Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector

Preisner Michal, Smol Marzena, Horttanainen Mika, Deviatkin Ivan, Havukainen Jouni, Klavins Maris, Ozola-Davidane Ruta, Kruopiene Jolita, Szatkowska Beata, Appels Lisa, Houtmeyers Sofie, Roosalu Kati

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Abstract

The European Union is currently in the process of transformation toward a circular economy model in which different areas of activity should be integrated for more efficient management of raw materials and waste. The wastewater sector has a great potential in this regard and therefore is an important element of the transformation process to the circular economy model. The targets of the circular economy policy framework such as resource recovery are tightly connected with the wastewater treatment processes and sewage sludge management. With this in view, the present study aims to review existing indicators on resource recovery that can enable efficient monitoring of the sustainable and circular solutions implemented in the wastewater sector. Within the reviewed indicators, most of them were focused on technological aspects of resource recovery processes such as nutrient removal efficiency, sewage sludge processing methods and environmental aspects as the pollutant share in the sewage sludge or its ashes. Moreover, other wide-scope indicators such as the wastewater service coverage or the production of bio-based fertilizers and hydrochar within the wastewater sector were analyzed. The results were used for the development of recommendations for improving the resources recovery monitoring framework in the wastewater sector and a proposal of a circularity indicator for a wastewater treatment plant highlighting new challenges for further researches and wastewater professionals.

Keywords: Indicators, Wastewater sector, Resource recovery, Wastewater treatment, Sewage sludge, Nutrients, Phosphorus, Fertilizers, Circular Economy

1. Introduction

By following the European Commission (EC) guidelines published in the communications "*Towards a circular economy: A zero waste programme for Europe*" in 2014 (European Commission, 2014a) and "*Closing the loop – An EU action plan for the circular economy*" in 2015 (European Commission, 2015) the wastewater sector faced new goals which achievement demanded a wide set of measures to be introduced. Those measures were related to the main assumption of a circular economy (CE) model which was to save the value of products, materials and resources and maintain them in the economy for as long as possible with constant minimization of waste generation (European Commission, 2015). In the EC's communication, the water scarcity issue in some European Union (EU) regions was highlighted and stated to have a destructive effect on the EU's environment and economy. As far as water scarcity is irreplaceably connected to water resources, the problem of wastewater treatment efficiency was re-opened (van der Hoek et al., 2016). When the wastewater treatment was identified to have a major contribution to the over-exploited water resources in Europe, the EC stated that several measures are needed to promote the reuse of treated wastewater, including legislation on minimum requirements for reused water (Guerra-Rodríguez et al., 2020; Ramm, 2021). However, to provide acceptable wastewater quality that will make effluents safe to be reused for non-consumption or consumption needs can be especially expensive (Bashar et al., 2018; Bauer et al., 2020; Verstraete et al., 2009). According to the latest reports on the current state of urban wastewater treatment in Europe in 2017, in most European countries 69% of the population were connected to tertiary level treatment and 13% to secondary level treatment and in countries such as Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Ireland, Italy, Lithuania, Poland, Romania, Serbia, Slovakia and Slovenia less than 80% of the population were connected to public urban wastewater treatment systems (European Environmental Agency, 2020).

Furthermore, the wastewater sector was identified to have a high potential in terms of nutrient recovery because of the significant content of nitrogen (N) and phosphorus (P) in almost all municipal wastewater treatment plants (WWTPs). Nutrients are a distinct and important category of secondary raw materials present in wastewater which in the treatment process are deposited in the sewage sludge or are released into the atmosphere as in the case of N (Cieślik and Konieczka, 2017). Nutrient recovery from the sewage sludge, sludge dewatering liquors or sewage sludge ashes (SSA) is a reasonable and sustainable method for alternative fertilizer production, which can replace mineral fertilizers (Venkiteshwaran et al., 2018). However, in the EU-27 countries, sewage sludge direct land application is the main method for sludge management what limits the efficiency of resource recovery (Eurostat, 2017).

The reduction of mineral fertilizers production, which has negative environmental impacts and depends on phosphate rock imports, can be achieved by reusing organic and inorganic matter from wastewater-derived waste products (Smol, 2019). Moreover, mineral fertilizers contain large amounts of easily bioavailable nutrients not only to crops but also to aquatic vegetation which results in surface water eutrophication (Funkey et al., 2014). Due to limited P reserves and the location of main deposits outside the EU Member States, phosphate rock was included in the critical raw material list for the European economy in 2014 (European

Commission, 2014b) and in 2017 in the updated list the EU included also white P to facilitate rapid development of reliable technologies for P recycling and recovery (European Commission, 2017). Furthermore, P recovery is one of the major problems of many WWTPs. P cycle circularity and recovery approaches are important measures under development by many WWTPs operators. In some countries, P recovery is currently based on SSA processing methods (e.g. Germany, Austria, Belgium, Finland) or struvite precipitation (e.g. USA, Japan, Netherlands) while many countries still have not introduced P recovery from the wastewater sector-derived waste (Smol et al., 2020b).

In order to systematize the EU's legislation, a Circular Economy Action Plan (CEAP) was released in 2020 (European Commission, 2020). The new CEAP highlights the previous CE model assumptions with special attention given to the entire life cycle of products, eco-design, promoting CE processes, fostering sustainable consumption to ensure that resources will remain in the EU economy as long as possible (Shahbazi and Jönbrink, 2020). Within the CEAP, a new Regulation 2020/741 on minimum requirements for water reuse was published in May 2020 which is designed to encourage circular approaches to water reuse in agriculture and industry (European Parliament and the Council of the European Union, 2020). Furthermore, the EC announced an Integrated Nutrient Management Plan to ensure more sustainable application of nutrients and stimulating the markets for recovered nutrients (European Commission, 2020) followed by a review of current legislation on wastewater treatment and sewage sludge processing and analysis of chemical-free methods of nutrient removal based on absorbents application, algal bioreactors or crystallization (Cepan et al., 2021). Because of the above-mentioned reasons, the EU policy under the new policy framework will highly likely be focusing on many relevant issues for the wastewater sector including the update of the Urban Wastewater Treatment Directive (UWWTD), Europe's sustainable bioeconomy and food policy.

The CE model highlights many aspects relevant to the wastewater sector. More sustainable resource management gains importance with the resource-efficiency focus of the EU policy. This has a major impact on the current level of nutrient recovery from wastewater in the European WWTPs and the nutrient content in the excessive sewage sludge. Regarding such demanding challenges included in the current direction of the European policy approach, there is a high need to provide accurate indicators to monitor the CE model implementation in the wastewater sector.

In the thematic literature, there is a wide range of circularity indicators examples established worldwide regarding micro, meso and macro scales for various CE aspects (Saidani et al.,

2019) with well-described examples of applying CE indicators in specific countries and regions (mainly China) (Pintér, 2006).

