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CHAPTER

7

Circularity and efficiency assessment of resource recovery solutions

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7.1 Introduction

The water sector provides essential services for maintaining human and environmental health. Clean drinking water and sanitation are indispensable for a healthy human society. While great progress has been made to expand access to improved drinking water and sanitation yet, about 27% of the global population still lack access to safely managed drinking water and approximately 43% lack access to safely managed sanitation services (UNICEF, JMP, & WHO, 2022). Thus, these basic services need to be extended to a growing global population. On the other hand, numerous studies show that the high intensity of resource consumption by the water sector is unsustainable. Globally, the wastewater treatment plants (WWTPs) have been shown to have a net negative environmental impact due to the high energy and chemical inputs (Hao et al., 2019). For example, WWTPs were found to be responsible for nearly 1% of the total electricity consumption of European cities (Maktabifard, Zaborowska, & Makinia, 2018). Accordingly, the water sector needs to become more resource efficient. Simultaneously, the urban water cycle is a source of valuable resources that remain untapped (Van Der Hoek, De Fooij, & Struker, 2016). Recovering the resources can reduce our reliance on virgin extraction that is environmentally damaging. Resource recovery can thus not only reduce the resource use intensity of the water sector but also benefit other sectors.

As resource recovery solutions continue to develop in the water sector, some important decisions have to be taken. These relate to the resources for recovery, the technology to be used, and the application of the recovered resources. Also, numerous criteria such as circularity, energy, and economic efficiencies need to be accounted for. Thus, methods are required to assess and compare the circularity and efficiency improvements achieved by different resource recovery solutions; a method of assessment is required.

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The methods presented in this chapter have been developed for resource recovery solutions in the water sector and tested on case studies in Europe and Africa. The case studies were in Norway, the Netherlands, the Czech Republic, Italy, and Ghana. The resource recovery solutions included using treated wastewater (TW) for irrigation, recovering resources such as cellulose and calcite to manufacture biocomposites, phosphorus recovery as struvite, biogas production, sewage sludge-based organic fertilizers, and biochar.

The system boundary includes the recovery of resources from a waste/drinking water treatment plant as well as the application process of the recovered resource. The former constitutes the resource recovery (RR) phase, and the latter is included in the resource application (RA) phase. To illustrate this, say sewage sludge is recovered from a WWTP, anaerobically digested at the WWTP, and applied to agricultural soil. While the WWTP and the anaerobic digestion constitute the RR phase, the soil application belongs to the RA phase.

7.2 Circularity assessment

7.2.1 Definitions and assessment methodology

The circular bioeconomy refers to the emphasis on producing renewable biological resources and reducing their wastage by converting the waste streams into products such as feed, fuel for energy, and bio-based products (Carus & Dammer, 2018). In contrast, the circular economy (CE) is defined as a concept for a restorative and regenerative economic system (Ellen MacArthur Foundation, 2019). Within the CE concept, the technical and biological cycles are treated differently. The technical cycle consists of resources that cannot freely enter the biosphere and thus must be circulated within the economy to extract maximum value (Ellen MacArthur Foundation, 2019; Navare, Muys, Vrancken, & Van Acker, 2021). In contrast, the biological cycle contains resources that can safely cycle in and out of the biosphere since these resources flow in natural biogeochemical cycles (Navare et al., 2021).

Resources flow in these cycles between different industrial and biological processes. To illustrate, nitrogen (N) from the atmosphere is obtained using an industrial process and gets used in the manufacture of fertilizers. These are used in agriculture to produce crops that are consumed by people. The N atoms present in the crops are partly used in the human body for building/maintaining cells and partly excreted, ending up in a wastewater treatment process.

The above-illustrated resource flows can be characterized as restorative, regenerative, or linear. Restorative flows refer to those resource flows that originate from reused or recycled sources and/or get reused or recycled at the end of their use phase (Ellen MacArthur Foundation, 2019). Regenerative flows return the biotic resources to their natural sources such that they remain biologically accessible and the production capacity of the natural source is maintained (Ellen MacArthur Foundation, 2019). Lastly, linear flows originate from virgin sources and terminate in landfills or at energy recovery facilities. The circular economy aims to reduce linear flows and maximize restorative and regenerative flows. Thus, to measure the progress towards the CE achieved through a resource recovery solution, the proportion of all the resource flows that are restorative and/or regenerative must be assessed. The circularity assessment method proposed here is based on the material circularity indicator (MCI) approach developed by the Ellen MacArthur Foundation (2019).

Resource recovery solutions in the water sector often involve a combination of technical and biological cycles. The original MCI method was developed for the technical cycle resources and later extended to include biological resources. Yet, direct application of the original MCI method to water-related resource recovery solutions is not possible because of the restricted way in which linear and restorative flows have been defined. To illustrate this point, we take the example of N recovery from wastewater and its application to agriculture. Use of N fertilizers in agriculture can result in flows such as nitrate leaching, which effectively translates to the loss of the nutrient. Although N does not end up in landfills or energy recovery processes, the leaching of nitrate is a form of linear flow since the resource is lost for all practical purposes. A similar argument can be used for water and other (waste) water-related resources such as P. Since the circular bioeconomy is centered around the renewable resources that mostly flow in the biogeochemical cycles, the definitions of linear and restorative flows need to be extended to also account for such resources. These definitions are presented below.

A Restorative flow is that which recovers a resource for direct human use (e.g., recovery of the struvite fertilizer out of wastewater through precipitation).

A Regenerative flow is that which returns a resource to the state in which it was originally appropriated from nature for human use. This is to promote the self-renewal and ecosystem-sustaining capacity of biogeochemical cycles in response to overexploitation (e.g., releasing reactive nitrogen as N_2 into the atmosphere to close the nitrogen cycle).

A Linear flow is that which is obtained from virgin sources and/or discarded in a form different from how the resource was originally obtained for human use (e.g., returning water obtained from a river as water vapor to the atmosphere).

7.2.2 Generalized classification of recovered resources

The way efficiency is calculated and interpreted depends on the type of resource considered (Huysman et al., 2015). A wide variety of resources may be recovered from the water sector. Defining restorative/regenerative and linear flows for each of them is impractical. Therefore, we classify the resource most commonly recovered in the water sector into four categories presented below.

7.2.2.1 Abiotic or mixed materials

This category includes resources that originate from nonliving matter such as metals, minerals, synthetic materials, or from fossilized organic matter such as fossil fuels. A resource falling in this category is characterized by a finite stock and nonrenewability. For resources belonging to this category, restorative and linear flows are defined as in the original MCI method. Thus, flows that originate from virgin extraction that end up in landfills or energy recovery processes constitute linear flows. Flows that originate from reused or recycled sources and end up being reused or recycled after use constitute restorative flows.

7.2.2.2 Biotic materials

These resources originate from living organisms, for example, aquatic plants and biological sludge. The appropriation rate of such resources refers to the quantity of the resource collected for human use in a year. Regeneration rate is the time rate of production of the biotic resource. The regeneration rate relates the growth of the resources with their stock (Klaassen & Opschoor, 1991). Biotic resources are inherently considered renewable if their appropriation rates are maintained lower than their regeneration rates. Therefore, linear flows for biotic materials can be defined as flows that have their appropriation rate greater than the regeneration rate and that end up in landfills or energy recovery processes. For biotic resources, the possibility of composting must be included while defining restorative flows. Thus, restorative flows are those that have an appropriation rate smaller than the regeneration rate and that are reused, recycled, or composted after use.

