
Losses (Consumption - WWTP Inlet)	20 %	Linear (unrecoverable)
$FeCl_3$ (40 % solution)	<1 % (negligible)	Linear (virgin)

Table 2
Circularity fractionation of water outflows.

Stream	Water content	Destination	Status
Screenings	50–90 %	Landfill	Linear
Fats, Oil, Grease (FOG)	15–95 %	Landfill	Linear
Grit	13–65 %	Landfill	Linear
Effluent	>99.9 %	Restoration (groundwater, lake, river)	Circular
		Recycling (irrigation or further upgrading)	Circular
		Sea Water	Linear
		Discharge Fails to Meet Permit Limits	Linear
		Overflow Discharge	Linear
Biosolids	65–85 %	Landfill	Linear
		Incineration	Linear
		Land Application	Circular/ Linear

2.2.1.2. Outflow circularity. Firstly, an outflow is defined as circular if *it is discharged at the required regulatory quality used for restoration of a*

Table 3
Circularity fractionation of NP inflows.

Phosphorus			Nitrogen		
Stream	Input fraction	Status	Stream	Input fraction	Status
Urine	30 %	Circular	Urine	80 %	Circular
Faeces	10 %		Faeces	14 %	
Food scraps	1 %	Linear	Greywater (kitchen, laundry, or bathroom)	6 %	Linear
Food additives	29 %				
Automatic dishwashing	9 %				
Laundry detergents	14 %				
Tap water dosing	6 %				
Personal care product	1 %				

freshwater body (in the same catchment) or upgraded for purposes that reduce virgin water abstraction (recycling, reuse, reclamation) by supplementing the needs of other processes. This step requires regulatory limits to be established that confirm the restorative abilities of wastewater discharges, such as the DSNH criteria (2021/C58/01) for 'the sustainable use and protection of water and marine resources'. This is appropriate for assessing European WWTPs and states to follow requirements of the Water Framework Directive (WFD) (2000/60/EC) to assess environmental degradation risks (European Commission, 2021). The WFD uses the Urban Wastewater Treatment Directive (UWWTD) (91/271/EEC) for classifying discharges to water bodies (European Parliament, 2000) and can be used to guide quality requirements (Council of the European Union, 1991). However, an additional action is needed when the receiving water body is reaching its allowable limit of pollution (according to the WFD). In these cases the grey-water footprint is used to calculate the critical load of discharges, to ensure the freshwater flow sufficiently dilutes contaminants, according to the method of Aldaya et al. (2011). If not, then the discharge of treated wastewater by a WWTP cannot be seen as a regenerative action and will receive a linear classification until water body quality or effluent concentrations are improved to satisfy the critical load. Lastly, the linear outflows are defined as water that is *discharged at a level of contamination that does not meet regulatory limits and is therefore harmful to environmental and human health, not returned in a controlled manner for freshwater body restoration, or is used in a way that does not result in the reduction of virgin water abstraction.* Table 2 summarises common outflows and destinations, with the expected fraction of water in each stream taken from literature (Tchobanoglous et al., 2014), showing how this influences the circularity classification.

2.2.1.3. Additional considerations – Biosolids. In the case of biosolids application to land, their moisture must be compared with that of the receiving soil. Data is collected from appropriate literature, as European soil moisture can fluctuate between 5 % and 44 % in arid and cold climates respectively (Almendra-Martín et al., 2022), whereas biosolids solids content can be approximately 25 % when dewatered, 50 % when composted, and >75 % when dried (Tchobanoglous et al., 2014). Therefore, it is possible for soil to have greater moisture content than the applied solids, meaning application will not improve soil water deficit.

Table 5
Nitrogen applied to cropland in EU-27 countries in 2020.

Total mass to crops				Status
14,241,375		tonnes		Neutral/Circular
Total fractions		**Mass**		**Status**
Synthetic fertilisers	62 %	8796,622	tonnes	Neutral
Manure applied to soils	28 %	3979,757	tonnes	Circular
Atmospheric deposition	7 %	1031,166	tonnes	Neutral
Biological fixation	3 %	433,829	tonnes	Circular

Table 6
Fractionation of fossil carbon in wastewater system outflows.

Outputs		Notes
Effluent	5.0 %	
Sludge (no anaerobic digestion (AD))	64.5 %	
Sludge (post AD)	56.8 %	88 % of fossil carbon to sludge and 12 % to biogas
Biogas (from AD)	7.7 %	
Direct Gas Emissions	30.5 %	

Table 4
Circularity fractionation of NP outflows.

Phosphorus				Nitrogen			
Stream	Nutrient fraction	Destination	Status	Stream	Nutrient fraction	Destination	Status
Effluent	1–2 mg/L	Sea Water	Linear	Effluent	5–15 mg/L	Sea water	Linear
		Freshwater Body	Linear			Freshwater body	Linear
		Water Upgrading/ Recycling e.g. fertigation	Circular/ Linear			Water Upgrading/ Recycling e.g. fertigation	Circular/ Linear
	>2 mg/L	Discharge Fails to Meet Permit Limits	Linear		>15 mg/L	Discharge Fails to Meet Permit Limits	Linear
	3.7–11 mg/L	Overflow Discharge	Linear		23–69 mg/L	Overflow Discharge	Linear
Biosolids	approx. 1.9 %DS	Landfill	Linear	Biosolids	approx. 4.4 %DS	Landfill	Linear
		Incineration	Circular/ Linear			Incineration	Linear
		Land Application	Circular/ Linear			Land application	Circular/ Linear
		Other	Circular/ Linear			Other	Circular/ Linear
				Gas Emissions *in the case of nitrification-denitrification	1.6 % Influent N (0.016 - 4.5 %) (Doorn et al., 2019)	N_2O	Linear
					29 % of Total N removed minus N_2O	N_2 (from organic fertilisers and biological fixation)	Circular
					65 % of Total N removed minus N_2O	N_2 (from synthetic fertilisers and atmospheric deposition)	Neutral
					6 % of Total N removed minus N_2O	N_2 (from greywater)	Neutral

Table 7
Circularity fractionation of OC outflows.