Therefore, the present study aims to review the existing indicators for resource recovery in the wastewater sector showing the essential features of well-designed indicators and providing key recommendations for the selection of the most appropriate indicators.

2. Research Framework

A literature review of existing indicators describing CE aspects has been done with special attention given to the following aspects of the wastewater sector: technical (effectiveness of nutrients removal and resources recovery), legal (regulations regarding the removal of pollutants from wastewater and the final content of nutrients in the excessive sewage sludge), environmental (impact on the water environment by eutrophication and toxic compounds discharge) and others related issues (Barquet et al., 2020).

Article screening was based on searching publication databases for relevant keywords presented in Table 1. No additional limitations regarding the period, region of the study or open access availability, was used in the article screening (Cwiklicki and Wojnarowska, 2020). Primary selected scientific articles published in open access were found using scientific search engines such as: ScienceDirect, SpringerLink, Multidisciplinary Digital Publishing Institute - MDPI publications database, Google Scholar and Web of Science (Smol et al., 2020a). Publications without access to the full text were secondly searched in ResearchGate and other scientific repositories provided by various academic or research institutions.

Table 1. Main keywords used for article screening

Aspects	Technical	Legal	Environmental	Other
Used keywords	"wastewater treatment", "WWTP", "nutrients recovery", "phosphorus recovery", "water recycling", "sewage sludge", "sewage	"effluent requirements", "heavy metals content", "maximum nutrient loads", "maximum pollutants loads",	"bio-based fertilizers", "organic fertilizers", "compost", "eutrophication", "water pollution",	"circular economy", "secondary raw materials", "nutrient bioavailability", "phosphorus solubility", "CE

	sludge ashes”, “struvite”, “MAP”, "calcium phosphate”, "Ca-P”, “water recycling”, “biogas”, “anaerobic digestion”, “hydrochar”	“sewage sludge regulations”, “waste ordinance”, “water ordinance”	“water scarcity”	indicator”

From the selected literature 83 scientific publications, 13 documents by governmental bodies, 1 PhD thesis and 1 project presentation were included in the study as shown in Figure 1.

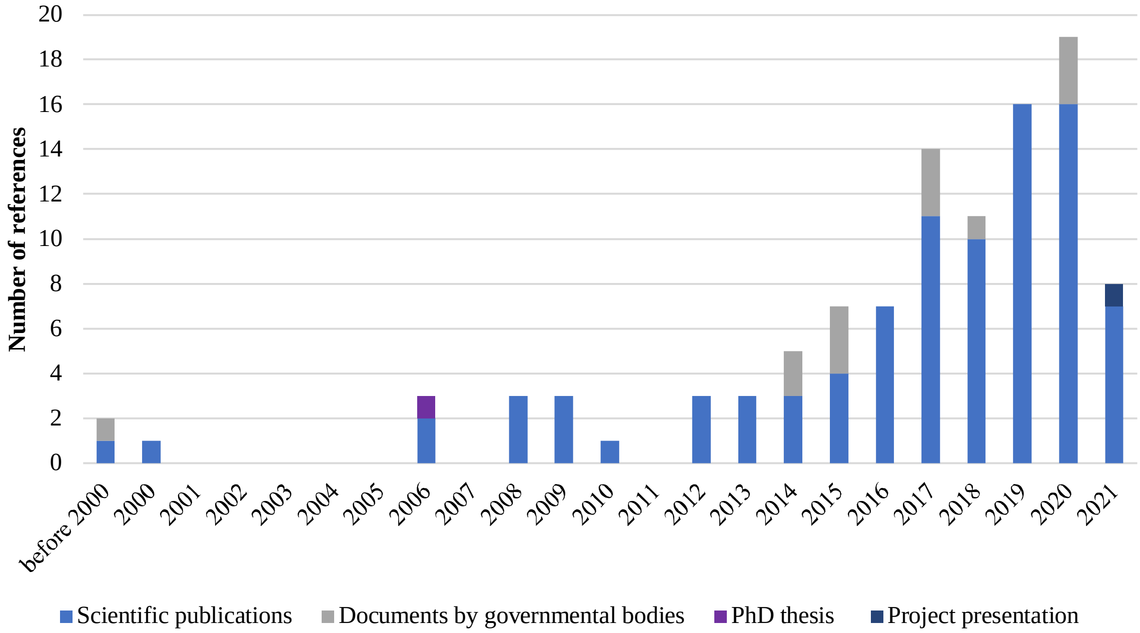

Figure 1. Number of references used in the present study on indicators related to wastewater sector and associated processes

The identified indicators were described, precisely analyzed and summarized to present a set of indicators for monitoring the wastewater sector transition in terms of resource recovery following the CE model (Table 2).

3. Results

Within the present study, numerous indicators for resource recovery have been identified as a potential tool for the CE model implementation in the wastewater sector covering a wide range of aspects such as nutrient removal and recovery, sewage sludge processing, and biofertilizer production, among others. In the majority of indicators, equations with appropriate formulas have been presented.

3.1. Wastewater service coverage indicator (I_{WSC})

One of the most basic indicators that have several implications for other CE measures is the coverage of the wastewater service. The number of inhabitants connected to the sewage system is increasing worldwide, however, there are still countries and regions where there are only a few municipalities with a centralized wastewater collection system (Simha et al., 2017). On the contrary, in most developed countries, the level of sewage system coverage reaches nearly 100% of inhabitants connected to the sewage system in urban living areas (Słyś and Stec, 2020). This satisfactory level was achieved mainly due to the implementation of national programs on municipal wastewater treatment as a result of the UWWTD implementation in the EU countries (European Environmental Agency, 2020). The monitoring of the wastewater service coverage was considered as an important CE indicator in many studies (ESCAP, 2015; Nika et al., 2020; OCED, 2018; Water Sector Regulatory Council of Palestine, 2017) due to the wider possibilities of pollutants discharge control and energy and resources recovery in large WWTPs (Panepinto et al., 2016). Wastewater service coverage can be calculated according to Equation (1) (Chen et al., 2015):

$$I_{WSC} = \frac{n_{connected}}{n_{total}} \cdot 100\% \qquad (1)$$

where:

$n_{connected}$ – number of inhabitants connected to the sewage system in a certain area (e.g. city, region, country etc.) [capita/km^2],

n_{total} – total number of inhabitants in the analyzed area [capita/km^2].