7.2.2.3 Nutrients

This category mainly includes nitrogen (N) and phosphorous (P), which are commonly found nutrients in domestic wastewater. Atmospheric N is fixed in reactive forms through natural and artificial processes. Of the artificial processes, the Haber-Bosch process is the most widely used (Cherkasov, Ibhadon, & Fitzpatrick, 2015). N fixed through this process accounts for the doubling of the total N fixed in the last century (Schlesinger & Bernhardt, 2020). N waste can be attributed mainly to the losses in the form of ammonia volatilization, ammonia discharge into the aquatic environment, denitrification, runoff, nitrate leaching, and nitrogen oxide emissions (NO_x, N_2O) (Raun & Johnson, 1999; Slootweg, 2020; Zhu & Chen, 2002). While denitrification of N oxides to N_2 is also a form of industrial emission, it is largely free from adverse implications (Li, Clough, Moinet, & Whitehead, 2021). Therefore, N_2 emissions are here considered a form of regenerative flow. To define regenerative and linear flows of nutrients, we make use of their biogeochemical cycles. For N, we developed a simple reservoir model as shown in Fig. 7.1.

We define linear flows of N as those originating from the industrial conversion of unreactive N_2 to reactive N species, predominantly through the Haber-Bosch process, and ending up as reactive N emissions to air or water. In contrast, regenerative flows are those that originate from reuse or recycled sources and end up as biomass accumulation, soil fixation, or unreactive emissions.

For P, the primary source is phosphate rocks (Smol, 2019). The transportation of P by flowing water to the ocean through the weathering of phosphate-containing rocks is the largest flux of P in the ecosystem (Schlesinger & Bernhardt, 2020). The P in ocean water eventually gets sedimented on the ocean floor. Over several millions of years, these sediments are uplifted and again subjected to weathering, thus completing the P cycle (Schlesinger & Bernhardt, 2020). Since this process takes millions of years to renew the P stocks back into the forms that can be mined, P is not renewed on a time scale relevant to humans and is therefore a nonrenewable resource. Moreover, P is unsubstitutable for crop fertilization but can be reused repeatedly, yet large

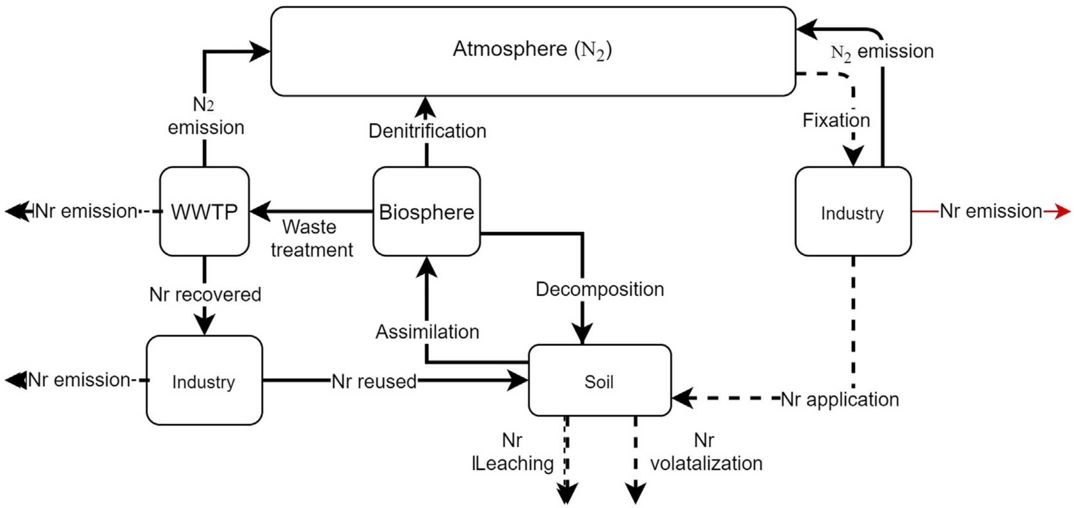


FIGURE 7.1 Schematic representation of the nitrogen cycle. The dotted arrows represent linear flows; the solid arrows denote restorative flows.

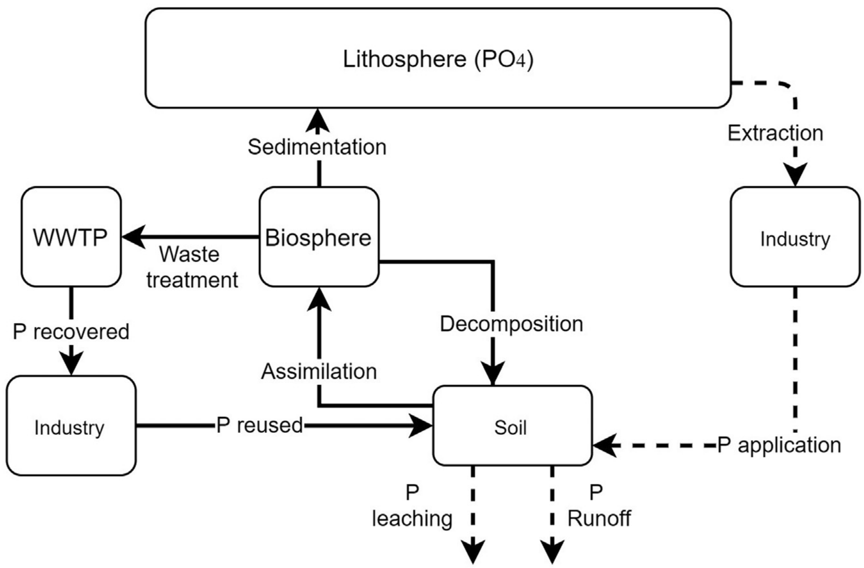


FIGURE 7.2 Schematic representation of the phosphorus cycle. The dotted arrows represent linear flows; solid arrows denote restorative flows.

dissipations of P into low-grade ores, manure, surface water, groundwater, and the oceans can be found (Withers et al., 2015).

The linear flows for P are defined as those that originate from phosphate rocks (or other virgin sources) and that end up dissipated in surface water, groundwater, rivers, or oceans.

Regenerative flows are those that originate from reuse/recycle sources and end up biologically assimilated. A simple reservoir model of flows and reservoirs of P is shown in Fig. 7.2.

7.2.2.4 *Water*

Even though water flows in a renewable hydrological cycle, the spatio-temporal distribution of its supply and demand can lead to water scarcity (Arora, Yeow, Cheah, & Derrible, 2022). Three possibilities exist for the destination of water after use: (1) it may be returned to a WWTP for further treatment; (2) it may be reused for the same or another application; (3) it may be discharged to the natural environment (river/groundwater or lake/sea). Linear flows for water can be defined as water flows obtained from natural sources such as groundwater and surface water and end up evaporated or lost in any other way for the water bodies or human use. Regenerative flows are here defined as those that originate from recycled or reused sources and end up either getting reused/recycled, discharged with appropriate quality into the receiving body, or assimilated by a living organism (e.g., water contained in crops).

Based on the general definitions presented in Section 7.1 and the resource categories described in Section 7.2, Table 7.1 describes the linear and restorative/regenerative flows for the water-related resources.