Stream	OC fraction	Destination	Status
FOG	77 % TS	Landfill	Linear
Screenings	41.3 % TS	Landfill	Linear
Effluent	approx. 10 mg/L	Sea water	Linear
		Fresh water body	Linear
		Water upgrading/ Recycling	Circular/Linear
	109–328 mg/L	Overflow discharge	Linear
Biosolids	19–35 %DS	Landfill	Linear
		Incineration	
		Fossil emissions	Linear
		Biogenic emissions	Circular (CO_2)/ Linear (CO and CH_4)
		Ash (landfill)	Linear
		Land application	
		Fossil	Linear
		Biogenic	Circular
		Other	Circular/Linear
Direct gas emissions *in the case centralised aerobic processes	Total carbon removal minus CH_4 emissions	**CO_2**	
		Fossil	Linear
		Biogenic	Circular
	Emission factor of 0.0075 $kgCH_4/kgCOD$ (Doorn et al., 2019)	CH_4	Linear
Biogas	approx. 65 % CH_4 (remainder assumed CO_2)	**Biogas combustion**	
		Fossil CO_2 and Fugitive CH_4	Linear
		Biogenic CO_2	Circular

Finally, the water fraction is considered circular when high water content biosolids or sludge is applied to dry soils that *reduce the water deficit, resulting in the reduction of raw water abstraction.*

2.2.2. Phosphorus and nitrogen

Comber et al. (2013) completed substance flow analysis (SFA) of domestic wastewater nutrients entering sewage treatment works and is used to divide nutrient fractions based on their origin, and categorised by whether they originate from human waste or unnatural sources. MFA and SFA allow the inflows to be tracked through the system, and outflow streams quantified, which enables the degree of harm to be established.

2.2.2.1. Inflow circularity. The objective of defining nitrogen and phosphorus (NP) nutrient circularity relies on understanding their renewability within biological systems. Firstly, NP inflows are defined as circular if *it is from a source that contributed to the natural human diet and cycling of nitrogen or phosphorus*, such as human excreta. Next, any farming or animal wastes entering the system are classified as linear, as these nutrients should be kept within the farming/food system and applied to crops. Then NP is considered to have non-circular properties when sourced *from preventable or non-natural sources and is part of the non-natural and unnecessary use of nitrogen or phosphorus*. Table 3 provides a summary of the fractions of domestic wastewater, with the data for the fractionation of inflows taken from studies by Comber et al. (2013) and van der Hoek et al. (2018).

2.2.2.2. Outflow circularity. The first step is to define circular outflows as being *effectively recovered for controlled release to soil (for fertilisation or conditioning) or safe return to the atmosphere, or are utilised in products to extend the life of nutrients in the human system, substituting the use of virgin resources.* Then linear flows are the opposite as they *are not recovered effectively and are released to the environment (atmosphere, water, and soil) in a way that is harmful to the natural functioning of ecosystems*. During classification of linear flows, it is critical to consider atmospheric emissions, especially N_2O as it is a reactive form of nitrogen produced during nitrification–denitrification processes and is a powerful greenhouse gas (GHG) making it harmful to the environment. Additionally, the eutrophic properties of NP mean that any release of these nutrients in wastewater discharge is assumed to be potentially harmful following the DNSH principles, as well as being a loss of useful resources from the human system, so are deemed linear.

Table 4 provides a summary of the properties of WWTP NP resource outflows, with typical concentrations taken from Tchobanoglous et al. (2014). It is worth noting that some streams have the potential to be linear or circular depending on their destination, for example if water is recycled to be used in agriculture, then NP nutrients are used in a circular manner in cases such as fertigation. The phosphorus in incineration ash can be leached and collected before landfill to be used in a circular manner, and the circularity of 'Other' uses of biosolids depends on the scenario, including composting or land reclamation processes. Therefore, the circular properties of nutrient outflows are dependent on the specific scenario and how resource outflows are used.

2.2.2.3. Additional considerations – N_2 emissions. For nitrogen gas (N_2) emissions, a unique classification of 'neutral' is defined and used in combination with circular fractions. Initially, the circular allowance of N_2 is calculated as the fraction of nitrogen in human excreta (94 % of inlet) from organic fertilisers (manure) and nitrogen fixation, as this facilitates the extended life of nutrients in the human system and natural cycling. Then the remaining fraction is calculated from synthetic fertiliser application and atmospheric deposition of nitrogen, and whilst the N_2 gas generated from this does not cause environmental harm, it is not part of natural nitrogen cycling, nor does it contribute to the replenishment of atmospheric nitrogen sinks, so it is considered neutral. The other neutral fraction is calculated from the greywater inlet (6 %), as this is not part of natural nitrogen cycling. The N_2 fractions in Table 4 are collected from values in the Food and Agriculture Organization database (Food and Agriculture Organization of the United Nations, 2020) for nitrogen applied to cropland in EU-27 countries (year 2020) and are provided in Table 5. Lastly, in the cases of nitrification–denitrification it is recommended to calculate an additional indicator for the fraction of 'non-harmful' nitrogen outflow, so that linear, neutral, and circular resource flows are compared. This ensures that true nitrogen cycling is rewarded whilst good practices of biological nutrient removal (BNR) are not penalised by the assessment.

2.2.2.4. Additional considerations – NP release. The mechanism of release is important for NP classification, which is why land application has been defined as potentially circular or linear. The first step is to consider the efficiency of NP application to farmland, as the particularities of each case, the amount applied, the time of year, and the method used can impact the utilisation of nutrients by cropland. For example, nutrients returned to an ecosystem at a rate higher than it is able absorb them can negatively impact nutrient cycling (Navare et al., 2021). Poor practice has the potential for serious environmental and health risks, such as the downstream generation of ammonia emissions from biosolids, which poses a threat to air quality and can cause respiratory issues, as well as contributing to nitrogen deposition. Therefore, land application can be classified as circular if *applied to croplands in an efficient manner considering the NP needs of crops, such that crop growth is enhanced and synthetic NP fertiliser requirements are reduced.* For example, WWTPs that use $FeCl_3$ dosing to enhance phosphorus removal produces a fraction of biosolids nutrients that are unavailable to the soil and are considered linear.