3.2. Nutrient removal efficiency indicator ($I_{RE(N/P)}$)

The current legislation concerning wastewater treatment among others in the EU Member States is based on maximum permissible concentrations of nutrients and a minimum level of nutrients removal depending on the WWTP size set in population equivalent (PE) (European Commission, 1991). Therefore, regarding the limits included among others in the UWWTD, basic indicators concerning the removal efficiency for N ($I_{RE(N)}$) and P ($I_{RE(P)}$) can be calculated according to Equations 2a and 2b, respectively (European Commission, 1991):

$$I_{RE(N)} = \frac{(Ci_N - Ce_N)}{Ci_N} \cdot 100\% \tag{2a}$$

where:

Ci_N – total N content in raw wastewater (influent) [mg/l],

Ce_N – total N content in treated wastewater (effluent) [mg/l], and

$$I_{RE(P)} = \frac{(Ci_P - Ce_P)}{Ci_P} \cdot 100\% \tag{2b}$$

where:

Ci_P– total P content in raw wastewater (influent) [mg/l],

Ce_P – total P content in treated wastewater (effluent) [mg/l].

The above indicators set in mg/l could be based on the monitoring data required by law in most WWTPs globally, mainly as daily averages (Neverova-Dziopak and Preisner, 2015). However, they can be also expressed as nutrient loads in the influent and effluent per year e.g. as tones of removed N and P per year [MgN/year] or [MgP/year] which is also a commonly used indicator (HELCOM, 2018).

3.3. Organic matter removal efficiency indicator (I_{RECOD})

Besides nutrients also organic matter plays a key role for the WWTPs circularity. Especially chemical oxygen demand (COD) removed load is an important indicator for calculating energy recovery potential, while carbon is main the energy source for further processing (Pitas et al., 2010). Therefore, a load of COD removed and deposited in the sewage sludge can be calculated following Equation 3 (Yan et al., 2017):

$$I_{RECOD} = \frac{Q_w(\mathrm{COD}_{in} - \mathrm{COD}_{\mathrm{eff}})}{10^6} \tag{3}$$

where:
Q_w – wastewater flow [m^3/day],
COD_{in} – chemical oxygen demand concentration in the influent [mg/l],
COD_{eff} – chemical oxygen demand concentration in the effluent [mg/l].

3.4. Sewage sludge processing indicators (*Iss_{proc}*)

The existing methods for resources recovery at WWTPs are mainly focused on P recovery as it is a critical raw material and there are currently various available technical methods of its recovery from raw wastewater, sewage sludge, dewatering liquors, and SSA (Egle et al., 2016; Havukainen et al., 2016; Shaddel et al., 2019a).

Sewage sludge is a common by-product of the wastewater process and its amounts depend on the applied wastewater treatment technology and the pollutants load in the influent (Chiavola et al., 2020). Regarding the CE model assumptions, it is essential to ensure a rigid monitoring system for the applied methods concerning sewage sludge processing and nutrient recovery. A study by Rosiek (2020) presents, among a range of indicators concerning wastewater and sewage sludge treatment methods, a set of more precise indicators (a-i) including sludge application types in terms of the total sewage sludge generated during the year. Additionally, energy recovery from sewage sludge is a CE indicator by using anaerobic digestion or application for cultivating energy crops (Antonkiewicz et al., 2019; Dubis et al., 2020) or as a secondary fuel in a cement plant (Fang et al., 2015):

a) applied in agriculture [Mg/year] or [%],
b) applied in land reclamation [Mg/year] or [%],
c) applied in cultivation of plants intended for compost production [Mg/year] or [%],
d) applied in cultivation of energy plants [Mg/year] or [%],
e) anaerobically digested [Mg/year] or [%],
f) applied as an alternative fuel in cement plants [Mg/year] or [%],
g) incinerated [Mg/year] or [%],
h) landfilled [Mg/year] or [%],
i) stored at the WWTPs [Mg/year] or [%].

Moreover, there are different purposes to use the above indicators in the form of their share rather than absolute units. Based on the example of landfilled and incinerated sewage sludge as a share of the total sludge generated different regions or countries can be compared in terms of their transition towards CE.

3.5. Treated wastewater recovery indicator for irrigation (I_{WR})

Wastewater reuse in agriculture has been identified as a measure to mitigate water scarcity, improve crop productivity and environmental sustainability (Kanyoka and Eshtawi, 2013). Despite this fact, it has been reported that only 2,4% of treated wastewater has been reused for agricultural needs in Europe (European Commission and Deloitte, 2015). At the same time, southern European countries with a dry and warm climate had serious issues with water scarcity (Voulvoulis, 2018). To mitigate water scarcity, some countries including Greece, Italy, Portugal and Spain have already adopted national regulations on the reuse of wastewater (Ungureanu and Vladut, 2018). However, using wastewater for irrigation of consumable crops has many risks concerning its potential contamination and forces the farmers to use extra caution and means (Ungureanu et al., 2020). Nevertheless, there are many types of agricultural products that have a high potential to be irrigated with treated wastewater and therefore it is important to monitor the treated wastewater reuse for irrigation for a certain WWTP or area, region or country based on Equation 4 (Pistocchi et al., 2017):

$$I_{WR} = \frac{Q_{ir}}{Q_{ef}} \cdot 100\% \tag{4}$$

where:

Q_{ir} – treated wastewater flow reused for irrigation [m^3/year],

Q_{ef} – total effluent flow [m^3/year].

The data used by water recovery indicator could be obtained from a flow measuring devices in the final effluent line (at the discharge point) and by installing an additional measuring unit for the recovered water that will be applied for irrigation.

3.6. *Effluent inorganic content indicator (I_{EIC})*

An important feature of effluents from WWTPs is the content of inorganic nutrients compounds. This is because the bioavailability of nutrients to aquatic vegetation is tightly associated with the share of inorganic (mineral) forms, such as ammonia nitrogen (NH_4-N), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N) and orthophosphates (PO_4-P) (Preisner et al., 2021a). Similar to crops fertilization, the level of directly bioavailable nutrients introduced into water bodies is often a decisive factor of the undesired eutrophication process progress (Thieu et al., 2010). Moreover, many studies have confirmed a direct link between loads of inorganic nutrients discharged with municipal and industrial effluents with the degradation of natural water ecosystem balance in terms of trophic state (Callisto et al., 2014; Zaragüeta and Acebes, 2017; Zhang et al., 2018). The indicator showing the content of inorganic N ($I_{EIC(N}$) and P ($I_{EIC(P)}$) compounds in their total load can be calculated according to Equations 5a and 5b, respectively (Li and Brett, 2015, 2012; Preisner et al., 2020):

$$I_{EIC(N)} = N_i \cdot Q_d \tag{5a}$$

$$I_{EIC(P)} = P_i \cdot Q_d \tag{5b}$$

where:

N_i – inorganic nitrogen concertation [mg/l],

P_i – inorganic phosphorus concentration [mg/l],

Q_d – daily average effluent flow [l/day].

The inorganic N and P concentration values should be included in the permanent monitoring of the WWTP (e.g. as daily average), which in many cases is focused only on total nutrient forms according to legal requirements.