7.2.3 Circularity assessment tool

We have developed a spreadsheet-based circularity assessment tool. This assessment is done in two phases: the RR phase and the RA phase. This tool has two input sheets and one output sheet. The two input sheets are for the RR and the RA phases. In the input sheet, a user finds the resource categories (discussed in Section 7.2). Under each category, the user may enter the name of a resource, its total mass or volume flowing through a particular phase, its fractions from reuse/recycled sources, and fractions of the resource going into processes such as reuse, recycling, composting, etc. Upon entering this data, the sheet shows the results related to total virgin quantity and the total unrecovered waste quantity for each resource category. A screenshot of the input sheet is shown in Fig. 7.3.

Once all relevant resources have been entered under the different categories and their MCIs calculated, the user may check the compiled results in the output sheet as shown in Fig. 7.4.

7.3 Efficiency assessment

7.3.1 Definitions and assessment methodology

Efficiency can be broadly defined as the ratio between intended effects (benefits) and the inventoried costs in terms of resources, energy, money, or environmental impacts. Along similar lines, Huysman et al. (2015) defined two levels of efficiency: level 1 refers to the ratio between benefits and inventoried flows, and level 2 is the ratio between the benefits and the environmental impact (more commonly known as ecoefficiency). Here, we present a set of efficiency indicators based on different benefit and cost indicators that a user may select. This framework for efficiency assessment is shown in Fig. 7.5.

TABLE 7.1 Linear and restorative/regenerative flows for defining circularity of different resources found in the water sector.

Material category	Linear flow	Restorative/regenerative flow
Abiotic or mixed resources	Originates from virgin extraction and ends in a landfill or energy recovery process.	Originates from a reused or recycled source and ends up getting reused or recycled.
Biotic (renewable resources)	Appropriation rate higher than the regeneration rate and ends up in a landfill or energy recovery process.	Appropriation rate lower than the regeneration rate and ends up getting reused, recycled, or composted.
Nutrients (Nitrogen)	Nitrogen that originates from industrial conversion of unreactive N_2 that ends up dissipated as	Nitrogen that originates from reused or recycled sources that ends
	reactive emission (e.g., N_2O) to air or water bodies.	up as biomass accumulation or unreactive emission.
Nutrients (Phosphorus)	Phosphorus that originates from phosphate rocks that ends up dissipated in water bodies.	Phosphorus that originates from reused or recycled sources that ends up as biomass accumulation or fixed in the soil.
Water	Originates from a natural water source and ends up evaporated or discharged with a significantly lower quality than a receiving body.	Originates from a reuse or recycle source and ends up getting recycled, reused, or discharged with appropriate quality.

7.3.2 Benefit indicators

There are several ways to quantify benefits related to a resource recovery solution. Through the recovery and use of the recovered resources, there may be economic, material, energy, health, or environmental benefits. Moreover, the benefits may be enjoyed by a

Circularity assessment

Alternative 1

Resource category	Unit	Value
Abiotic or mixed resources		
Biotic resources		
Water		
Total water	m^3/y	100
Fraction of water obtained from WWTP (F_{WWTP})	Fraction	0.6
Fraction of water reused within the same process (F_U)	Fraction	0
Fraction of water originating from another application process (F_R)	Fraction	0
Fraction of water going to a WWTP after use (C_{WWTP})	Fraction	0
Fraction of water reused within the same application process (C_U)	Fraction	0
Fraction of water going into another use process (C_R)	Fraction	0.3
Fraction of water discharged with a quality suitable to the receiving body (C_D)	Fraction	0.4
Total virgin mass	kg	40
Total unrecovered waste mass	kg	30
Nutrients		

FIGURE 7.3 Screenshot of the circularity assessment input sheet of the assessment tool.

Resource recovery process

	Default	Alternative 1	Alternative 2	Alternative 3
AMCI	0.85	0.50	0.50	0.65
BMCI	0.71	0.71	0.74	0.73
WCI	0.00	0.00	0.00	0.00
NCI	0.00	0.00	0.00	0.00

Resource application process

	Default	Alternative 1	Alternative 2	Alternative 3
AMCI	0.08	0.72	0.80	0.45
BMCI	0.50	0.98	0.85	0.87
WCI	0.35	0.35	0.20	0.10
NCI	0.60	0.70	0.10	0.50

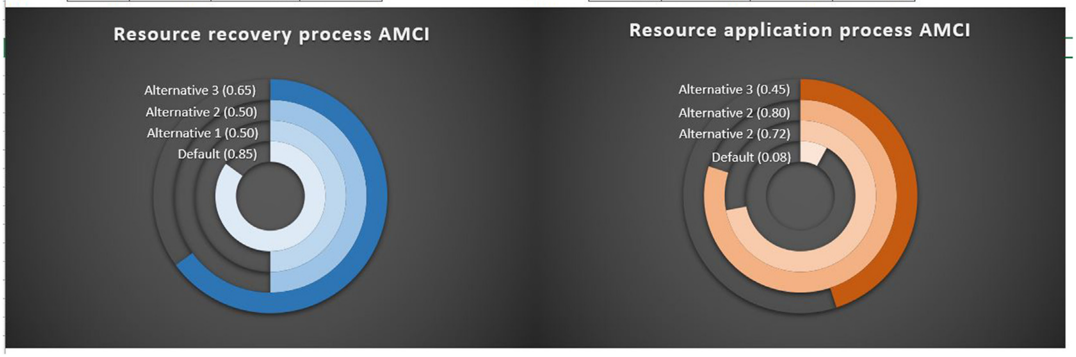
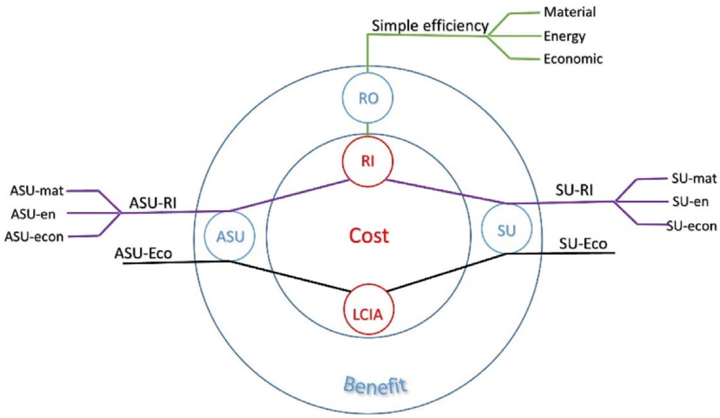


FIGURE 7.4 Screenshot of the circularity assessment output sheet that shows the results of circularity for all relevant resource categories in tabulated and graphical forms for each of the compared alternatives. AMCI, Abiotic material circularity indicator; BMCI, biotic material circularity indicator; WCI, water circularity indicator; NCI, nutrient circularity indicator.

water treatment plant, users served by the treatment plant, users of the recovered resource, the natural environment, or society in general. The most straightforward way to quantify benefits is to use the service units of a process. Service unit (SU) refers to the



SU-RI	Service unit - resource input efficiency
SU-Eco	Service unit - ecoefficiency
ASU-RI	Auxiliary service unit - resource input efficiency
ASU-Eco	Auxiliary service - ecoefficiency
SU-mat	Service unit - material resource efficiency
SU-en	Service unit - energy efficiency
SU-econ	Service unit - economic efficiency
ASU-mat	Auxiliary service unit - material resource efficiency
ASU-en	Auxiliary service unit - energy efficiency
ASU-econ	Auxiliary service unit - economic efficiency

