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CIRCULAR ECONOMY INDICATORS APPLIED TO WASTEWATER TREATMENT PROCESS

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The present paper presents the results obtained for the evaluation of the circularity index using a methodology existing in the literature. The evaluation methodology of the technological process in the conceptual circular economy is based on the 3R principle (Reuse, Reduce, and Recycle) and it uses the life cycle analysis - LCA, and material flow analysis - MFA. The circularity indices are calculated for a wastewater treatment plant WWTP (Constanta Nord WWTP). Four possible scenarios were considered in which the economic circularity concept was hypothetical applied, for different materials and energy in the technological circuit of the sewage treatment plant. The four scenarios considered are in accordance with hypothetical situations of the technological development of the wastewater treatment plant. Thus, "Scenario 4" in which: the technology used would allow the drying of the sewage sludge and it's recycling, the fermentation of the sludge and the obtaining of biogas, the use of energy from renewable energy sources and the reuse of purified water in human activities, the circularity index is 88%. Compared to "Scenario 1" with circularity indicators quite close to those of "Scenario 4", but without a tertiary water treatment technology at the exit from the treatment plant for drinking water, the circularity index is increased in "Scenario 4" with 25%.

Keywords: 3R, circular economy, circularity indicators, methodology, wastewater treatment plant

1. Introduction

Wastewater treatment plants (municipal or industrial) aim to return wastewater to the specific physic and chemical parameters of effluent water by removing suspended solids, removing dissolved organic substances, nitrogen, phosphorus and other harmful substances [1-3]. Through their activity of returning wastewater to the natural water cycle, sewage treatment plants are technological systems whose activity is directly linked to environmental protection. Under these conditions, the activity of a wastewater treatment plant (WWTP) can easily be included in the concept of circular economy.

The circular economy is the opposite of the linear, traditional economic model according to which we "produce-consume-throw away". The circular

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economy is a model of production and consumption based on the regeneration and reuse of materials and products so that the life cycle of products is increased and the waste obtained is minimized. Thus, the term circular economy includes extending the life cycle of products by sharing, renting, reusing, refurbishing, and recycling existing materials and products. The circular economy model is based on the 3R principles (Reduce, Reuse, and Recycle) [4-6].

In 2021 the European Parliament adopted a resolution on the actions to be taken by 2050 by the member states in the EU to be able to have a transition to a circular economy [7, 8].

The advantages of the circular economy concept are: (i) environmental protection: reuse and recycling of materials and materials from consumed products will reduce the rate of consumption of natural resources, reduce the negative impact on the environment and limit the loss of biodiversity; (ii) reducing dependence on raw materials; (iii) jobs and savings for consumers. It is estimated that 700,000 new jobs will be created in the EU by 2030 [7, 8].

From the point of view of the circular economy, a modern municipal wastewater treatment plant [5] must secure a large part of the energy required for the technological process from renewable energy sources, to recover raw materials and minimize the amount of waste resulting from the wastewater treatment process. For example, the treated wastewater can be used for agricultural purposes and the sludge resulting from the various technological treatment steps can be used for energy production through the production of biogas or it can be processed and transformed into a product with a high phosphorus content that can be used as agricultural fertilizer [9].

In Romania, through the "Action Plan for the National Circular Economy Strategy" - APNCES, specific cross-cutting and sectorial actions were established. Thus, for the "water and wastewater" activity sector, the existing challenges and barriers were identified, emphasizing the "insufficiency and inadequacy of public policies" towards the transition to the circular economy in the water sector. The insufficiency of knowledge regarding the "risks and benefits of treated water and sludge (finished product/waste) that can be used in the economy is emphasized, too. Added to these is the "unsustainable way of managing water" having the effect of reducing the water resource used in agriculture for crop irrigation [10].

According to the data from APNCES, of the 19.8 million PE (population equivalent) in Romania, 66% are connected to the sewage system, and of these only 63.5% are connected to a WWTP. In Romania, wastewater is treated in 1,242 treatment plants, of which 847 WWTPs serve urban agglomerations with a number greater than 2,000 PE. Added to these data is the fact that 12% of wastewater in Romania is treated according to European standards (respectively, mechanical – biological – chemical treatment). Also, the wastewater recovery rate is low – most of the purified wastewater flows into a running water emissary or the Black Sea; and only 24% of excess sewage sludge is used for agricultural or composting purposes.