2.2.3. Carbon

Organic carbon (OC) plays a key role in wastewater treatment performance but is also critical in many resource recovery strategies. When completing GHG accounting of WWTPs, there is already an emphasis placed on understanding the emissions that occur due to fossil OC in the influent (Tseng et al., 2016). Therefore, a similar approach is followed when assigning circularity to OC flows. It is important to distinguish that biogenic carbon is absorbed and emitted by organic matter as part of the natural carbon cycle, whilst fossil carbon is created over very long timescales from dead organic matter, meaning its release disturbs the natural equilibrium which increases atmospheric concentrations. Thus, fossil carbon release causes environmental harm, substantiating its inclusion in GHG accounting protocols and classification as a linear action in this work.

2.2.3.1. Inflow circularity. OC classification is different to the NP definitions of circularity but aligns the methodology with GHG accounting principles, as this is a priority of many sustainability targets. Therefore, OC is defined as circular if it *contributes to the natural cycling of biogenic carbon*, whereas it is considered linear if it *contributes to the unnatural use of avoidable fossil carbon*. For domestic wastewater, approximately 94.5 % of influent OC is biogenic, and therefore circular, whilst the remaining 5.5 % is fossil and linear (Law et al., 2013). When applying the classification framework to define OC circularity, it is recommended to start by understanding influent carbon composition of the WWTP in question as fossil and biogenic fractions are variable, especially if the plant is treating a proportion of wastewater from industrial sources, before SFA is completed.

2.2.3.2. Outflow circularity. Determining the circular fraction of OC outflows requires SFA of this resource through WWTPs, to determine the quantity in each outflow as well as the fraction that is fossil carbon. Therefore, the first step is to collect data for quantifying the fraction of fossil carbon in each outflow stream, for example Table 6 summarises those for activated sludge plants (Law et al., 2013).

Then OC outflows are considered circular if there is *controlled release of biogenic carbon dioxide to the atmosphere or biogenic carbon to soil (for fertilisation or conditioning), or is utilised in products to extend the life of carbon in the human system, substituting the use of fossil resources*. This step requires the important distinction between types of carbon emissions, as only biogenic CO_2 released to the atmosphere can be considered circular as this contributes to natural carbon cycling, whereas fossil CO_2 or other GHGs do not. The difference in timescales of fossil and present-day biogenic carbon cycling must be considered to assess the circularity of biosolids application to land. Fossil fuel-derived CO_2 emissions release carbon that has been stored for millions of years, whereas biogenic feedstock consumption and CO_2 production is balanced by uptake during growth of new biomass on a timescale of years to decades. Therefore, biogenic carbon output as biosolids is considered circular. In contrast, the fossil carbon fraction in biosolids is considered linear, as it has been shown that only 35–60 % of carbon is retained in soils over 20 years (McLeod and Lake, 2021), with the rest lost to the atmosphere before fossil carbon stocks are replenished. Lastly, linear organic carbon outflows are defined as being *not effectively recovered for controlled release back to natural cycles, including fossil carbon dioxide or other powerful GHGs released to the atmosphere or fossil carbon to soil, with the potential to harm the environment*. This classification aligns with the wastewater sector's current carbon accounting rules (U.S. Environmental Protection Agency, 2011) and Table 7 summarises the characteristics of important OC outflows.

2.2.3.3. Additional considerations – outflows. Carbon emissions in effluent discharge do not have the same harmful eutrophic properties as nitrogen and phosphorus, but this represents a useful resource that is lost to the environment, has potential to be released as GHGs downstream, and the ability to negatively alter river carbon dynamics (Lee et al., 2023), meaning it is classified as linear. Additionally, a caveat is needed when biochar is generated and applied to soil, as this carbon has a turnover time of hundreds to thousands of years making both biogenic and fossil carbon fractions circular, as OC is adequately sequestered compared with conventional biosolids (McLeod and Lake, 2021). Lastly, for the case of advanced resource recovery, fossil carbon that is stored usefully within a product for the human system, replacing the need for fossil carbon extraction (such as paint production) would be considered circular using the definition of outflow circularity provided.

To conclude, it is not possible for all flows to be classified as fully linear or circular, for example there are losses during many circular recovery processes. Therefore, to collect data with a sufficient level of detail when applying the framework to real-world WWTPs it is critical to engage with local process operators and environmental scientists to understand downstream processing steps and environmental interactions.

2.3. Assessment

The development of process models is required for SFA and MFA of resources to complete the circularity characterisation approach described in Section 2.2, enabling the calculation of indicators for assessment of WWTP resource circularity. The circularity indicators selected cover the key areas of material inflows and outflows, water, energy, and economics, following a similar structure to the Circular Transition Indicator framework (wbcsd, 2022). Using the classification of Section 2.2 to assign circularity facilitates more standardised and robust analysis of key resources during the assessment, enabling the comparison of results across different wastewater systems (plant location, technology, or size). The selected resource flow indicators are summarised in Table 8.

Table 8 includes the circular inflow and outflow indicators, calculated using the scheme developed in Section 2.2, and the fraction of renewable resources as useful insights are provided when comparing results of these indicators. The removal efficiency of the treatment process is a common indicator of WWTP operational performance (von

Table 8

Indicators selected for resource flow analysis.

Category	Indicator	Equation
Materials	Circular inflow (as defined by classification approach) (%)	$\frac{\text{Mass Circular Inflow}}{\text{Total Mass of Inflow}}$
	Renewable recirculation outflow (%)	$\frac{\text{Mass Renewable Ouflow}}{\text{Total Mass of Outflow}}$
	Circular outflow (as defined by classification approach) (%)	$\frac{\text{Mass Circular Outflow}}{\text{Total Mass of Outflow}}$
	Total circular flow (%)	$\frac{\text{Circular Inflow} + \text{Circular Outflow}}{2}$
	Wastewater nutrient removal efficiency (%)	$1 - \frac{\text{Output Concentration}}{\text{Input Concentration}}$
Water	Water discharged in accordance with CE principles (%)	$\frac{\text{Volume of Circular Discharge}}{\text{Volume of Water Withdrawal}}$
	Water use from circular sources (%)	$\frac{\text{Volume Water Used from Circular Sources}}{\text{Volume of Water Required by the Process}}$
Energy	Energy consumed from renewable sources (%)	$\frac{\text{Renewable Energy Consumption}}{\text{Total Energy Consumption}}$
Value	Circular material productivity (€/kg)	$\frac{\text{Total Revenue}}{\text{Mass of Linear Inflow}}$
	Value-based resource efficiency (€/€)	$\frac{\text{Gross Output} - \text{Personnel and Service Costs}}{\text{Input Energy and Material Value}} - 1$
	Product value per mass (€/kg)	$\frac{\text{Product Revenue}}{\text{Mass of Virgin Resources}}$

Sperling et al., 2020), as the most important result is the treatment of wastewater to a satisfactory standard. The Value-based Resource Efficiency (VRE) shows the economic efficiency of the WWTP (Di Maio et al., 2017), revealing how the gross output (revenue) compares to the cost of energy and materials. The product value per mass indicator is included as the recovery of high value products from wastewater will become more popular, enabling the impacts to revenue streams to be understood and analysis of product revenue separately from service fees. However, in conventional WWTPs this will often be zero as there is little market for the low value resources recovered, such as biosolids. This indicator is useful in cases when comparing alternate resource recovery technologies or strategies to determine the economic efficiency of value-added product generation.