3.7. *Nutrient recovery indicator ($I_{rec(N/P)}$)*

On the contrary, a high level of nutrients is highly desired in the sewage sludge which can be used as a base for producing alternative (secondary) fertilizers (Chrispim et al., 2019). One of the most applied solutions for P recovery is struvite – magnesium ammonium phosphate (MAP) precipitation from the sludge dewatering liquors with high P concentration (Chrispim et al., 2019), while the other method is based on P recovery from SSA (Krüger and Adam, 2015). Moreover, there are technologies capable to recover P by calcium phosphate (Ca-P) precipitation and phosphoric acid (H_3PO_4) production (Folino et al., 2020).

Besides P, also N-based fertilizers can be produced out of sewage sludge. What is important in terms of energy efficiency, the production of synthetic N-based fertilizers is based on ammonia produced by the Haber-Bosch process which is a very energy-consuming process that results in large emissions of greenhouse gases (GHGs) into the atmosphere (Deviatkin et al., 2019; Rossi et al., 2018). Therefore, the recovery indicators for N ($I_{rec(N)}$) and P ($I_{rec(P)}$) are expressed by the total mass of N and P recovered from sewage sludge at a WWTPs annually (Mg/year) (Cornel and Schaum, 2009; Sena et al., 2021; Sengupta et al., 2015) or as a share of N or P input and output at the WWTP according to Equations 6a and 6b, respectively (Shaddel et al., 2019b):

$$I_{rec(N)} = \frac{N_{initial} - N_{final}}{N_{initial}} \cdot 100\% \qquad (6a)$$

$$I_{rec(P)} = \frac{P_{initial} - P_{final}}{P_{initial}} \cdot 100\% \qquad (6b)$$

where:

$N_{initial}$ – nitrogen content before recovery operations [MgN/year],

$P_{initial}$ – phosphorous content before recovery operations [MgP/year],

N_{final} – nitrogen content after recovery operations [MgN/year],

P_{final} – phosphorous content after recovery operations [MgP/year].

While calculating nutrient recovery indicators it is important to use the same form (compound) of N or P being recovered (e.g. NH_4-N or PO_4-P used in struvite precipitation) (Sena et al., 2021).

3.8. *Biological dephosphatation potential indicator (I_{BDP})*

The biological nutrient removal (BNR) processes are considered to be the most reliable methods to obtain the base for further nutrient recovery processes while the application of biological wastewater treatment is characterized by the lack of unwanted residues in the sewage sludge (Meena et al., 2019). On the other hand, chemical treatment with metal-based precipitants can result in some metal salts residues bound to P compounds in the sewage sludge what might influence consequent sludge processing and the potential to apply CE concept by nutrients recovery to produce secondary bio-based fertilizers (BBFs) (Szabó et al., 2008). However, not every wastewater can be efficiently treated using biological methods only due to its various characteristics. The wastewater sensibility to biological P removal (dephosphatation) can be initially assessed based on the ratio between COD and total phosphorus (TP) according to Equation 7 (Lu et al., 2016).

$$\mathrm{I_{BDP}} = \frac{\mathrm{COD}}{\mathrm{TP}} \tag{7}$$

where:

COD – chemical oxygen demand concentration in the influent [mg/l],

TP – total phosphorous concentration in the influent [mg/l].

The I_{BDP} indicator values above 50 suggest a reasonable biological dephosphatation potential of wastewater resulting in the TP content of <2 mg/L in the final effluent without chemical precipitation (Aboulhassan et al., 2006; Lu et al., 2016; Sikosana et al., 2017). Values below 50 indicate that biological treatment needs to be supported by other physical or chemical treatment methods (Miksch and Sikora, 2012) that might affect the final composition of sewage sludge and its potential in terms of the CE assumptions.

3.9. The technological nutrient performance indicator for the recovered sludge (I_{sg})

A CE indicator of technological nutrient performance for the recovered sludge ($I_{sg,tn}$) was proposed by Molina-Sánchez et al. (2018) for the paper industry. The $I_{sg,tn}$ indicator informs about the amount of the recovered sludge from treating paper mill wastewater and about the reuse efficiency of the recovered sludge for the paper production process according to Equation 8 (Molina-Sánchez et al., 2018):

$$\mathrm{I_{sg,tn}} = \frac{\mathrm{m_{sg,r}}}{\mathrm{Q_{PMW}}} \tag{8}$$

where:

$m_{sg,r}$ – mass of the sewage sludge recovered [Mg/year],

Q_{PMW} – wastewater flow of the paper mill [m^3/year].

In terms of the wastewater sector, the productive sludge generation indicator ($I_{sg,ce,p}$) might be applied for e.g. cellulose recovery from wastewater or other raw materials recovery from industrial sewage sludge and calculated according to Equation 9 (Molina-Sánchez et al., 2018):

$$I_{sg,ce,p} = I_{sg,tn} \cdot \frac{Q_{PMW}}{P_p} \cdot 100\% \tag{9}$$

where:

$m_{sg,r}$ – mass of the sewage sludge recovered [Mg/year],

Q_{PMW} – wastewater flow of the paper mill [m^3/year].

P_p – mass of product produced from recovered material [Mg/year]

3.10. Composting indicator for sewage sludge ($I_{c,ss}$)

Composting of sewage sludge is a simple and cost-effective treatment method based on the organic matter decomposing process (Fang et al., 1999). Due to the high share of organic matter in the composted sewage sludge it is also used for soil conditioning and non-consumable fertilization due to the possible content of toxic heavy metals.

In practice, sewage sludge is mixed with structural materials, such as wooden shavings, sawdust, bark, straw, grass, leaf litter in a suitable proportion to obtain a C:N ratio of about 30:1 in the compost (Kosobucki et al., 2000). Regarding the CE model implementation in the wastewater sector, Salguero-Puerta et al. (2019) proposed an indicator of CE efficiency for composting of organic waste fractions. Based on the above study a wastewater sector-oriented composting indicator for sewage sludge ($I_{c,ss}$) can be calculated according to Equation 10 (Salguero-Puerta et al., 2019):

$$I_{c,ss} = \frac{m_{BW}}{m_{bio}} \cdot 100\% \tag{10}$$

where:

m_{BW} – total amount of biodegradable waste generated for potential composting (e.g. organic fractions of sewage sludge that are subject to composting) [Mg/year],

m_{bio} – total amount of biodegradable waste generated (e.g. total mass of dewatered sludge) [Mg/year].

Even though this indicator was developed for biodegradable waste including organic matter and paper fractions, it can also be used in the wastewater sector in the context of sewage sludge composting.