The purpose of this paper is to evaluate the circular economy indicators specific to the technological process of wastewater treatment plant, to determine the circularity index. Thus, circularity indicators and their calculation method are presented using a working methodology known in the literature [11]. This information is presented in the second section of this work. In the third section, there is a description of the wastewater treatment plant in Constanta Nord. The characteristic values regarding the amount of treated water and the resulting treatment sludge are mentioned.

It also shows the amount of electricity consumed by the treatment technological process. In the fourth section, the indicators of the circular economy are calculated, and the circularity index is evaluated for four theoretically possible scenarios considering the technical possibilities of the WWTP to reuse, reduce and recycle materials and waste from the station. The results obtained are discussed and compared.

2. Circular economy indicators and method of evaluation

2.1. About indicators of circular economy

The growing up of Circular Economy CE concept could contribute to a sustainable development of the modern society.

In Europe Union the concept of CE was turned into specific action plans [12] of each member state and so a question arises: how to measure the circularity? The scientific literature refers to “micro scale indicators” that are considered the technological process with or without of a Life Cycle Thinking (LCT), and “macro scale indicators” that are approached by European Union. The micro or macro indicators are focused on the three green principles 3Rs [13].

In scientific and grey literature is no consensual point of view regarding circular economy strategies because the concept is addressed as “an economic model” in general but are a lot of sub models developed. For example, the innovative business model as Product Service-System that use and reuse the products in a more intensive way [13]. Also, a circularity index can be calculated looking to the effectiveness of the packaging waste recycling rate [14]. So, “the whole complexity circular economy paradigm is far from being considered” [15].

The examples from the relevant journals show that circularity indicators are specific to each field of activity in the economy, including (or especially) industrial processes. For any product or technological process, circularity indicators regarding the consumption of raw materials, materials and energy can be estimated, right from the design phase. Currently, there are tools for estimating the performance of a product in the context of the circular economy, but there is no official recognition of them or of the way of evaluating the indicators of the circular economy [15]. They are in an initial stage of development.

On the other hand, the circularity index evaluation methods can be discussed not only from the point of view of the impact on materials, energy, waste, but respectively the elements participating in the technological process of making a product. The circularity index can also be discussed from an economic point of view, regarding the economic growth it brings the recycling and losses reduction in process production [16]. The connection between technological and economic elements is indissoluble and must also be found in the indicators of the circular economy considering that the 3Rs for materials and energy create added value [17].

2.2. Methodology of integral circularity index

A municipal wastewater treatment plant could get a transition to the circular economy model, if the technological flow of raw materials, materials and energy is designed in this way. In Fig. 1 we show the scheme of the technological process of a wastewater treatment plant with two treatment stages (mechanical and biological) and which respects the linear economic model: the raw material at the entrance to the treatment plant is represented by wastewater; the finished product is the purified water brought to the physic and chemical parameters of the water from the effluent; the waste sludge obtained is dried with maximum 20% by centrifugation and disposed in the sludge dump; the energy used in the wastewater treatment process is delivered from the national grid.