FIGURE 7.5 Framework for the efficiency assessment of resource recovery solutions in the water sector. In this framework, the cost can be expressed with total resource input (RI) or the life cycle impact assessment (LCIA). Benefits may be expressed in service units (SU), auxiliary service units (ASU), or resource output (RO). Simple efficiencies are dimensionless ratios of RO to RI. SU-based efficiencies can be calculated using total RI to give SU-RI efficiency or LCIA to calculate SU-ecoefficiency and the same goes for ASU-RI and ASU-ecoefficiency.

product or service provided by a process for society (Mancini, Lettenmeier, Rohn, & Liedtke, 2012). The SU can be expressed in terms of the primary function that a process provides, for example, the SU of a water softener can be to soften 2x10^6 m^3 y^{-1} of hard water for domestic consumption. The service unit-material resource efficiency can then be defined as follows:

$$\mathrm{Eff}_{\mathrm{SU-mat}} = \frac{\mathrm{SU}}{\mathrm{MIR}} \tag{7.1}$$

where $\mathrm{Eff}_{\mathrm{SU\text{-}mat}}$ is the service unit-material resource efficiency, SU is the service unit of a process, and MIR is the material resources input rate (kg y^{-1}).

To illustrate, suppose a water softening process, treating 2x10^6 m^3 y^{-1} of water, uses 1000 kg y^{-1} of mineral resources as input. The resource efficiency of the process would be 2000 m^3 kg^{-1} (=2,000,000 m^3/1000 kg). Now, if, through resource recovery, half of the mineral input can be reused, then the process continues to treat 2x10^6 m^3 of water with 500 kg of mineral resources. This would improve the service unit material efficiency to 4000 m^3 kg^{-1}. Therefore, service unit efficiency improvement implies that the process can provide the same quantity and quality of service with a lower resource input.

Some processes may provide multiple auxiliary services in addition to a primary service. For example, the primary service provided by a WWTP may be to treat 2x10^6 m^3 y^{-1} of domestic wastewater, while recovering P to supply a fertilizer manufacturer may be an auxiliary service. One can calculate the auxiliary service efficiency of a resource recovery or application process. To illustrate, suppose 2000 kg y^{-1} P can be supplied for fertilizer production and the recovery process requires an additional 50 kWh y^{-1}. Then the energy efficiency of providing the auxiliary service of P supply can be calculated as follows:

$$\mathrm{Eff}_{\mathrm{ASU-en}} = \frac{Q_{\mathrm{P}}}{\mathrm{EIR}} \tag{7.2}$$

where $\mathrm{Eff}_{\text{ASU-en}}$ is the auxiliary service-based energy efficiency of the recovery process, Q_{P} is the quantity of P supplied for fertilizer production, EIR is the energy input rate to the process (kWh y^{-1}). Therefore, the environmental efficiency $\mathrm{Eff}_{\text{ASU-en}}$ in the above example is $2000/50 = 40$ kg kWh^{-1}.

Another way to measure benefit, especially suited for resource recovery processes, is by simply quantifying the useful outputs of a process. Useful outputs can be material resources, energy, or income that are obtained as a result of a resource recovery process. These indicators can be used with material and energy resource input indicators to calculate simple efficiencies. These simple efficiencies are dimensionless since they are calculated as ratios between inputs and outputs of the same type (energy/material/economic).

$$\mathrm{Eff}_{\mathrm{mat}} = \frac{\mathrm{MOR}}{\mathrm{MIR}} \tag{7.3}$$

where $\mathrm{Eff}_{\mathrm{mat}}$ is a simple material resource efficiency, MOR is the annual material resource output rate (kg y^{-1}), and MIR is the annual material resource input rate (kg y^{-1}).

To illustrate, suppose a water softening process takes 1000 kg y^{-1} of material resource input, and 500 kg y^{-1} resources are recovered from the softener for further use, then the resource efficiency ($\mathrm{Eff}_{\mathrm{mat}}$) of the process would be 0.5 (=500/1000).

7.3.3 Cost indicators

Costs can also be expressed in different terms, such as resources used, waste produced, economic investment, and environmental impacts. These costs may be from the perspective of a treatment plant, human society, or some other stakeholder. Therefore, we present a collection of cost indicators to cover these options. The first option is to directly use quantities of material resources and waste in kg y^{-1} or m^3 y^{-1}, energy used in kWh y^{-1}, and economic investment in € y^{-1}. The second option is to express costs in terms of environmental impacts, which can be calculated using the life cycle assessment (LCA) method. Based on these options, two categories of efficiency indicators may be calculated.

7.3.3.1 Level 1 efficiency

To calculate level 1 efficiency, the denominator must be the annual resource input, waste produced, or economic investment. Suppose a water filtration unit must be added to an existing WWTP with an influent volume of 2,000,000 m^3 y^{-1} to purify water for reuse. We assume the annual cost of the WWTP is 620,000 € y^{-1}. The annualized investment cost of the added filtration unit is 20,000 € y^{-1}. We want to apply a SU-based benefit indicator along with the total economic investment as the cost indicator to compare how the economic efficiency of delivering a service unit changes due to the added filtration process. In this case, efficiency may be calculated using the following equation:

$$\mathrm{Eff}_{\mathrm{SU-econ}} = \frac{\mathrm{SU}}{\mathrm{EI}} \tag{7.4}$$

where $\mathrm{Eff}_{\text{SU-econ}}$ is the service unit-based economic efficiency of a process, SU is the service unit of a process, and EI is the economic investment required to set up and run the process (€ y^{-1}).

Thus, for the base line WWTP efficiency can be calculated as follows:

$$\mathrm{Eff}_{\mathrm{SU-econ}} = \frac{2,000,000}{620,000} = 3.23\ \mathrm{m}^3\ €^{-1} \tag{7.5}$$

And for the WWTP supplemented with a filtration process, efficiency would be as follows:

$$\mathrm{Eff}_{\mathrm{SU-econ}} = \frac{2,000,000}{640,000} = 3.13\ \mathrm{m}^3\ €^{-1} \tag{7.6}$$

Thus, for level 1 efficiency assessment, we only need to enter annual flows of material resources or wastes, energy used, or economic investment. While the disadvantage lies in the lack of discrimination between distinct types of resource and waste flows, the ease of calculation is an advantage.

7.3.3.2 Level 2 efficiency

While level 1 efficiency is based on the flows of resources, level 2 efficiency estimates the costs in terms of environmental impacts associated with these flows. Since environmental relevance can vary dramatically for different kinds of resources and wastes (Hauschild & Huijbregts, 2015), one needs to use characterized impacts of the resource and waste flows. These characterized impacts may be calculated using LCA.

LCA is a method to calculate environmental impacts over the life cycle of a product using characterization models (Rebitzer et al., 2004). These models help to translate the life cycle inventory (LCI), that is, the flows of resources/waste (expressed in units such as kg, kWh, or m^3) into impacts of a particular environmental category (Hauschild & Huijbregts, 2015). There are several characterization models available, such as CML 2002, Eco-Indicator 99, EDIP 2003, and ReCiPe 2016, among others; however, no single method enjoys universal acceptance (Hauschild et al., 2013). Since no characterization method is universally accepted to be the best, we make a choice to use ReCiPe 2016 in our framework. This is because the ReCiPe model has one of the widest ranges of mid-point indicators (18 in total), and the model also allows for end-point characterization (three categories).