3.11. Biogas production indicator from sewage sludge ($I_{b,ss}$)

Biogas is obtained within the decomposition of organic matter in the absence of oxygen by the application anaerobic digestion process and it consists mainly of methane gas (CH_4) in approx. 60-70% and carbon dioxide (CO_2) in approx. 30-40% with trace amounts of water vapor (Jin et al., 2009). Due to its high calorific value (approx. 23 MJ/m^3), biogas is a prominent energy source (Kacprzak and Kupich, 2021). Moreover, biogas obtained from sewage sludge is considered as a renewable energy source (Piwowar, 2020). The composition of biogas depends mainly on the type of organic matter source, digestion time and temperature (Appels et al., 2008). However, sewage sludge is often used for biogas production with some addition of biodegradable waste (Gandiglio et al., 2017). While biogas production is a sustainable method of waste management due to its lower environmental footprint compared to natural gas as an energy source, the indicator of CE efficiency for biogas ($I_{b,ce}$) proposed by Salguero-Puerta et. al (2019) was modified to include information about the energy recovery potential from sewage sludge with potential biodegradable additives from another sectors (Equation 11):

$$I_{b,ss} = \frac{Q_b}{m_{bio}} \tag{11}$$

where:

Q_b – amount of biogas obtained from anaerobic digestion of sewage sludge [m^3/year],

m_{bio} – total amount of biodegradable waste generated (e.g. total mass of dewatered sludge) [Mg/year].

3.12. Pollutant content indicator for the recovered sewage sludge (I_{CDUP})

The application of recovered sewage sludge is limited by various legal regulations in different countries based on their pollutant content, such as heavy metals, organic pollutants and microbial parameters, etc. (Vogel et al., 2017). To assess the quality of recovered sludge regarding the biggest concern for their land application – the heavy metals content – damage units are used as an indicator (I_{CDUP}). The damage units inform about the pollutant load as a harmful coefficient by including the set limit values for particular heavy metals (e.g. direct land application) and calculating the coefficient by dividing each heavy metal content of a final product by the limit value according to Equation 12 (Egle et al., 2016):

$$\mathrm{I_{CDUP}} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{Ci}{Ci^{ref}}}{\mathrm{P_{concentration}}} \tag{12}$$

where:

C_i – concentration of heavy metal in the recovered material [mg/kg],

C_i^{ref} – concentration of heavy metal in the reference material (e.g., compost of a certain class, sewage sludge eligible for direct land application) [mg/kg].

The average damage units per 1 g P of untreated sewage sludge is approx. 0.5 while for SSA only 0.35 and for a commercial fertilizer (Single Superphosphate - SSP) is 0.23 and the lowest damage units are observed in the digester supernatants ($I_{CDUP} < 0.02$) (Egle et al., 2016).

3.13. Quality indicators for SSA recovery ($I_{SSA,q}$)

Mono or co-incineration of sewage sludge is used in many countries as a primary method of sewage sludge processing (Nättorp et al., 2015). SSA has a higher P concentration than raw sewage sludge, however, they may contain many impurities affecting the quality of recovered P compounds (Krüger and Adam, 2017). After efficient treatment, SSAs can be used as a substitute for natural raw material according to the CE model principles (Havukainen et al., 2016; Herzel et al., 2016). One of the important parameters of sewage sludge processing is the content of various minor impurities such as iron (Fe), aluminum (Al) and magnesium (Mg) oxides. Gorazda et al. (2017) have used specific indicators regarding the (a) minor element (Fe, Al and Mg) ratio and (b) the Fe to Al ratio to recover P in the form of P_2O_5. Regarding the Ca content in the SSA an additional indicator (c) has been used for CaO to P_2O_5 ratio:

a) Minor element ratio indicator (I_{MER}) can be calculated according to Equation 13a (Gorazda et al., 2017):

$$\mathrm{I_{MER}} = \frac{\mathrm{C_{Fe}+C_{Al}+C_{Mg}}}{\mathrm{C_{P_2O_5}}} \tag{13a}$$

where:

C_{Fe} – Fe_2O_3 content in the SSA [mg/kg],

C_{Al} – Al_2O_3 oxides content in the SSA[mg/kg],

C_{Mg} – MgO content in the SSA [mg/kg],

C_{P2O5} – P_2O_5 content in the SSA [mg/kg].

b) Fe and Al ratio ($I_{Fe\&Al}$) can be calculated according to Equation 13b (Gorazda et al., 2017):

$$I_{Fe\&Al} = \frac{C_{Fe}+C_{Al}}{C_{P_2O_5}} \tag{13b}$$

where:

C_{Fe} – Fe content in the SSA [mg/kg],

C_{Al} – Al content in the SSA [mg/kg].

Therefore, the lower I_{MER} and $I_{Fe\&Al}$ indicators are, the higher quality is the obtained SSA.

c) The $I_{Ca/P}$ indicator can be calculated according to Equation 13c (Gorazda et al., 2017):

$$I_{Ca/P} = \frac{C_{CaO}}{C_{P_2O_5}} \tag{13c}$$

where:

C_{CaO} – CaO content in the SSA [mg/kg],

C_{P2O5} – P_2O_5 content in the SSA [mg/kg].

Moreover, the $I_{Ca/P}$ indicator has high importance regarding the quality of obtained SSA (usually $I_{Ca/P}$ <1) due to its pH impact and several biological functions critical for plant growth, while a naturally occurring phosphate ore has $I_{Ca/P}$ up to 1.6 (Gorazda et al., 2017).

3.14. Indicator for chemicals used for wastewater treatment ($I_{WWT,chemicals}$)

To achieve effluent quality according to legal regulations for P removal, metal-based coagulants are added to wastewater in many WWTPs to support biological P removal or as the main P removing method (Korving et al., 2019). With the increase of P removal efficiency, there are important downsides of this practice in the CE context (Wilfert et al., 2018). Chemicals used in WWTPs for P removal (coagulants) are based mainly on Al and Fe salts so their addition result in the presence of Al and Fe compounds in the sewage sludge which lowers the bioavailability of the potential recovery product to be used as alternative fertilizer or limits the recovery method to sludge incineration and SSA processing (Forrest et al., 2008). There is also a possibility to use lime instead of Al or Fe salts. However, due to a large amount of sludge generated and higher investment and operating costs, this method is not often used in full-scale large WWTPs (Przywara, 2006). Therefore, the volume of wastewater being treated with different P removal methods is an important indicator to decide about the method of sewage sludge processing to provide the highest P recovery potential. The indicators describing the above issue are as follows (Korving et al., 2019):

a) wastewater treated using only non-chemical P removal methods ($I_{non\text{-}chem}$):

$$I_{non-chem} = \frac{Q_{non-chem}}{Q_w} \tag{14a}$$

b) wastewater treated using mainly non-chemical P removal methods but requiring temporary chemical support ($I_{supp\text{-}chem}$):

$$I_{supp-chem} = \frac{Q_{support-chem}}{Q_w} \tag{14b}$$

c) wastewater treated using only chemical P removal methods ($I_{pure\text{-}chem}$):

$$I_{pure-chem} = \frac{Q_{pure-chem}}{Q_w} \tag{14c}$$

where:

$Q_{non\text{-}chem}$ – wastewater treated without chemical addition for P removal (e.g. biological P removal, membrane bioreactors, adsorbents, etc.) [m^3/year],

$Q_{supp\text{-}chem}$ – wastewater treated with the domination of non-chemical method but with temporary chemical support (e.g. due to exceeding the legal requirements for P content in the effluent) [m^3/year],

$Q_{pure\text{-}chem}$ – wastewater treatment based only on chemical P removal methods [m^3/year],

Q_w – total wastewater flow [m^3/year].