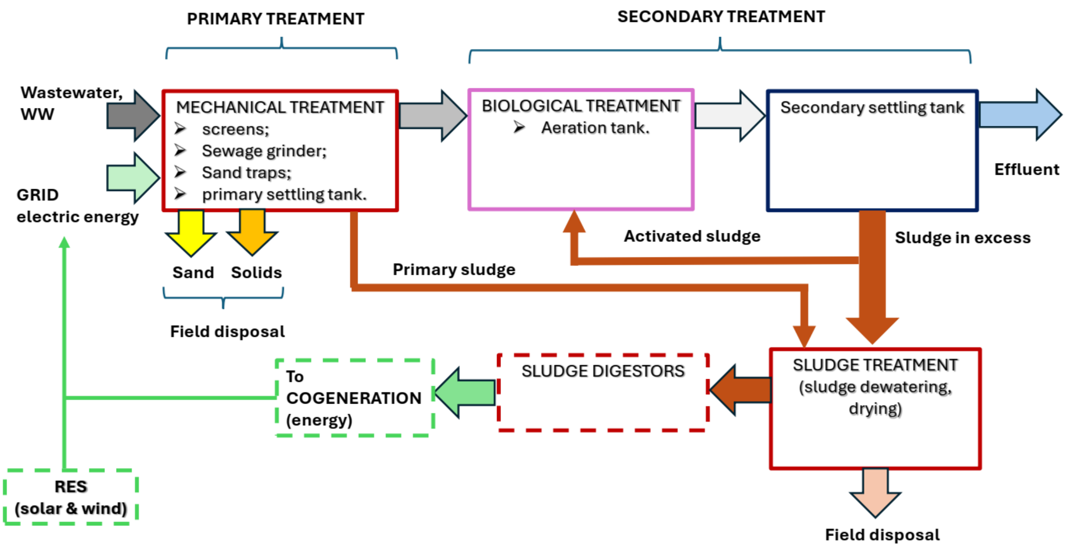

Fig. 1. Wastewater treatment technological process (authors compilation)

In order to bring a WWTP to the circular economy model, some additional investments are needed, respectively: investments for the conversion of energy from renewable energy sources into electrical and thermal energy, including the use of biogas from sludge fermentation; investments in equipment for drying the excess sludge as much as possible and turning it into a fertilizer product in agriculture or into fuel bricks; investments in equipment for the tertiary treatment of treated water to bring it to the parameters as close as possible to those of drinking water so that the finished product of the WWTP can be used in agriculture or other uses. In Fig. 1, the new technological elements that should be brought to the WWTP have been marked with a broken line so that part of the electrical energy requirement from the treatment plant is covered by renewable energy sources.

For the "water and wastewater" field in APNCES, the name of the performance indicators is specified in accordance with the indications of the European Commission from the document "A new Circular Economy Action Plan For a cleaner and more competitive Europe" [18]. For example, the share of fertilizers and biogas obtained from sewage sludge in the total quantities of fertilizers and biogas produced at the national level is evaluated as a percentage [10]. To monitor the WWTPs that have the necessary technology to fit the WWTP into the circular economy concept, we need a methodology for estimating the circularity index at the treatment plant level.

Kiselev et al. in 2019 [11] presents such a methodology in which they considered a set of 7 circular economy indicators (CEIs) whose average value will represent the integral circularity index (ICI). The circular economy indicators were determined starting from the Life Cycle Analysis (LCA) and Material Flow Analysis (MFA) framework and consider the 3R green principles applied to the flow of wastewater, the flow of sludge and the energy used in the treatment plant. The set of 7 circular economy indicators proposed are [11]: CEI_{WP} - reduce CEI for wastewater flow; CEI_{DM} - reduce CEI for sewage sludge flow; CEI_{EE} - reduce CEI for energy flow; CEI_{RU} - reuse CEI for wastewater flow; CEI_{AD} - reduce CEI for sewage sludge flow; CEI_{EG} - reuse CEI for energy flow; CEI_{RC} - recycle CEI for sewage sludge flow.

In Table 1 is presented the estimation methodology of CEIs mentioned above. The integral circularity index is calculated as:

$$ICI_n = \frac{\sum_{i=1}^{7} CEI_i}{7}. \quad (1)$$

The method of calculating the circular economy indicators and the circularity index for the wastewater treatment plant Constanța Nord (WWTP_CTN) is presented below.

Table 1

CEI estimation methodology [11]

	Circular Economy Indicator (CEI)	Relation [11]	Observations
REDUCE	CEI_{WP} for wastewater flow	$CEI_{WP} = \frac{\sum_{i=1}^{j} MW_i}{j}$	MW_i is the multiplicity weight of each j pollutants on the water.
	CEI_{DM} for sewage sludge flow	$CEI_{DM} = DM = \frac{M_{SS}^{DM}}{M_{SS}}$	M_{SS}^{DM}, total mass of dry mater DM in sewage sludge; M_{SS} total mass of sewage sludge.
	CEI_{EE} for energy flow	CEI_{EE} is chosen from Table 2 depending on EE_{NET} (kWh/m^3) and V (m^3/day)	$EE_{NET} = \frac{EC_T - EG_R}{Q_{TWW}}$ EE_{NET}, energy efficiency indicator; EC_T , total WWTP energy consumed; EG_R, total WWTP energy generated from renewable sources; Q_{TWW}, total volumetric flow of treated wastewater; V, total volume of treated wastewater.
REUSE	CEI_{RU}, for wastewater flow	$CEI_{RU} = \frac{Q_{RU}}{Q_{TWW}}$	Q_{RU}, volumetric flow of reused wastewater.
	CEI_{AD}, for sewage sludge flow	$CEI_{AD} = \frac{Q_{AD}}{Q_{TSS}}$	Q_{AD}, volumetric flow of sewage sludge in anaerobic digestion; Q_{TSS}, total volumetric flow of generated sewage sludge.
	CEI_{EG}, for energy flow	$CEI_{EG} = \frac{EG_R}{EC_T}$	EG_R, total energy generated from renewable sources (solar, wind, biogas) in WWTP; EC_T, total energy consumed in WWTP
RECYCLE	CEI_{RC}, for sewage sludge flow	$CEI_{RC} = \frac{M_{TDSS}^{Rcl}}{M_{TDSS}}$	M_{TDSS}^{Rcl}, total mass of recycled dewatered sewage sludge; M_{TDSS}, total mass of dewatered sewage sludge.