The ReCiPe method translates the LCI, which is a list of used resources, produced wastes, and emissions, into mid-point environmental impact categories. This is achieved through a set of characterization factors unique to the ReCiPe method. The conversion of resource/waste flows into mid-point impacts is done as follows:

$$I_m = \sum_i Q_{mi}.m_i \tag{7.7}$$

where m_i is the mass or volume of a resource or waste flow, Q_{mi} is the characterization factor for the particular flow, and I_m is the indicator result for a mid-point impact category m.

Similarly, the translation of midpoint impacts into end-point categories is achieved by the following equation:

$$I_e = \sum_m Q_{em}.I_m \tag{7.8}$$

where I_m is a midpoint indicator, Q_{em} is the characterization factor that connects a midpoint category m to an endpoint category e, and I_e is the indicator result for an end-point impact category.

We provide two options for calculating the environmental impacts: the full life cycle approach and the direct impact approach. In the full life cycle approach, the user conducts an LCA of the RR and RA phases separately using the ReCiPe 2016 method. We also offer a simplified alternative to using an LCA wherein users have an option to directly calculate the environmental impacts of a process when a complete LCA is not possible due to a lack of time or data. In this approach, we make two simplifications:

1. We only account for direct emissions from the resource recovery and application processes instead of considering the entire life cycle.
2. We use a nonexhaustive list of relevant emissions and their characterization factors.

Based on a literature review done by Zang, Li, Wang, Zhang, and Xiong (2015), the environmental impact categories most relevant to water treatment plants are global warming potential, eutrophication potential, toxicity, acidification, photochemical oxidant potential, ozone layer depletion, energy use, land, and water use. However, this list is not comprehensive and final. Since the choice of environmental impact categories depends upon the nature of a particular case study and its surrounding environment, the relevant categories should be individually determined while assessing these case studies.

Using either the complete LCA or the simplified option, a list of environmental impacts associated with the RR and the RA phases can be generated. These impact indicators can be combined with benefit indicators, discussed in Section 7.2, to provide estimates for level 2 efficiency, also known as ecoefficiency. The equation to calculate ecoefficiency takes the following form:

$$\text{Eff}_{\text{eco}} = \frac{\text{BI}}{\text{LCIA}_i} \tag{7.9}$$

where Eff_{eco} is the ecoefficiency of a process, BI is the benefit indicator estimating a benefit resulting from the process, and LCIA_i is the life cycle impact assessment result for an environmental impact category i. Users also have an option to use aggregated environmental impact scores (e.g., end-point ReCiPe categories and shadow pricing).

To illustrate, suppose a user wants to calculate the ecoefficiency of a case wherein an ultraviolet (UV) disinfection unit is used to produce irrigation water from $2\text{x}10^5$ m^3 y^{-1} WWTP effluent. We assume the UV disinfection requires 0.13 kWh m^{-3} energy based on Fenu et al. (2010) and the energy is sourced from a coal-based power plant. A total energy generation of 26,000 kWh y^{-1} leads to certain environmental impacts. A quick LCA on Simapro tells us that the total freshwater ecotoxicity impact of this energy generation is 685 kg 1,4-DCB. Also, we assume, the user expresses the benefit in the form of useful output (i.e., $2x10^5$ m^3 y^{-1} of irrigation water). Then, the ecoefficiency of this RR process can be calculated as follows:

$$\mathrm{Eff}_{eco} = \frac{200,000}{685} = 291.97\ \mathrm{m^3\ kg^{-1}}\ 1,4-\mathrm{DCB} \tag{7.10}$$

This implies that the UV disinfection process can produce 291.97 m^3 of irrigation water with an environmental impact of 1 kg 1,4-DCB of freshwater ecotoxicity.

7.3.4 Efficiency assessment tool

Below, we present screenshots of the efficiency assessment spreadsheet tool. Fig. 7.6 shows the input sheet wherein a user enters the total input and output material, energy, and economic resources. The user has an option to modify the units as long as the units represent the quantity (mass or volume) of flow per year.

Fig. 7.7 is a screenshot of the output sheet of the efficiency assessment. The table shows the values of simple efficiency of a resource recovery process, and the diagram under the table shows the comparison of efficiencies of the three alternatives used as examples.

7.4 Case study

7.4.1 Case description

The town of Corleone has an activated sludge WWTP treating about 3800 m^3 d^{-1} of domestic wastewater. The TW is currently discharged into a nearby river. The WWTP is being modified with the purpose of resource recovery. The objective is to use a part of the TW to replace groundwater for agricultural and public garden irrigation.

The wastewater treatment train will be modified by adding an oxic settling anaerobic (OSA) step after the activated sludge biological treatment. Further, intermittent aeration (IA) will be implemented for the activated sludge treatment step. To produce irrigation water of sufficient quality, an ultrafiltration (UF) unit is added to the WWTP. Close to the WWTP, there is a storage tank, which was conceived for irrigating the surrounding fields with the UF-TW. The

Resource recovery process

Enter service unit: Softening of 60 000 000 m^3/y of drinking water.

		Base line
Service unit (SU)	m^3/y	60000000
Auxiliary service unit 1 (ASU-1)		
Auxiliary service unit 2 (ASU-2)		
Annual flows	**Unit**	**Value**
Material resource input rate	kg/y	7034
Waste output rate	kg/y	4717
Material resource output rate	kg/y	535
Energy input rate	kWh/y	710000
Energy output rate	kWh/y	0
Economic input rate	€/y	3000
Economic output rate	€/y	1500

FIGURE 7.6 Screenshot of the input sheet for the efficiency assessment.

Simple efficiency (output/input)	Base line	Alternative 1	Alternative 2
Material efficiency	0.30	0.80	0.53
Energy efficiency	0.00	0.45	0.25
Financial efficiency	0.25	0.97	1.00

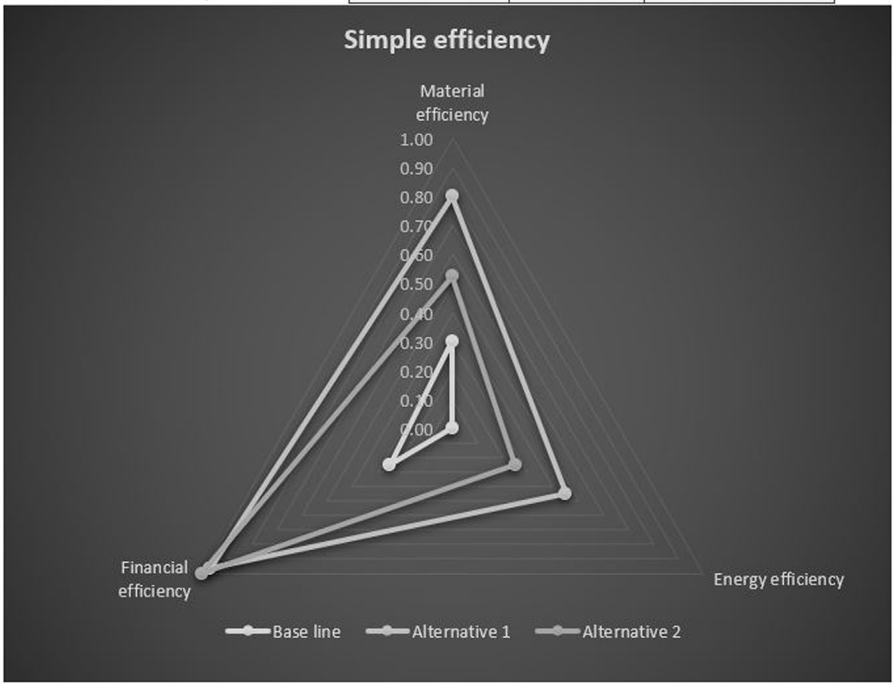


FIGURE 7.7 Screenshot of the output sheet for efficiency assessment from the spreadsheet tool. The table shows results of a simple efficiency assessment of a resource recovery process while the spider-web chart shows a comparison of three alternative recovery processes.

treated water will be pumped to this storage tank through a pumping station inside the WWTP. The stored water will be supplied using a gravity pipeline to fields downstream from the WWTP. This storage tank has already been realized and does not require any significant work, while the pipeline upstream the tank as well as the distribution network have to be realized. The public garden belongs to the city that has hired a management team. The existing UF system requires repair, which is being paid for by the city and the park management company. Table 7.2 lists the four alternatives being compared in this case study.