The above values could be obtained from the annual reports by WWTPs that should exactly know how much coagulants (chemicals) have been used annually for P removal.

3.15. BBFs indicators ($I_{BBF(N/P)}$)

The indicator for the usage of BBFs produced based on wastewater sector-derived products can be expressed as follows (Nika et al., 2020):

a) BBFs applied (as N content) [MgTN/year],
b) BBFs applied (as P content) [MgTP/year].

Moreover, the ratio between BBFs to conventional fertilizers is used to present the current trends in the usage of BBFs produced out of sewage sludge, its dewatering liquors or SSA in terms of N content (Equation 15a) and P content (Equation 15b) (Nika et al., 2020):

$$I_{BBF(N)} = \frac{N_{BBF}}{N_{CF}} \cdot 100\% \tag{15a}$$

where:

N_{BBF} – N content in BBFs [mg/kg],

N_{CF} – N content in the conventional fertilizers [mg/kg].

$$I_{BBF(P)} = \frac{P_{BBF}}{P_{CF}} \cdot 100\% \tag{15b}$$

where:

P_{BBF} – P content in BBFs [mg/kg],

P_{CF} – P content in the conventional fertilizers [mg/kg].

As the above indicators are based only on the wastewater sector-derived products (mainly sewage sludge and digestate), it is important to consider a separate indicator for manure usage in agriculture (Recap Project, 2021).

3.16. Hydrochar yield indicator for hydrothermal carbonization of sewage sludge ($I_{y,hydrochar}$)

Sewage sludge valorization is an important element for CE implementation in the wastewater sector (Klavins et al., 2021). According to the latest publications (Kapetanakis et al., 2021; Knötig et al., 2021; Xiong et al., 2021), hydrochar produced from thickened sewage sludge shows satisfactory fuel properties in terms of higher heating value and reduced ash content. In a study by Merzari et al. (2020) three types of sewage sludge (thickened, digested and dewatered sludge) have been investigated in terms of resulting hydrochar properties using hydrothermal carbonization. Therefore, an indicator for the hydrochar yield has been included (Equation 16) (Merzari et al., 2020):

$$I_{y,hydrochar} = \frac{M_{hydrochar,dry}}{M_{sludge,dry}} \quad (16)$$

where:

$M_{hydrochar,dry}$ – dry mass of obtained hydrochar [Mg/year],

$M_{sludge,dry}$ – dry mass of the used sewage sludge [Mg/year].

Due to a high thermal reactivity hydrochar could be co-incinerated with fossil fuels such as hard coal (Arauzo et al., 2020). However, considering the current climate neutrality approach set by the European Green Deal strategy (Preisner et al., 2021b) hydrochar could be also used as a soil amendment (Merzari et al., 2020).

Table 2 summarizes the results of the study showing their acronyms, core application, measured parameters, and references used as a source of information about the reviewed indicators.

Table 2. Set of indicators to measure the transition of the wastewater sector towards CE

Indicator	**Acronym**	**Core application**	**Measured parameter**	**Reference**
Wastewater service coverage indicator	I_{WSC}	Wastewater treatment	number of inhabitants connected to the sewage system / total population	OECD 2018, Chen et al. 2015

			in the area	
Nutrient removal efficiency indicator	$\mathrm{I}_{\mathrm{RE(N)}}$, $\mathrm{I}_{\mathrm{RE(P)}}$	Wastewater treatment	Reduction (%) of a total load of N and P	Based on the UWWTD (91/271/EEC)
Organic matter removal efficiency indicator	$\mathrm{I}_{\mathrm{RECOD}}$	Sewage sludge treatment	Mg of removed COD load per year	Yan et al. 2017
Sewage sludge processing indicators	-	Waste management	Mg or share (%) of dry matter of sewage sludge processed using different waste management methods	Rosiek 2020
Treated wastewater recovery indicator for irrigation	I_{WR}	Agricultural water use	Share (%) of treated wastewater flow to the wastewater flow reused for irrigation	Pistocchi et al. 2017
Effluent inorganic content indicator	$\mathrm{I}_{\mathrm{EIC(N)}}$, $\mathrm{I}_{\mathrm{EIC(P)}}$	Wastewater treatment	Share (%) of inorganic to total nutrient compounds in the WWTP effluent	Li and Brett 2012
Nutrient recovery indicator	$\mathrm{I}_{\mathrm{rec(N)}}$, $\mathrm{I}_{\mathrm{rec(P)}}$	Sewage sludge or dewatering liquors treatment	Mg of N or P recovered annually	Shaddel et al. 2019
Biological dephosphatation potential indicator	$\mathrm{I}_{\mathrm{BDP}}$	P recovery potential from sludge dewatering liquors	COD/TP ratio	Miksch and Sikora 2012
Technological nutrient performance indicator for the recovered sludge	I_{sg}	Paper industry	Mg of recovered sludge (used as a mineral load during the manufacturing process) per m^3 of discharged wastewater	Molina-Sánchez et al. 2018
Composting indicator for sewage sludge	$\mathrm{I}_{\mathrm{c,ss}}$	Wastewater treatment	kg of biodegradable fraction / kg of produced sewage sludge	Based on Salguero-Puerta et al. 2019
Biogas production indicator from sewage sludge	$\mathrm{I}_{b,ss}$	Sewage sludge treatment	m^3 of biogas obtained in anaerobic digestion / kg of produced sewage sludge	Based on Salguero-Puerta et al. 2019
Pollutant content indicator for the recovered sewage sludge	$\mathrm{I}_{\mathrm{CDUP}}$	Sewage sludge processing and application	mg of Zn, Cu, Ni, Pb, Cd, Cr or Hg / kg of sewage sludge	Egle et al. 2016
Quality indicators for SSA recovery	I_{MER}, $\mathrm{I}_{\mathrm{Fe}\&Al}$, $\mathrm{I}_{\mathrm{Ca/P}}$	Sewage sludge incineration	mg of Fe, Al, Mg, Ca oxides / mg of P_2O_5	Gorazda et al. 2017
Indicator for chemicals used for	$\mathrm{I}_{\mathrm{non-chem}}$, $\mathrm{I}_{\mathrm{supp-chem}}$,	Wastewater treatment	Mg of metal-based coagulants / m^3 of raw wastewater (optionally a	Korving et al. 2019

wastewater treatment	$\mathrm{I}_{\mathrm{pure-chem}}$		number of WWTPs without chemical P removal)	
BBFs indicators	$\mathrm{I}_{\mathrm{BBF(N)}}$, $\mathrm{I}_{\mathrm{BBF(P)}}$	Agriculture	kg/ha/year of pure P (or N) in BBFs	Nika et al. 2020
Hydrochar yield indicator for hydrothermal carbonization of sewage sludge	$\mathrm{I}_{\mathrm{y,hydrochar}}$	Sewage sludge treatment	Mg of hydrochar dry mass / Mg of sewage sludge dry mass	Merzari et al., 2020