3. Integral Circularity index ICI_n for Constanța Nord wastewater treatment plant

The Constanța Nord wastewater treatment plant treats wastewater for 40% of the total wastewater collected in the municipality of Constanța, i.e. the equivalent of 250,000 inhabitants. After the last modernization of the station in 2013, WWTP_CT has a mechanical and a biological treatment stage. Being in the coastal area of the Black Sea, it benefits from renewable sources of energy, wind and solar, so that part of the energy required for the technological process in the WWTP can be covered by them [19, 20]. WWTP_CTN is designed for an annual volume of 37,000,000 m^3 (~101,370 m^3/d) wastewater. The treated waters are discharged into the Black Sea. The treatment plant does not have digesters for the transformation of sewage sludge into biogas. The resulting sludge as waste (excess treatment sludge) has a mass flow rate of 18,870 kg/d.

Fig. 2 shows the values of energy consumption monitored in the treatment plant in the period 2018 - 2023 for each stage of the technological flow of WWTP_CTN. An average consumption of the electrical energy requirement of 13,667 kWh/d can be estimated.

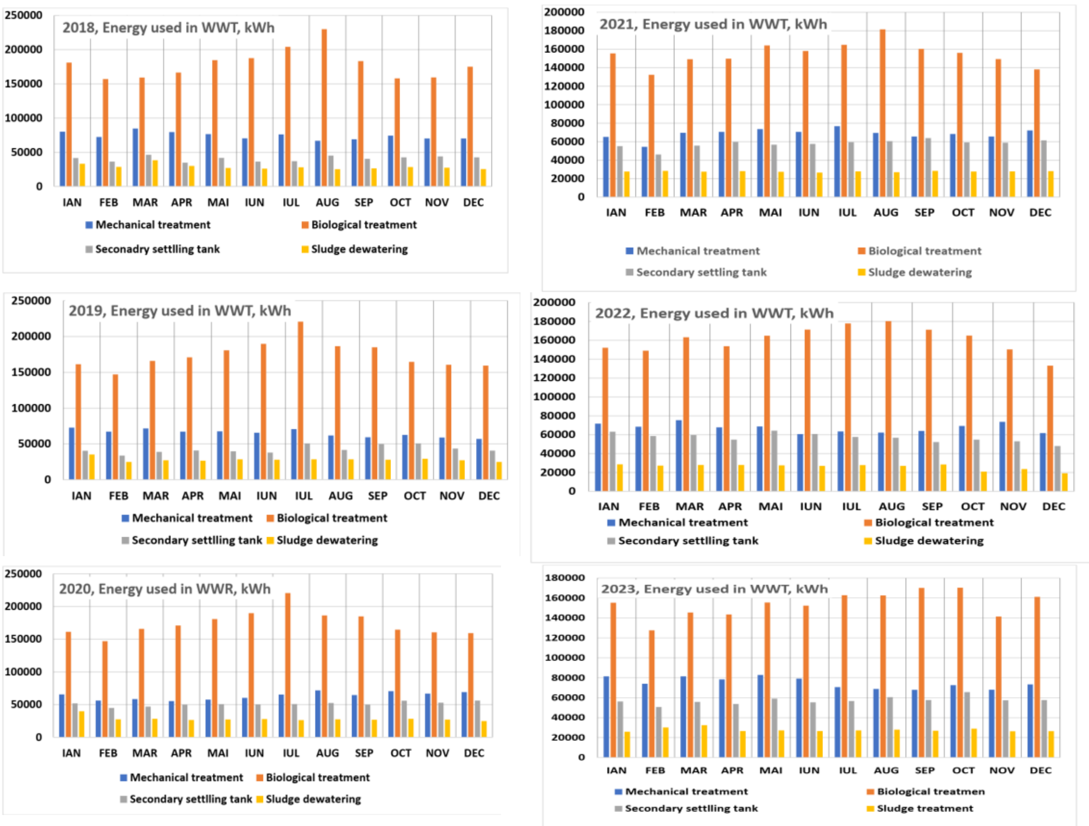

Fig. 2. WWTP Constanța Nord energy consumption (kWh/d) on each month between 2018-2023

For the CEI_{WP} calculation, 5 characteristic polluting substances (pollutants) were considered to define the quality of the effluent water in which the treated water is discharged, respectively: total suspended solids TSS, biochemical oxygen demand BOD_5, chemical oxygen demand COD, total nitrogen T-N, total phosphorous T-P. The five polluting pollutants chosen are representative in the specialized literature for the characterization of water bodies [11]. Table 2 mentions the values of pollutants in the wastewater at the entrance in the WWTP_CTN, the values of pollutants in the treated water (at the exit of WWTP_CTN) that is discharged into the Black Sea and the limit values of the pollutants according to Directive 91/271/EEC.