To interpret assessment outcomes, a combination of Sankey diagrams and indicator results from Table 8 are then used to complete hotspot analysis of the WWTP. Sankey diagrams visualise the results of MFA, showing the viewer both the pathway and magnitude of resource flows in the system, as the width of each stream is proportional to its magnitude (Renfrew et al., 2022). Indicator results build upon this, showing how the size and destination of these streams impact the circularity of resource flows in the WWTP. The same analysis must then be applied for the investigation of potential scenarios that alter the circularity of WWTP resource flows, validating how any decision maker actions will impact the upstream and downstream, or for comparing alternate systems to identify better practices in terms of circularity (Section 3).

3. Results

This section demonstrates implementation of the classification approach developed in Section 2 to assess a conventional WWTP. Potential scenarios impacting process upstream and downstream are utilised to elucidate how the approach can be used for evidence-based decision making considering the actions of water users.

3.1. System definition

A centralised conventional activated sludge WWTP at a scale of 270,000 population equivalents, with an average load of 12,000 m^3/d, in Estiviel, Spain was selected for the assessment (Rodríguez-Chueca et al., 2019). This is a common treatment process across Europe so is an interesting case to test the capabilities of the resource classification approach.

3.2. System boundaries

The WWTP is assumed to operate with conventional pretreatment to remove grit, screenings, and FOG, followed by primary clarification. From the effluent quality quoted in literature (Rodríguez-Chueca et al., 2019), it was assumed secondary treatment consists of aerobic and anoxic zones to facilitate nitrification–denitrification, with ferric dosing to chemically remove phosphorus. Primary and waste activated sludge (WAS) are stabilised using anaerobic digestion (AD) with the generated biogas utilised for energy recovery to heat digesters and supply electricity to the plant. System boundaries are drawn from when wastewater leaves the water user and flows into the WWTP (meaning the impacts of leakages are considered), until wastewater effluent is discharged from the plant and biosolids are applied to land as shown in Fig. 2.

3.3. System modelling

A model of the WWTP was constructed for the physical, chemical, and biological treatment units using parameters taken from literature provided in Tables S1–S4 of the Supplementary Material, enabling MFA for each wastewater resource to be completed. Influent and effluent loadings were taken from literature describing a WWTP of this scale located in Estiviel, Spain (Rodríguez-Chueca et al., 2019).

3.4. Resource flow characterisation

The circularity assessment was completed using the tables and definitions from Section 2.2 to characterise the water, nitrogen, phosphorus, and carbon resource flows. A summary is provided throughout Tables S5–S8 in the Supplementary Material. Combining MFA results with the assigned circular properties enables the calculation of assessment indicators in Table 8.

3.4.1. Scenario investigation

As stated previously, one of the main goals of this approach is to support CE policy by investigating the impacts of water user behaviour and upstream decisions on WWTP circularity and the downstream environment. Therefore, once MFA and resource classification has been completed, assessors should use this information combined with water related policy (UWWTD) or regional goals (CE Action Plan) to create alternate scenarios for quantifying potential changes to WWTP circularity. To reveal the value of the resource classification approach, targeted scenarios impacting WWTP inlet and outlet have been created to reflect plausible real-world changes to the system that influence process upstream and downstream circularity:

1. A company starts operating in the municipality, producing an additional 400 m^3/d of wastewater for treatment containing 1000 mgC/l of fossil carbon.
2. Due to local farmers changing fertiliser application practices and more intensive rainfall due to climate change, runoff from local farmland entering the sewage system increases NP concentration by an average of 5 %.
3. A local campaign in the region has raised consumer awareness regarding the negative environmental impacts of dishwashing and washing machine detergents, reducing consumption by 50 %.

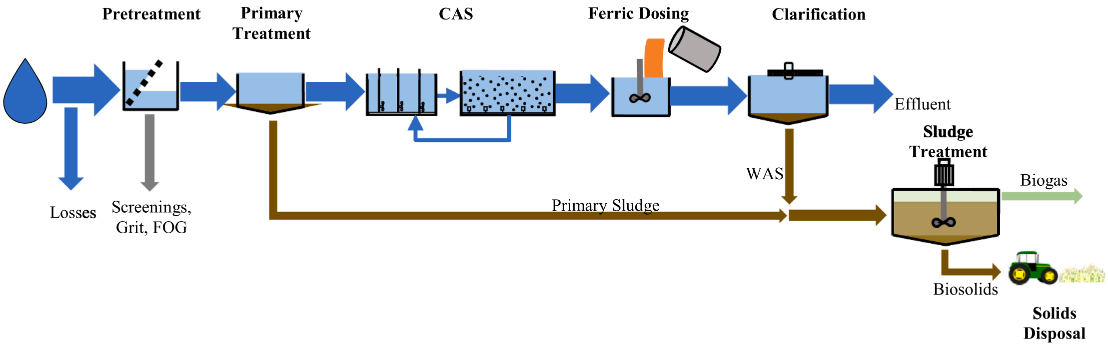

Fig. 2. Process stages of the WWTP.

4. The local water utility decides to invest in biogas upgrading for biomethane production to directly inject it into the grid, generating additional revenue and excess CO_2 as a by-product.
5. Improved nutrient management plans from EC regulation result in a 50 % reduction of synthetic fertiliser use by local farmers, with demand matched by an increase in organic fertilisers application.