A schematic diagram of the base case is shown in Fig. 7.8.

Fig. 7.9 shows a diagram of the AS_irr alternative wherein the activated sludge effluent is UF treated and used for public garden/agricultural irrigation.

Fig. 7.10 shows the schematic diagram of the OSA_irr alternative, wherein an oxic settling anaerobic treatment step is added after the activated sludge treatment. The secondary effluent is UF treated and used for the public garden/agricultural irrigation.

Fig. 7.11 shows the schematic diagram of the IA_OSA_irr alternative, wherein an intermittent aeration-activated sludge process is implemented followed by an oxic settling

TABLE 7.2 The four alternatives considered in this report.

Alternative	WWTP effluent	Agricultural + garden irrigation
Base case	The WW is treated using the AS process and discharged into a river.	Using groundwater
AS_irr	The WW is treated using the AS process and partly used for irrigation.	Using treated wastewater
OSA_irr	The WW is treated using the AS + OSA process and partly used for irrigation.	Using treated wastewater
OSA_IA_irr	The WW is treated using the IA-AS + OSA process and partly used for irrigation.	Using treated wastewater

WW, Wastewater; *AS*, activated sludge; *OSA*, oxic settling anaerobic; *IA-AS*, iIntermittent aeration – activated sludge.

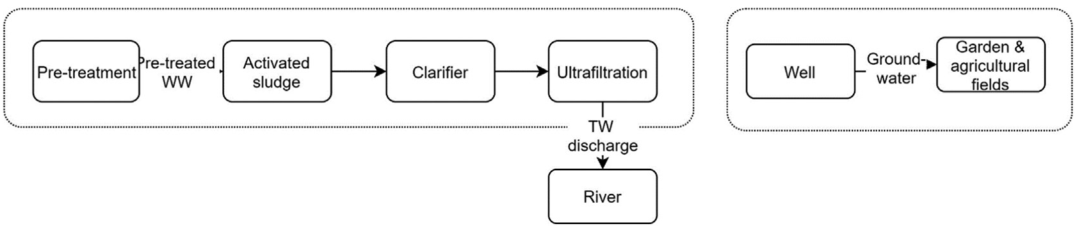


FIGURE 7.8 Base case – secondary effluent is ultrafiltration treated and discharged into river. Groundwater is pumped from a well and used for public-garden and agricultural irrigation.

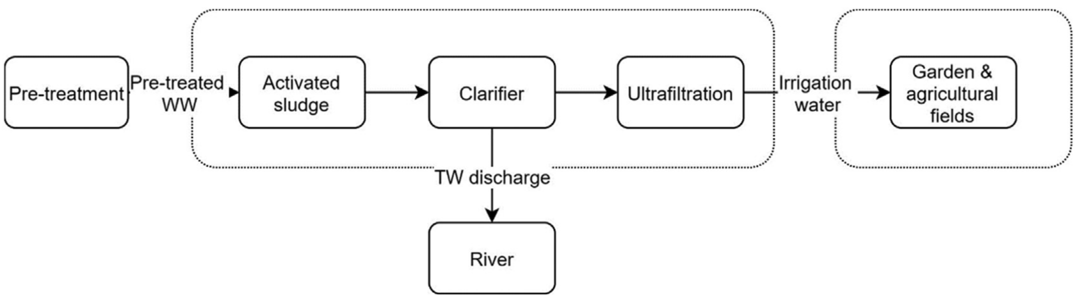


FIGURE 7.9 AS_irr – Part of the treated wastewater is used for irrigation and the rest is discharged.

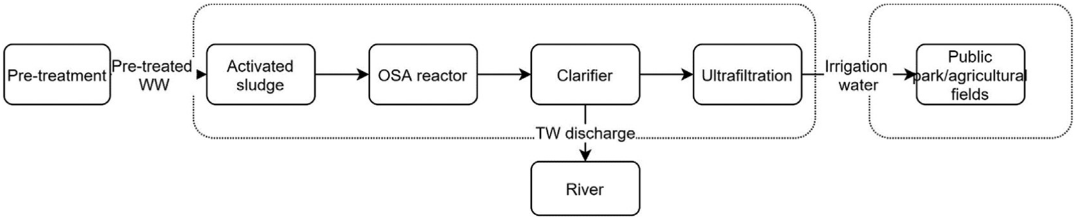


FIGURE 7.10 OSA_irr – auxiliary service effluent is treated in an oxic settling anaerobic reactor and then partly used for irrigation, the rest is discharged.

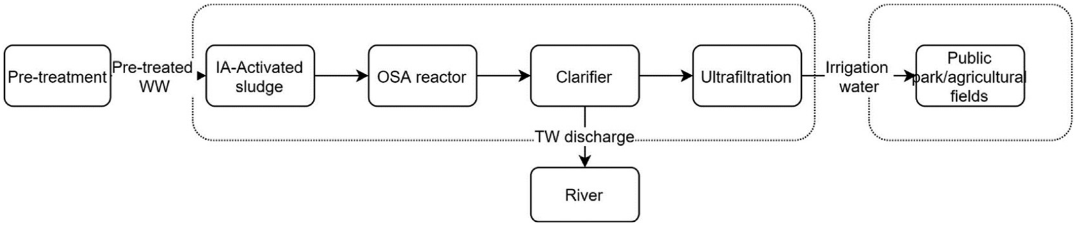


FIGURE 7.11 IA_OSA_irr – intermittent aeration activated sludge effluent is oxic settling anaerobic-treated and then partly used for irrigation, the rest is discharged.

TABLE 7.3 The user inputs to assess the efficiency of the resource recovery phase of the case study.

Alternatives	Base case	AS_irr	OSA_irr	IA_OSA_irr
WWTP influent (10^6 m3/y)	1.39	1.39	1.39	1.39
Energy input (10^5 kWh/y)	3.56	3.57	4.65	3.94
Economic investment (10^5 €/y)	1.93	2.72	3.03	2.83

WWTP, Wastewater treatment plants; *AS*, auxiliary service; *OSA*, oxic settling anaerobic; *IA*, intermittent aeration.

anaerobic treatment step. The secondary effluent is UF-treated and used for public gardens or agricultural irrigation.

For the circularity assessment of this case study, the user inputs are presented in Tables 7.A1 and 7.A2 presented in the appendix. In Table 7.3, the inputs related to the RR phase of the case study are presented. These user inputs were obtained from the case study owners and will be used to calculate the efficiency of the RR phase of the resource recovery solution.