According to Table 1, CEI_{WP} - reduce CEI for wastewater flow is calculated as average value of multiplicity weight of each substance, MW_i. Also, MW_i is calculated as function of multiplicity factor M_i of pollutant i which is given as: $M_i = \frac{C_i^p}{MPC_i^p}$, with C_i^p annual average concentration of pollutant i, and MPC_i^p maximum permissible concentration of pollutant i admitted in accordance with Directive 91/271/EEC. In Table 3, based on the values of the quality indicators from Table 2, are calculated the multiplicity factors M_i. Also, using the data from Table 4 the multiplicity weight of each substance MW_i are calculated too, and given in Table 3, and CEI_{WP} = (1+1+1+1+0,5)/5 = 0,9. In the calculation of the circular economy indicators, the value of the CEI_{WP} indicator it was considered the same, in all considered scenarios, because the limit concentrations for the substances considered polluting remained valid for the same body of water.

Table 2

Quality indicators for wastewater, effluent water and limits in case study, WWTP_CTN

Water treated quality indicator	Wastewater [20] (mg/L)	Treated water (effluent) (mg/L) [20]	According to Directive 91/271/EEC (mg/L)
Total suspended solids, TSS	327	23,6	35
Biochemical oxygen demand, BOD_5	133	9,6	25
Chemical oxygen demand, COD	247	19,8	125
Total nitrogen, T-N	30,1	9,7	10
Total phosphorous, T-P	3,96	1,08	1

Table 3

Calculus of multiplicity pollutants i

Pollutants name, i	C_i^p	MPC_i^p	M_i	MW_i
TSS	23.6	35.00	0.674	1.00
BOD_5	9.6	25.00	0.384	1.00
CCO	19.8	125.00	0.1584	1.00
T-N	9.7	10.00	0.97	1.00
T-P	1.08	1.00	1.08	0.50

Table 4

Multiplicity weight coefficient MW_i [11]

	Multiplicity value M			
	$0 < M \leq 1$	$1 < M \leq 5$	$5 < M \leq 15$	$M > 15$
MW_i	1.00	0.5	0.25	0.00

In the calculus of the Reduce CEI for energy flow, CEI_{EE}, (see Table 1) the WWTP_CTN energy consumption is $EG_T = 13{,}667$ kWh/d and EG_R, is the electric energy produced from renewable energy sources. CEI_{EE} is calculating using the values from Table 5 with EE_{NET} calculated and with $V \geq 30{,}000$ m^3/d because the wastewater flow is 101,370 m^3/d.