3.5. Assessment

3.5.1. Material flow analysis

Fig. 3 provides the Sankey diagram for water (3A) and nutrients (3B) flowing through the WWTP, revealing the circular and linear resources in the system.

The MFA is usually applied for identifying hotspots in terms of material losses, but further insights can be found by integrating the classification approach for use as a tool to highlight which resource flows must be targeted to improve WWTP circularity. Fig. 3A shows that the majority of water resources are lost to the environment as effluent discharge, however, UWWTD requirements are met and effluent is below the critical load of the receiving water body, so this can be considered a regenerative and therefore circular action. Still a significant proportion of influent water is lost during collection (from user to WWTP), warranting further investigation into leakage reduction measures as this would result in the greatest benefits to water circularity. The water in biosolids is seen as a loss of resources, as in its current form the water balance of the soil is not improved. By diluting biosolids this could be reversed to reduce water abstraction for irrigation and be seen as a circular water flow, however, this must be considered against potential impacts such as additional transportation.

The impacts of losses during wastewater collection are also shown for nutrient resources in Fig. 3B, therefore, investments in leakage reduction would be of benefit for improving overall process circularity. There is also a large loss of carbon from FOG removal during pretreatment, which could be overcome by adding this resource to AD units to improve WWTP circularity. Additionally, there are losses of nitrogen and carbon gaseous emissions to the atmosphere in a harmful manner, meaning better WWTP control is needed to reduce N_2O production, as well as strategies to reduce inlet fossil carbon and investments in technology to sequester these emissions. There is also a significant fraction of N_2 emissions from secondary treatment (41.6 % of total resources directly emitted) that have a 'neutral' classification, evidencing that a high proportion of nutrient inflow comes from synthetic nitrogen sources. Lastly, it is shown that a fraction of biosolids nutrients are linear as they are unavailable to the soil due to the use of chemical phosphorus removal, meaning a biological treatment process that removes phosphorus is needed improve resource circularity.

Ultimately, MFA quantified that only approximately 75 % and 50 % of water and nutrients resource outflows are circular in the assessed

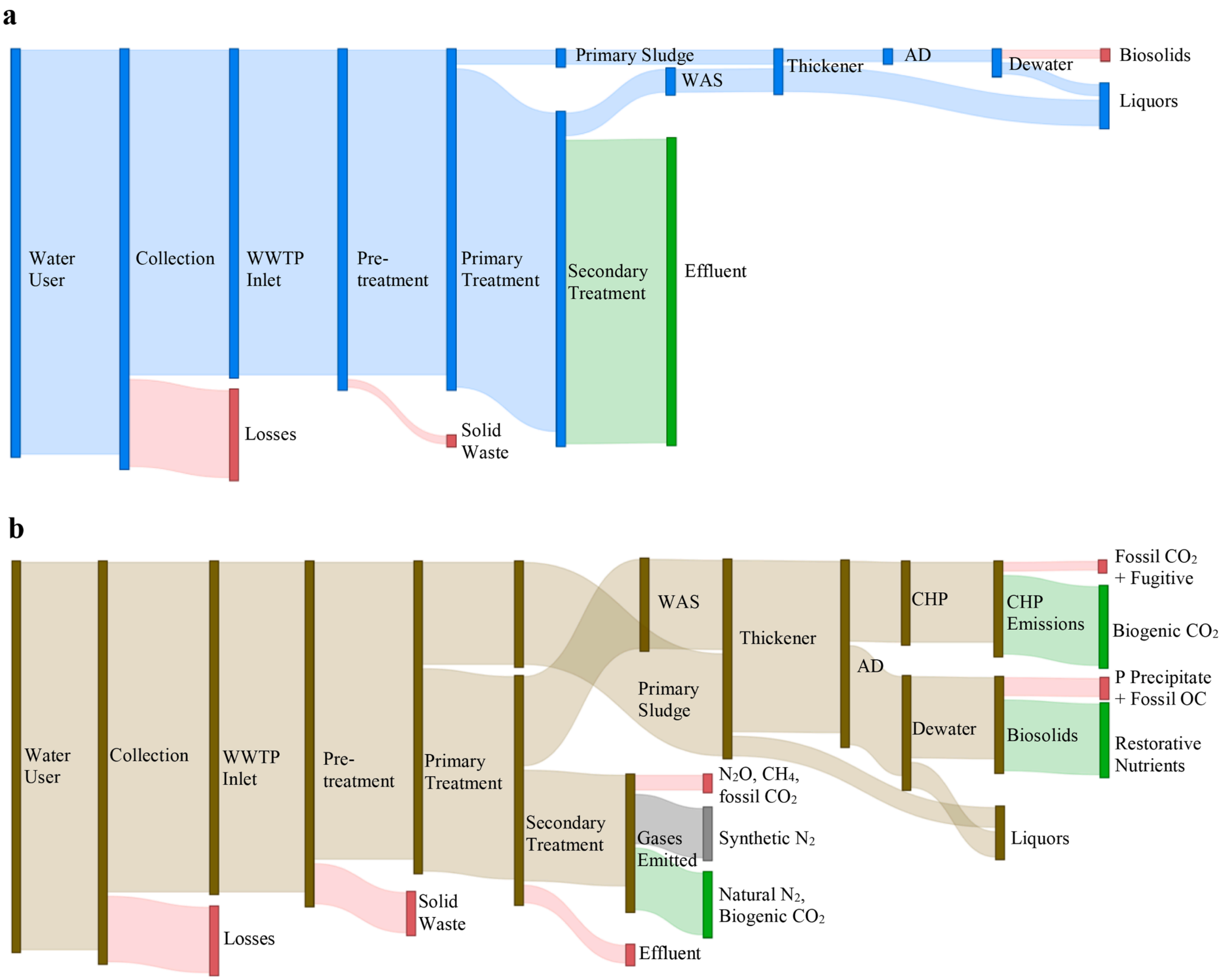

Fig. 3. MFA of the WWTP system with circular flows in green and linear flows in red for a; water resources b; nutrient resources.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

WWTP respectively, showing there is still significant scope for improvement. It also highlights the importance of boundary selection during the assessment, as here the collection losses are considered before WWTP inlet, limiting outflow circularity indicators, as 20 % of all resources are lost from the system, emphasising the impacts of leakage on circularity. However, decision makers may wish to define boundaries of the WWTP itself to investigate the circularity of process operation only.