4. Discussion

Resource recovery from various material flows present in WWTPs has an important role in terms of the successful transition towards CE not only for the wastewater sector but for the entire economy. Nutrients, rare earth elements, biomass, cellulose, hydrochar, organic compounds and many other valuable resources can be recovered from wastewater or sewage sludge by using appropriate processing methods. CE indicators are needed to measure the circularity of WWTPs and to propose a counter-measure for their improvement with the CE framework.

4.1. Relevant findings of previous studies on CE indicators

The importance of CE indicators has been analyzed in numerous publications (Chen et al., 2015; De Pascale et al., 2021; Sánchez-Ortiz et al., 2020; Su et al., 2013) with a major contribution made by Moraga et al. (2019) which analyzed what aspects are measured with previously developed CE indicators. Their results show that among the indicators proposed by the EC in the communication (COM no. 29, 2018) on a monitoring framework for the CE (Cornel and Schaum, 2009), none of the parameters is dedicated to the monitoring within the wastewater sector. By omitting this critical area, the whole scope of the CE assumptions implementation can be highly questionable because the wastewater sector has significant importance for the secondary raw materials and water recovery (Frijns et al., 2013).

Within non-EU countries, a study by Geng et al. (2012) presents an evaluation of a national indicator system o the CE implementation from China. It was the first national CE indicators system developed to provide valuable metrics for policy and decision-makers and help to achieve CE goals and outcomes. Their study revealed the imperfections of the Chinese indicator system due to the lack of a comprehensive set of sustainability indicators in terms of social, business, urban and industrial symbiosis, absolute material and energy reduction, and prevention-oriented indicators including the wastewater sector (Geng et al., 2012).

Great progress in the CE indicators area for the wastewater sector was made by Molina-Sánchez et al. (2018) which have proposed sustainability indicators for managing waste and discharges from a paper mill. By the implementation of the CE model assumption, it was possible to develop indicators regarding the resource recovery from paper mill effluent treated in an on-site WWTP. Moreover, Molina-Moreno et al. (2017) presented similar findings and indicators for pig manure treatment. These concepts and used methodologies can be successfully transferred to other industrial and municipal plants and result in a set of new indicators to measure the CE assumptions implementation (Folino et al., 2020).

A detailed analysis of challenges and opportunities for the CE implementation in the wastewater sector was presented in a study by Guerra-Rodríguez et al. (2020). The authors have analyzed many important aspects that can be used as new indicators in this particular sector: wastewater reclamation and reuse, resources recovery, sewage sludge valorization and WWTPs energy self-sufficiency.

Moreover, a study by Buonocore et al. (2018) presents an analysis of 5 scenarios by life cycle assessment (LCA) for wastewater and sewage sludge management in a WWTP in Italy. LCA was used to establish impact indicators regarding freshwater eutrophication potential, human toxicity potential, global warming potential and fossil depletion potential (Buonocore et al., 2018).

A different scenario-based analysis was done by Chen et al. (2019) which have considered environmental, energy and economic aspects of integrated sewage sludge and municipal solid waste processing in China by mono-incineration and co-incineration. Their results refer to indicators on ozone layer depletion, terrestrial and aquatic eco-toxicity, global warming potential and carcinogens and non-carcinogens release, aquatic acidification and eutrophication, mineral extraction, land occupation, renewable energy production, etc. (Chen et al., 2019).

Furthermore, data from 20 Chinese WWTPs were used by Yan et al. (2017) to develop indicators for zero-energy WWTPs. The proposed zero-energy model consists of key energy-oriented indicators including excessive sludge yield [Mg/year], organic content in the sludge [%] based on COD flows, heat demand for sludge processing [kWh/day], electricity and heat recovery [MJ/day], etc (Yan et al., 2017).

The degree of circularity was analyzed based on the data from two WWTPs in Ekaterinburg, Russia by Kiselev et al. (2019) by including 3 scenarios for developing integral circularity indexes. The scenarios were based on 7 elementary indicators such as: "reduce" and "reuse" in terms of 3 indicators for wastewater flow, sewage sludge flow and energy flow and a separate "recycle" indicator for sewage sludge flow (Kiselev et al., 2019).

A different sustainability-oriented indicators were proposed for sewage sludge management by Grönlund (2019) based on four methods: LCA, exergy analysis, emergy analysis, and cost-benefit analysis. Additionally, environmental risk assessment was used regarding large WWTPs and complements the other four methods (Grönlund, 2019).

Moreover, an interesting contribution was made by Avdiushchenko and Zając (2019) which proposed numerous CE indicators to support regional development policy implementation according to the CE assumptions. The authors accurately pointed the levels of industrial and municipal wastewater purified in WWTPs requiring treatment and the level of reused wastewater as a zero-waste economy indicator to monitor CE implementation at the regional level. Furthermore, the above study shows the great importance of CE indicators as an efficient tool for monitoring regional development following CE model principles which cannot be achieved without a sustainable and circular wastewater sector.

The regional aspect seems to have even greater value for the entire wastewater sector while as it was mentioned the development of the secondary raw materials market is one of the biggest barriers in implementing the CE model (Kirchherr et al., 2018; Perdana et al., 2018).