In Table 7.4, the inputs related to the RA phase of the case study are presented. These user inputs were also obtained from the case study owners and will be used to calculate the efficiency of the RA phase of the resource recovery solution.

7.4.2 Results

We assessed this case study in two phases: the RR phase (involving the wastewater treatment plant) and the RA phase (involving the irrigation process). For the RR stage, the energy efficiency, economic efficiency, water, and nutrient circularities are shown in Table 7.5.

The energy efficiency was found to decrease in the OSA_irr (2.98 m^3 kWh^{-1}) and the IA_OSA_irr (3.52 m^3 kWh^{-1}) alternatives when compared to the base case and the AS_irr

TABLE 7.4 The user inputs to assess the efficiency of the resource application phase of the case study.

Alternatives	Base case	AS_irr	OSA_irr	IA_OSA_irr
Irrigation area (10^4 m^2)	6.50	6.50	6.50	6.50
Water input (10^4 m^3/y)	6.13	6.13	6.13	6.13
Nitrogen (10^2 kg/y)	9.25	9.25	9.25	9.25
Phosphorus (10^2 kg/y)	3.58	3.58	3.58	3.58
Energy input (10^2 kWh/y)	46.23	5.55	5.55	5.55
Economic investment (10^3 €/y)	6.74	18.17	18.17	18.17

AS, Auxiliary service; *OSA*, oxic settling anaerobic; *IA*, intermittent aeration.

TABLE 7.5 Efficiency and circularity comparison of the four resource recovery stage alternatives.

Alternatives	Energy efficiency (m^3/kWh)	Economic efficiency (m^3/€)	Water circularity (%)	Nutrient circularity (%)
Base case	3.89	7.18	95	71
AS_irr	3.89	5.09	95	71
OSA_irr	2.98	4.58	95	74
IA_OSA_irr	3.52	4.91	95	73

AS, Auxiliary service; *OSA*, oxic settling anaerobic; *IA*, intermittent aeration.

alternatives (3.89 m^3 kWh^{-1}). In the AS_irr alternative, no modifications are introduced in the treatment processes, and thus, the energy efficiency remains the same as that of the base case. In the OSA_irr alternative, the addition of new mixers and pumps leads to the highest energy requirement and thus the lowest energy efficiency. Introducing intermittent aeration helps to lower the energy consumption compared to the OSA_irr alternative.

The highest economic efficiency (7.18 m^3 $€^{-1}$) is achieved in the base case. The capital costs involved for constructing the pipe connections from the WWTP to the storage tank in the AS_irr alternative reduce its economic efficiency. For OSA_irr, the cost of the secondary treatment process increased due to added mixers and pumps, leading to the lowest economic efficiency. Lastly, for the IA_OSA_irr alternative, there is a slight increase in the economic efficiency as compared to the OSA_irr alternative, mainly due to lowered energy consumption of the intermittent aeration.

The water circularity of the WWTP was found to be 95% in all the alternatives. The TW earlier discharged into a river is going to be used for irrigation. We consider the discharge of TW into a river as a regenerative flow and the reuse of TW for irrigation as a restorative flow. Therefore, the diversion of discharge water for irrigation does not affect the overall circularity of the WWTP.

In the base case, the nutrients present in the TW get discharged into a river, leading to the lowest nutrient circularity (71%). In the AS_irr alternative, the nutrients present in the TW end up being used for fertilization instead of being discharged into a river when the TW is diverted for irrigation. However, the effect on nutrient circularity is negligible because the volume of the TW used for irrigation is small compared to the total wastewater influent (about 3%). The introduction of the OSA process leads to a higher P recovery from the sludge. This improves the nutrient efficiency for the OSA_irr alternative (74%) and for the OSA_IA_irr alternative (73%).

For the RA stage, that is, the irrigation process, the results are shown in Table 7.6. We assessed the water, nutrient, energy, and economic efficiencies along with water and nutrient circularities for the four irrigation alternatives.

Here, we found the water efficiency of the three alternatives (2.50 m^2 m^{-3}) to be higher than that of the base case (1.15 m^2 m^{-3}). This is because the water circularity of the base case is only 8% in comparison to 58% for the other three alternatives. This improvement in water circularity is because groundwater is replaced by TW for irrigation.

With regards to nutrient efficiency, again, all alternatives perform better than the base case. However, the AS_irr alternative performs the best (2624.27 m^2 kg^{-1}) due to the lowest linear flow of nutrients. Including the OSA process ensures a higher removal of nutrients from the water phase and therefore a lower nutrient concentration in the TW used for irrigation. The lower nutrient content in the TW must be compensated for by using industrial fertilizers, leading to lower nutrient efficiency for the OSA_irr (329.64 m^2 kg^{-1}) and the IA_OSA_irr (376.40 m^2 kg^{-1}) alternatives.

Likewise, the energy efficiency of the latter three alternatives (117.16 m^2 kWh^{-1}) is higher than for the base case (14.06 m^2 kWh^{-1}). This is because the energy use of pumping TW for irrigation is much lower than that of pumping groundwater from an assumed average depth of 25 m. This pumping energy is avoided when TW is used for irrigation because gravity pipes are used for transporting TW from the storage tank to the fields.

On the contrary, the economic efficiency of the base case (9.65 m^2 €$^{-1}$) was found to be the highest compared to the other three alternatives (3.58 m^2 €$^{-1}$). This is because of the added capital cost of installing a drip irrigation system at the public gardens, repairing the UF unit, and connecting the WWTP to the storage tanks.

The water circularity of the irrigation process improves (from 8% to 58%) when TW replaces groundwater. The nutrient circularity was found to be the highest for the AS_irr alternative (98%). A reduction in the nutrient circularity was observed for the OSA_irr (85%) and the IA_OSA_irr (87%) alternatives. This is because the OSA process reduces the P content in the TW meant for the irrigation, which must be compensated for by using industrial fertilizers.

TABLE 7.6 Comparison of the efficiency and circularity of the resource application stage alternatives.

Alternatives	Water efficiency (m^2/m^3)	Nutrient efficiency (m^2/kg)	Energy efficiency (m^2/kWh)	Economic efficiency (m^2/€)	Water circularity (%)	Nutrient circularity (%)
Base case	1.15	101.36	14.06	9.65	8	50
AS_irr	2.50	2624.27	117.16	3.58	58	98
OSA_irr	2.50	329.64	117.16	3.58	58	85
IA_OSA_irr	2.50	376.40	117.16	3.58	58	87

AS, Auxiliary service; *OSA*, oxic settling anaerobic; *IA*, intermittent aeration.

7.4.3 Summary

The Corleone WWTP is modified through the addition of an OSA tank and IA. The capital cost of adding the OSA tank, mixers, and pumps reduced the energy and economic efficiencies of the WWTP. The OSA process reduces the quantity of sludge and will lead to lower costs linked with sludge disposal. But the additional costs of the pumps and mixers led to a net increase in the cost of the treatment plant. Thus, the implementation of resource recovery solutions at a WWTP may lead to a lowered efficiency of wastewater treatment. A careful analysis is required to ensure the benefits from the resource recovery can justify the higher energy and economic inputs.

The use of TW led to an improvement in the water and nutrient efficiencies of irrigation. This is because of a lower linear flow of water and nutrients when TW replaces groundwater. However, as more nutrients are removed from the wastewater at the WWTP, the TW may not have sufficient N and P for the crops. In this case, industrial fertilizers may also have to be added, leading to a lower nutrient circularity.