3.5.2. Resource flow indicators

Fig. 4 provides the resource flow indicator results for material inflows and outflows. Using the classification framework, indicator results provide more detailed resource analysis than MFA alone or using the alterative definitions of circularity from literature. Fig. 4A shows outflow renewability and circularity are equal for phosphorus (42.2 %), as renewability is taken to be the material safely returned to soil for nutrient cycling. As biosolids are the only product containing phosphorus generated by the process (only other outflow is the effluent), renewability is also equal to the quantity circular resource outflows. This poor performance is related to the phosphate compound generated during chemical phosphorus removal, meaning that 43.8 % of biosolids phosphorus is unavailable to the soil. The production of N_2 emissions sourced from natural nitrogen cycling during secondary treatment is a circular outflow, thus it can be added to biosolids nitrogen, so outflow circularity reaches 29.3 % compared with renewability of 11.4 %. Outflow circularity is low for nitrogen, as 53.8 % of resources leaving the system is N_2 produced during nitrification–denitrification, which is neutral in terms of circularity and should be targeted by decision-makers. For carbon outflows, there is a large difference between renewability (25.8 %) and circularity (64.2 %), as the biogenic CO_2 produced during secondary treatment and biogas combustion are considered circular outflows, whilst the remaining linear fraction is from fossil CO_2 and methane emissions generated during secondary treatment, AD, and biogas combustion. Therefore, biogenic gaseous emissions make up a larger proportion of circular carbon outflows than those applied as biosolids to land for soil restoration.

Fig. 4B highlights that phosphorus is the resource with the lowest inlet circularity (40.0 %), meaning it should be prioritised for enhancement by changing water user habits, especially as it is the most finite and critical resource of those analysed. This is also evidenced in Fig. 4C, as phosphorus is the lowest performing resource for overall circularity (41.1 %). However, nitrogen's total circularity of 61.5 % shows inconsistency between its inflow and outflow performance, as it achieves the lowest outflow renewability and circularity ratings of the nutrients analysed, so these resource flows have the largest potential for improvement. Lastly, WWTP operational performance is assessed in Fig. 4D, which confirms that it performs well at removing all nutrient resources from wastewater (>90 %). Therefore, gaseous and solid outflows should be prioritised to see the most significant improvements to outflow circularity.

Table 9 summarises the results for water, energy, and economic resource flow indicators. The circular discharge indicator shows the fraction of wastewater effluent that is discharged within permit limits and recharges water sources, with the remaining water fraction coming from wastewater collection losses and solids production (pretreatment and biosolids), again highlighting the need to reduce leakages to improve circularity. The renewable energy fraction shows the WWTP performs well, however this comes from energy recovery from biogas combustion and the fact that 67 % of Spain's electricity is already generated from renewable sources (IEA, 2021). Therefore, the energy recovery system only results in a 20 % gain of renewables consumption, meaning higher value recovery strategies should be investigated. Material productivity reveals WWTP economic efficiency in terms of linear resource consumption, as gate fees (revenues) are relatively fixed so the linear fractions of wastewater inlets or virgin material consumption (polyelectrolyte or ferric chloride) should be mitigated to see the largest benefit to this indicator. Similarly, the VRE shows the WWTP operates in an economically favourable manner, but revenue is stationary so OPEX must be targeted by reducing material or energy consumption to leverage significant improvements. Lastly, circular water use and value

Table 9
Water, energy, and economic resource flow indicator results.

Water	
Circular discharge	78.8 %
Water use from circular sources	0 %
Energy	
Renewable fraction	86.8 %
Economic	
Material productivity (€/kg)	4.8
VRE (€/€)	2.7
Value per mass (€/kg)	0

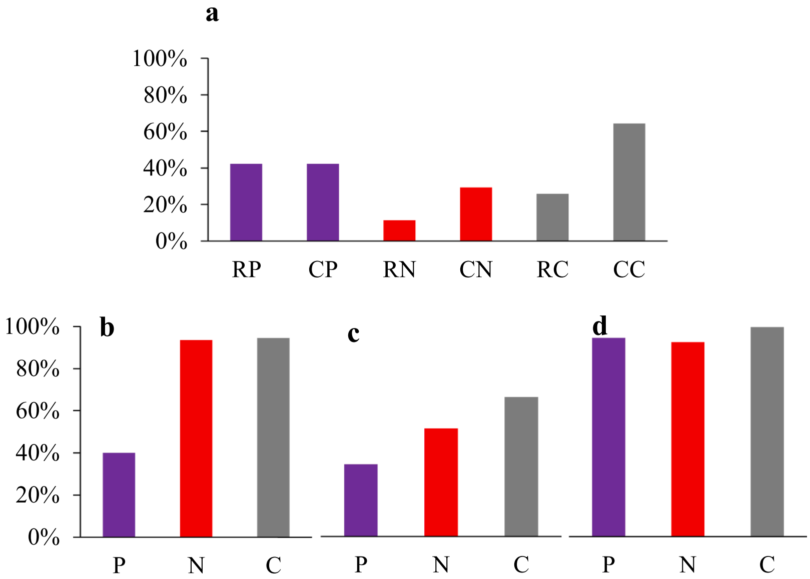

Fig. 4. a; Renewable (R) and circular (C) outflow, b; circular inflow, c; total circularity, and d; WWTP removal efficiency indicator results for carbon, nitrogen, and phosphorus nutrients.

per mass are zero, as it is assumed this municipality utilises water abstracted from virgin sources and the WWTP does not generate revenue from product sales respectively, emphasising aspects that are easily exploitable to see circularity enhancements.

3.5.3. Scenario investigation

Now considering the scenarios posed in Section 3.4 and outcomes in Table 10, the value of the classification framework is clear as it enables impacts of changing water user habits (at regulatory, regional, or human scales) to be quantified in terms of circularity, by connecting upstream and downstream impacts. A summary of the material indicator results for all scenarios investigated is provided in Table S9 of the Supplementary Material.