4.2. Recommendations for the design of indicators

Based on the above-mentioned aspects the Authors have proposed a list of important elements to be considered while designing indicators for resource recovery monitoring in the wastewater sector:

a) Importance for the global or local circularity level:

Depending on the measured aspect, the designed indicators should be highly relevant to the global, local or both dimensions of the CE. For instance, indicators such as P recovery level are relevant for both, global and local dimensions while in most regions P is imported from certain countries. On the other hand, water recycling would be valid only in regions suffering from water scarcity and only there water recycling from treated wastewater would be economically reasonable. Furthermore, an indicator for the separate sewer coverage would be less important for rural areas than for highly urbanized terrains with limited natural retention capacity.

b) Range of application:

By using the example of the quality indicators for SSA recovery (e.g. the content of Fe, Al, Mg, Ca oxides per a mg of P_2O_5) it can be explained that this indicator will only be relevant if the SSA are planned to be processed and recovered as a fertilizer. If there are no technical possibilities to process this waste, more attention should be given to other, less complex indicators that affect the circularity level (e.g. land application of sewage sludge).

c) Appropriate units:

Most indicators can be measured using various units. The selection of appropriate units has significant importance for data processing and analysis. Therefore, concentration, share or load can be measured regarding the particular material flow in a WWTP (e.g. agriculture application of sewage sludge can be measured as kg/year, a percentage of the total sludge generation or in other forms). Regardless of the chosen units, it is essential to make sure that data that will be used for compassion with other countries or regions are measured in the same units.

It can be assumed that well-designed indicators will allow monitoring the circularity level of the entire wastewater sector (or particular WWTPs) by showing in numbers the benefits of resource recovery that should result in promoting circular and sustainable policies among policy-makers. Therefore, the development of relevant indicators for the wastewater sector can additionally influence farmers' and consumers' attitudes to secondary fertilizing products from waste-derived products or treated wastewater reuse and many other secondary sources.

It might be difficult to select the most relevant indicator to measure the circularity of the wastewater sector or a particular WWTP. However, using a set of indicators it could be possible to provide an efficient monitoring tool. Therefore, a particular circularity indicator for resource recovery at a WWTP ($I_{CE,RR,WWTP}$) could be formulated as a sum of a minimum 3, most important indicators for the recovery of: nutrients (sum of TN and TP), organic matter and water. The above indicators should be summed up and divided by their number (n) as shown in Equation 17a:

$$I_{CE,RR,WWTP} = \frac{I_{Nutrients} + I_{Organic\ matter} + I_{Water}}{n} \quad (17a)$$

where:

$I_{Nutrients}$ - nutrient recovery rate (including an average recovery rate of both total N and P) [%],

$I_{Organic\ matter}$ - organic matter recovery rate (e.g. as a land application for agricultural or land reclamation purposes, as a soil amendment/fertilizer or as a compost) [%],

I_{Water} - treated wastewater recycling rate for internal processes at the WWTP and recycled wastewater used for irrigation or other local needs [%],

n - number of applied indicators (1-3).

As the values used in the proposed circularity indicator are expressed as a percentage, the $I_{CE,RR,WWTP}$ can range from 0 – 1, where results close to 0 mean low circularity level and results close to 1 mean high circularity level of the analyzed WWTP.

While this study focuses only on resource recovery-oriented indicators there were initially no typical energy-related aspects in the proposed circularity indicator. However, adding a

WWTP energy self-sufficiency indicator (I_{Energy}) would provide a wider CE monitoring framework. The proposal of a circularity indicator including additionally energy self-sufficiency of a WWTP ($I_{CE,RR+E,WWTP}$) is shown in Equation 17b:

$$I_{CE,RR+E,WWTP} = \frac{I_{Nutrients} + I_{Organic\ matter} + I_{Water} + I_{Energy}}{n} \tag{17b}$$

where:

$I_{Nutrients}$ - nutrient recovery rate (including an average recovery rate of both total N and P) [%],

$I_{Organic\ matter}$ - organic matter recovery rate (e.g. as a land application for agricultural or land reclamation purposes, as a soil amendment/fertilizer or as a compost) [%],

I_{Water} - treated wastewater recycling rate for internal processes at the WWTP and recycled wastewater used for irrigation or other local needs [%],

I_{Energy} - energy self-sufficiency calculated as the ratio of energy production to energy consumption [%],

n - number of applied indicators (1-4).

Further modifications could be applied to fit the proposed circularity indicator to the particular case (e.g. to focus only on P recovery and omit N recovery level if needed).

4.3. Drivers and barriers for applying circularity indicators in the wastewater sector

The main driver that should promote the use of circularity indicators in WWTPs is the vision of the clearly presented status of the operating process, which could be adjusted to become more circular. Moreover, resource recovery is irreversibly connected with the economy so the knowledge about which processes could be applied to increase the WWTP revenue encourages to use of circularity indicators becoming a significant driver. In the proposed circularity indicator, nutrient recovery [%] and energy recovery [%] have the highest potential for monitoring and foreseeing potential revenues (or savings) from resource recovery at WWTPs. Potential revenues are mainly connected to elementary indicators such as the biogas production from sewage sludge, nutrient recovery for producing fertilizers and their content in BBFs derived from the wastewater sector. However, drivers for using circularity indicators may be specific for different regions and climate zones. For example, in agricultural areas, dependent on imported mineral fertilizers or suffering from water scarcity there should be a high willingness to use organic matter and water recovery indicators respectively.

On the other hand, from the conducted review, new barriers have been revealed for applying circularity indicators in WWTPs. These barriers are e.g. issues on how to calculate the relevance (weight) of each component of the complex circularity indicator for a particular WWTP or the entire wastewater sector. The determination of which factor is more important than others and to what extent, could be a challenge for further researches and wastewater professionals. Moreover, methodology for parameters analysis differs often between countries so different values may be obtained due to some specific laboratory practices and regulations.

5. Conclusions

The study confirmed the importance of the development of efficient monitoring tools based on indicators capable to present in numbers the most critical information about the resource recovery processes used in the wastewater sector. Furthermore, the CE model assumptions in over their half are directly connected to the wastewater sector. Unfortunately, including many wastewater aspects in the policy framework has not resulted in implementing reliable indicators that could enable to monitor the sector's transition into CE.

Moreover, the study identified blind spots of the current monitoring framework e.g. the nutrients bioavailability aspect while the requirements regarding wastewater treatment are focused only on their total forms omitting the bioavailability of some mineral and organic nutrient compounds. Due to restrictive legal requirements regarding nutrient removal from municipal effluents, large loads of metal-based precipitants are added to wastewater which also has a significant impact on further possibilities of P recovery.

Policy incentives to increase the recovery of various resource streams in WWTPs seem to be not fully implemented in many countries. Therefore, the transformation from WWTPs to resource and energy recovery facilities is still less efficient than it could be. By presenting the identified indicators it was mentioned to influence the further decisions about policy directions regarding the used methods of resource recovery in the wastewater sector.

Recommendations were prepared for the design of indicators regarding resource recovery in the wastewater sector including essential elements of accurate indicators. Based on the review a proposal of a circularity indicator for a WWTP was made to present the application of existing indicators in practice regarding the wastewater sector.

Using the numerical indicators should increase the social and business awareness and willingness to adopt the circular and sustainable usage of waste and by-products from the wastewater sector instead of consuming new raw materials or freshwater and promoting the CE implementation in other economic sectors.

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