A significant improvement in the energy efficiency was found in the cases where TW was used for irrigation as compared to groundwater. This is because in arid regions like Palermo, the groundwater is likely to be located at large depths, requiring a very high pumping energy use. The high pumping energy of groundwater can be avoided by the reuse of TW.

7.5 Conclusions and perspectives

Resource recovery is meant to improve the efficiency and the circularity of the water sector. To assess these criteria, we developed a framework with the relevant indicators and demonstrated our assessment methods on a real-life case study from Italy. We divided the case study into a resource recovery and a resource application phase for the assessment. The resource flows can be restorative/regenerative types or linear in nature. The lower the proportion of linear flows, the more circular a resource recovery solution can be considered.

To assess the circularity, we modified the existing MCI method. Using our approach, one can segregate the resource flows into linear, restorative, or regenerative flows. Thereafter, using the spreadsheet-based assessment tool, one can calculate the MCI of a resource recovery solution in four categories of resources, namely, abiotic, biotic, nutrients, and water. Efficiency was described as the ratio between a benefit obtained from the resource recovery solution and the costs associated with it. We presented a collection of benefit and cost indicators. The benefits can mainly be expressed using the main service unit or the auxiliary services of a particular process. The costs may be expressed in terms of used materials, energy, or economic investment to calculate level 1 efficiency. Level 2 efficiency can be calculated using the environmental impact indicators calculated using an LCA.

The case study revealed that while there are several benefits to using TW for irrigation, such as improved nutrient and water circularity, the energy and economic efficiency of the WWTP itself can become lower due to the resource recovery. It is important to ensure that the benefits from the recovered resources outweigh the extra costs of recovering the resource from a WWTP. This also proves the need for an assessment framework like the one developed here to compare the efficiency and circularity of the resource recovery options.

Appendix A

TABLE A1 The user inputs for the four case study alternatives for the circularity assessment of the resource recovery phase.

Water		Base case	AS_irr	OSA_irr	IA_OSA_irr
Total water	10^4 m^3/y	6.12	6.12	6.12	6.12
Fraction of water obtained from WWTP (F_{WWTP})	Fraction	0	1.00	1.00	1.00
Fraction of water reused within the same process (F_U)	Fraction	0	0	0	0
Fraction of water originating from another application process (F_R)	Fraction	0	0	0	0
Fraction of water going to a WWTP after use (C_{WWTP})	Fraction	0	0	0	0
Fraction of water reused within the same application process (C_U)	Fraction	0	0	0	0
Fraction of water going into another use process (C_R)	Fraction	0	0	0	0
Fraction of water discharged with a quality suitable to the receiving body (C_D)	Fraction	0.13	0.13	0.13	0.13
Fraction of water biologically assimilated (C_{BA})	Fraction	0.02	0.02	0.02	0.02
Total virgin mass	m^3/y	**61250**	**0**	**0**	**0**
Total unrecovered waste mass	10^4 m^3/y	**5.21**	**5.21**	**5.21**	**5.21**
Nutrients		Base case	AS_irr	OSA_irr	IA_OSA_irr
Phosphorus	10^2 kg/y	3.58	3.58	3.58	3.58
Feedstock fraction from recycled source (F_R)	Fraction	0	0.87	0.43	0.31
Feedstock fraction internally recycled (F_U)	Fraction	0	0	0	0
Fraction immobilized after use (C_{imm})	Fraction	0	0	0	0
Fraction taken up by plants (C_P)	Fraction	0.27	0.27	0.27	0.27
Fraction stored/recovered for recycling (C_s)	Fraction	0.73	0.73	0.73	0.73
Total virgin mass	kg/y	**357.5**	**48.1875**	**204.375**	**247.25**
Total unrecovered waste mass	kg/y	**0**	**0**	**0**	**0**
Nitrogen	kg/y	925	925	925	925
Feedstock fraction from recycled source (F_R)	Fraction	0	1.00	0.79	0.89
Feedstock fraction internally recycled (F_U)	Fraction	0	0	0	0
Fraction immobilized after use (C_{imm})	Fraction	0	0	0	0
Fraction taken up by plants (C_P)	Fraction	0.14	0.14	0.14	0.14
Fraction emitted in unreactive form (C_{UR})	Fraction	0	0	0	0
Fraction stored/recovered for recycling (C_s)	Fraction	0.86	0.86	0.86	0.86
Total virgin mass	kg/y	**925**	**1.35**	**190**	**98.12**
Total unrecovered waste mass	kg/y	**0**	**0**	**0**	**0**

WWTP, Wastewater treatment plants; *AS*, auxiliary service; *OSA*, oxic settling anaerobic; *IA*, intermittent aeration.

TABLE A2 The user inputs for the four case study alternatives for the circularity assessment of the resource recovery phase.

Water		Base case	AS_irr	OSA_irr	IA_OSA_irr
Total water	10^6 m^3/y	1.39	1.39	1.39	1.39
Fraction of water obtained from WWTP (F_{WWTP})	Fraction	0	0	0	0
Fraction of water reused within the same process (F_U)	Fraction	0	0	0	0
Fraction of water originating from another application process (F_R)	Fraction	1	1	1	1
Fraction of water going to a WWTP after use (C_{WWTP})	Fraction	0	0	0	0
Fraction of water reused within the same application process (C_U)	Fraction	0	0	0	0
Fraction of water going into another use process (C_R)	Fraction	0	0.04	0.04	0.04
Fraction of water discharged with a quality suitable to the receiving body (C_D)	Fraction	0.9	0.86	0.86	0.86
Fraction of water biologically assimilated (C_{BA})	Fraction	0	0	0	0
Total virgin mass	m^3/y	**0**	**0**	**0**	**0**
Total unrecovered waste mass	10^5 m^3/y	**1.39**	**1.39**	**1.39**	**1.39**
Nutrients		Base case	AS_irr	OSA_irr	IA_OSA_irr
Phosphorus	10^4 kg/y	1.19	1.19	1.04	0.66
Feedstock fraction from recycled source (F_R)	Fraction	1	1	1	1
Feedstock fraction internally recycled (F_U)	Fraction	0	0	0	0
Fraction immobilized after use (C_{imm})	Fraction	0	0	0	0
Fraction taken up by plants (C_P)	Fraction	0	0	0	0
Fraction stored/recovered for recycling (C_s)	Fraction	0.41	0.44	0.68	0.64
Total virgin mass	kg/y	**0**	**0**	**0**	**0**
Total unrecovered waste mass	10^3 kg/y	**7.00**	**6.70**	**3.31**	**2.39**
Nitrogen	10^4 kg/y	5.17	5.17	4.23	4.34
Feedstock fraction from recycled source (F_R)	Fraction	1	1	1	1
Feedstock fraction internally recycled (F_U)	Fraction	0	0	0	0
Fraction immobilized after use (C_{imm})	Fraction	0	0	0	0
Fraction taken up by plants (C_P)	Fraction	0	0	0	0
Fraction emitted in unreactive form (C_{UR})	Fraction	0.41	0.41	0.41	0.41
Fraction stored/recovered for recycling (C_s)	Fraction	0	0.02	0.02	0.02
Total virgin mass	kg/y	**0**	**0**	**0**	**0**
Total unrecovered waste mass	10^4 kg/y	**3.05**	**2.96**	**2.42**	**2.48**

WWTP, Wastewater treatment plants; *AS*, auxiliary service; *OSA*, oxic settling anaerobic; *IA*, intermittent aeration.

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