Scenario 1

An additional 400 kg/d of non-renewable, fossil carbon discharged to wastewater from upstream production not only increases the linear influent fraction by 16.0 % but also reduces outflow circularity by 10.6 %. The reduction in outflow circularity is due to the significant increase of fossil CO_2 emissions production during secondary treatment and biogas combustion, and large quantities of fossil carbon in biosolids (four times greater). However, the additional fossil carbon inlet also increases nitrogen outflow circularity by 0.4 %, due to enhanced biomass production, reducing the emissions generated during secondary treatment required to achieve the same effluent quality. This quantifies both the direct impacts of the company on municipal wastewater and indirect impacts of their practices on the environment downstream, providing decision makers with the knowledge to lobby them to reduce wastewater production, pay greater fees for remediation, or utilise biogenic carbon sources.

Scenario 2

The effects of poor farming practice that results in greater runoff are quantified in terms of reducing inflow circularity of nitrogen and phosphorus by 4.5 % and 2 % respectively. Although the WWTP is modelled so that effluent quality remains the same, the principle of traceability is used to directly show the impacts on the wider process. Outflow phosphorus circularity reduces by 1.3 % as a greater quantity of ferric chloride is needed to maintain the desired effluent quality, meaning that the proportion of biologically unavailable phosphorus in biosolids increases by 10.6 %. These results are useful to educate both local governments and farmers to highlight the negative impacts of their choices, and change either regulation or behaviour through incentivising good or penalising poor practice.

Scenario 3

As the public become more environmentally conscientious, it could lead to changes in water use habits such as reduction in washing detergent use. These stakeholders will be aware that reducing material consumption has benefits, but now they can be educated upon the downstream consequences of this on wastewater circularity. It was shown that a reduction of 50 % improves the circularity of influent phosphorus by 5.2 %. However, phosphorus outflow circularity decreases by 1.2 % as the same effluent quality is maintained using chemical removal processes, reducing the quantity of biosolids phosphorus by 13.5 %. This emphasises the potential benefits of biological removal to simultaneously improve the circularity of wastewater effluent and biosolids, as in this case reducing ferric chloride dosage would have no impact on circularity as this action would only increase the quantity of effluent phosphorus.

Table 10
Impacts to resource circularity when WWTP is subjected to potential scenarios.

Scenario	Circularity impacts	
	Description	Quantitative change
1	Linear inflow of carbon increases	5.5 % to 21.5 %
	Circular outflow of carbon decreases	64.2 % to 53.6 %
	Fossil CO_2 emissions increase	by 370 %
	Total effluent carbon increases	by 33 %
2	Linear inflow of N increases	6.4 % to 10.9 %
	Linear inflow of P increases	60 % to 62 %
	Circular outflow of P decreases	42.2 % to 40.9 %
	Unavailable biosolids P increases	by 10.6 %
3	Circular inflow of P increases	40 % to 45.2 %
	Circular outflow of P decreases	42.2 % to 41.0 %
	Biosolids P decreases	by 13.5 %
4	Circular outflow of carbon increases	64.2 % to 64.6 %
5	Circular outflow of N increases	29.3 % to 49.4 %
	Total circular flow of N increases	61.5 % to 71.5 %

Scenario 4

Upgrading biogas to biomethane generates a higher value product and useful by-product, which are positive actions when viewed through a CE lens. However, this scenario actually produced few benefits in terms of resource circularity, only increasing carbon outflow circularity by 0.4 % as biogas created from fossil carbon was not combusted and released to the atmosphere, and fugitive emissions are still generated. Therefore, in cases such as these, wider assessments of the process are needed to justify investment decisions, including economic analysis as biomethane prices range from 26 to 78 €/MWh (Legrand et al., 2022) and environmental assessments to investigate changes to air quality and emissions production in the local area.

Scenario 5

Improving the management of wastewater nutrients is a priority of the proposal to update the UWWTD and CE Action Plan (European Commission, 2022), meaning it is important that assessment methods can account for these changes. Subsequently, reducing synthetic fertiliser usage by 50 % resulted in an increase of nitrogen outflow circularity by 20.1 % as these N_2 emissions, previously considered neutral, now receive a circular classification. Emitting this form of N_2 is seen as a regenerative action for the natural cycling of nitrogen, which increases from 29 % to 61.5 % of N_2 in this scenario. This increases nitrogen total circularity by 10.0 %, highlighting the benefits in terms of WWTP circularity resulting from regenerative emissions production. Therefore, the classification approach is able to investigate how nutrient utilisation in a specific geographical area meets new regulatory goals and targets, by monitoring the circularity performance of its WWTPs.

It is worth noting that although these results are useful for decision makers to understand the circularity of resource flows, wider assessments are needed to prioritise actions that will result in the greatest benefits or mitigation of impacts. For example, Fig. 4A highlights that nitrogen outflows are a large hotspot that should be improved, however, this could result in other impacts such as increased energy consumption, meaning it is economically or environmentally unfavourable. Therefore, the classification approach should act as the basis for the holistic assessment of wastewater systems, linking how physical changes to resource flow circularity impacts the sustainable value generated for stakeholders.

4. Discussion

4.1. Resource flow characterisation

Using the definitions of waste circularity described in Section 1 results in the overinflation of waste treatment process circularity performance, with little variation between systems, meaning the utility of CE assessments is limited for decision making. For example, a treatment plant that accepts mishandled, preventable, or contaminated waste, and sends it to landfill, would achieve an overall circularity of 50 %. When compared to an economic system that minimises waste production and applies circular principles to cascade resource use and extend its life, and sends 50 % to both landfill and recycling, only to gain 25 % in overall circularity, even though it is applying CE principles in the upstream and downstream, it emphasises current circularity assessment issues. The classification framework presented in this work enables the circularity of each wastewater resource to be scrutinised, resulting in more robust and detailed circularity analysis to enhance decision making capabilities from WWTP circularity assessments.

4.2. *Carbon emissions*

The decision to award particular resources a circular status may be subject to debate, one of those being biogenic CO_2. A circular classification was given as this is in line with the EPA's current carbon accounting protocol, as it is reasoned that biogenic CO_2 emissions have no net atmospheric impact, so biogenic processes sequester CO_2 during feedstock production equivalent to the direct biogenic CO_2 emissions from a stationary source such as waste management. Therefore, the chosen classification aligns with the common assumption that biogenic carbon emissions are carbon neutral (Navare et al., 2021). However, the European Chemical Industry Council (Cefic, 2022) argues that this justification does not incentivise the use of bio-based materials and suggests that carbon removal credits should be assigned when biomass is produced and penalise all CO_2 emissions, whether biogenic or fossil when released back to the atmosphere. Therefore, the classification of biogenic carbon developed here is not able to explicitly conclude whether climate neutrality is achieved, as this must consider time-dependent fluxes of carbon to verify that the production rate is lower than sequestration (Navare et al., 2021). Development of this approach for carbon accounting would enable more transparent analysis, remove the issues with assessment timelines, and avoid double counting of carbon credits.

This also highlights a larger issue with the current carbon accounting procedures of WWTPs, as influent carbon is usually assumed to be biogenic and ignores fossil carbon during assessments (Maktabifard et al., 2023). This is corroborated by the 2019 IPCC refinement, which encourages countries to evaluate these emissions during GHG inventory development and stating that 4–14 % of WWTP influent carbon is fossil (Doorn et al., 2019). However, this has not been followed as there is no standardised method for quantifying fossil carbon in WWTP outflows (IWA, 2023). The WWTP assessment example in this work showed the large impact that fossil carbon can have on circularity using this classification. Therefore, a similar approach, utilising resource traceability, could be implemented as the omission of potentially significant fossil carbon WWTP emissions puts the net-zero and carbon neutrality ambitions of the water sector at risk.

4.3. *Local considerations*

Another issue with the resource classification examples provided is that the fractionation was completed using values from literature. The composition of wastewater will change with geography depending on the local water users, whereas leakage and amount of water lost is impacted by local water infrastructure. Similarly, regulatory limits and the preferred method of wastewater treatment of a region will impact resource outflow concentration, production rates, and destination. Therefore, when a technology is being investigated for implementation in a real-world process, it is recommended to conduct a study to quantify missing information, such as the sources of wastewater nutrients and fraction of water loss. For better understanding of resource outflows, wastewater process operators should be consulted to validate the concentration and production rates of gaseous emissions, effluents, and waste streams. There are also several sources that detail how to test the fossil fraction of OC along each stage of a WWTP (Law et al., 2013; Tseng et al., 2016). This ensures that local factors are incorporated to accurately calculate circularity indicators when investigating the selection of technologies for integration within real-world processes.

4.4. *Resource recovery prioritisation*

This framework aims to enhance the circularity of wastewater processes, with a key aspect of this transition being resource recovery. Examples could not be provided for all potential resource recovery scenarios, so in the cases where certain resources or destinations are not covered in Tables 1–7, the definitions provided should be used for classification. Authors are aware that the definitions taken for some nutrient classifications may induce favourable resource flow indicator results for activities that may be perceived as 'less circular'. For example, in the framework provided, certain N_2 fractions and biogenic CO_2 emissions are classified as circular, which could result in greater circular outflows for a process employing nitrification–denitrification, than one investigating advanced nutrient recovery (due to process inefficiency losses). However, prioritisation of different wastewater solutions is case specific, for instance in many areas upgrading WWTPs with BNR secondary treatment will result in a more sustainable process, compared to some traditional or conventional processes. On the other hand, employing resource recovery technologies might result in additional wider benefits for stakeholders and therefore greater added value. To quantify the benefits of these value creating actions, alternative sustainability indicators are required, for example, eco-efficiency and LCA impact indicators can be selected to quantify changes in economic and environmental performance (Smol and Koneczna, 2021).

4.5. *Future work*

The results in Section 3.5 highlight the advantages of the classification approach for investigating the circularity of WWTP systems, showing how it can be implemented to standardise wastewater resource assessments. However, when applied to a single conventional process the usefulness of results for decision making is limited, such as in Scenario 4. Benchmarks should be used to unlock another type of decision making for optimal technology selection, which in that case include comparisons with appropriate technologies. Effort is needed to expand the scope of the assessment beyond just resource flow analysis, by incorporating wider sustainability analysis to quantify the sustainable environmental, social, and economic value of novel technologies facilitating investments in technologies that alter the circularity of physical resource flows, with maximum benefits for stakeholders. Additionally, this should consider the potential for accumulation of hazardous substances in recovered products, as well as the impacts to environmental and human health, using appropriate risk assessments for wastewater resource cycling. This holistic standardised assessment would act as the basis for transforming the water sector towards a CE, enabling multiple levels of decision-making including technology selection and subsequent process operation following implementation.

5. Conclusions

The attention given to the CE concept by industry in recent years has resulted in it becoming integrated within environmental policy. The vagueness and uncontroversial nature that resulted in its popularity has led to ambiguity that is now hindering the CE transition, signified by the lack of universal definitions and metrics needed for evidence-based decision making. The importance of water for the functioning of modern society and the potential to recover value from wastewater means this resource must be carefully managed to realise a fully CE. However, the provision of WWTP service is completely dictated by upstream water user habits, leading to water asymmetry, as upstream users are mostly unaware or unimpacted by their own usage. This creates many problems for water utilities but it is difficult to pass responsibility on to water users, and current definitions of waste streams lead to a paradox during WWTP circularity assessment, limiting decision making capabilities. Therefore, a classification approach was developed that uses the CE principle of traceability for water, carbon, nitrogen, and phosphorus, including definitions, example tables, and assessment indicators. It is hoped this can be used to assign responsibility to water users for the development of common and consistent policy and regulatory frameworks, which up until now have been developed in isolation to satisfy the goals of individual sectors, and focus on only promoting circularity rather than obstructing linear actions.

This was evidenced by applying the framework to a conventional WWTP and then investigating five potential scenarios that decision makers could face in the future. It showed that applying the classification approach can reveal how changes in agricultural, industrial, or human practices influences circularity, by connecting upstream actions and downstream impacts to the environment. Industrial actions increasing fossil carbon concentration (400 m^3/d effluent at 1000 mgC/l) reduced inflow and outflow circularity by 16 % and 10.6 % respectively, as secondary and sludge treatment fossil emissions increase significantly. Additionally, changes to human habits reducing detergent use by 50 % improved phosphorus inflow circularity by 5.2 % and better agricultural practices reducing synthetic fertiliser usage by 50 % increased nitrogen outflow circularity by 20.1 %. This can act as the basis for educating water users or creating policy to penalise water use that conflicts with CE principles. Future work must expand the assessment to include wider impacts to social, economic, and environmental aspects, to connect how circular resource flows result in sustainable value creation for stakeholders.

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

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