Table 5

Net energy efficiency weight values [11]

	EE_{NET} (kWh/m^3)	CEI_{EE}	CEI_{EE}
		$V \geq 30{,}000$ m^3/day	$V < 30{,}000$ m^3/day
1	$EE_{NET} \leq 0.3$	1.00	1.00
2	$0.3 < EE_{NET} < 0.44$	0.80	1.00
3	$0.44 < EE_{NET} < 0.7$	0.60	0.80
4	$0.7 < EE_{NET} < 1.0$	0.40	0.60
5	$1.0 < EE_{NET} < 1.5$	0.20	0.40
6	$1.5 < EE_{NET} < 1.8$	0.00	0.20
7	$EE_{NET} \geq 1.8$	0.00	0.00

Applying the CEI estimation methodology presented in Table 1, four theoretical working scenarios were considered that can also be applied in the case of the current WWTP_CTN if investments are made for appropriate technological transformations. In establishing the scenarios, the sensitive parameters that determine the values of the circular economy indicators and can influence the circularity index were considered. Table 6 presents these parameters, their values, the circular economy indicators influenced, and the scenarios in which the values of these parameters are found.

Table 6

Scenario Definition

Circular economy indicator	CEI_{WP}	CEI_{DM}	CEI_{EE} CEI_{EG}	CEI_{RU}	CEI_{AD}	CEI_{RC}
Sensitive Parameter	MW_i [%]	M_{SS}^{DM} [kg/d]	EE_G/EC_T [%]	Q_{RU} [m^3/d]	Q_{AD} [m^3/d]	M_{TDSS}^{Rcl} [kg/d]
	0,9	0	0,6; 0,5; 0,3	0	0	0
Used in Scenario	**All**	**2, 3**	**All**	**1, 2, 3**	**1, 3**	**2, 3**
Sensitive Parameter	MW_i [%]	M_{SS}^{DM} [kg/d]	EE_G/EC_T [%]	Q_{RU} [m^3/d]	Q_{AD} [m^3/d]	M_{TDSS}^{Rcl} [kg/d]
	0,9	1	0,6; 0,5; 0,3	1	1	1
Used in Scenario	**All**	**1, 4**	**All**	**4**	**2, 4**	**1, 4**

The values of the parameters in table 6 used to define the scenarios considered the inclusion of the indicators of the circular economy in the 3Rs green principles. Thus, regarding the "reduce" principle, the reduction of the amount of sewage sludge obtained from the treatment of wastewater will be $M_{SS}^{DM} = M_{ss}$, if the WWTP has the possibility of drying the sludge to reduce the volume as much as possible, which means an advanced drying of the sludge; if not, then $M_{SS}^{DM} = 0$.

The energy consumption EC_T in the WWTP can be reduce if a percent of EC_T will be covered by electric energy obtained from renewable energy sources including biogas from sewage sludge fermentation. So, EE_G = 0,6EC_T (or EE_G = 0,5EC_T; EE_G = 0,3EC_T) and the CEI_{EE} value obtained is 1 because $EE_{NET} \leq 0.3$ in all considered cases. But, if we consider that the WWTP is modernized with a tertiary treatment stage at the exit from the treatment plant so that the treated water can be reused in agriculture, then the energy consumption per plant becomes higher for the same amount of processed water and CEI_{EE}= 0,8 because $0.3 < EE_{NET} < 0.44$.

Regarding the "reuse" principle there is the problem of reusing treated water in agriculture and then $Q_{RU} = Q_{TWW}$ and if the treated water reaches the effluent $Q_{RU} = 0$. Using treated water in agriculture or other activities means investments in equipment for chemical treatment of water. Also, to reuse the swage sludge means (regarding reference [11]) to have in WWTP anaerobic digestion of the sludge and $Q_{AD} = Q_{TSS}$; if WWTP has no sludge fermentation digesters $Q_{AD} = 0$. In the "reuse" principle the parameter related to the use of energy from renewable energy sources EE_G has the same values previously mentioned.

Regarding the “recycle” principle it is considered only the sewage sludge that if it is dewatering in percentage of 100% and transformed into organic fuel bricks or material used in cement industry [21] the parameter M_{TDSS}^{Rcl} is $M_{TDSS}^{Rcl} = M_{TDSS}$.

The observations made previously regarding how to define the scenarios and the values considered for the parameters that define the estimation of the circular economy indicators can be found in tables 7 and 8. Since the calculation method of the CEI_{EE} indicator is not very sensitive in terms of estimates for low energy consumption, it was made a calculation of the circularity index without the contribution of the CEI_{EE} indicator. The results are listed in table 8.

In Fig. 3 the variation of the integral circularity index ICIn is plotted for all the four scenarios considered, and in the two variants considered of the reduce CEI for energy flow, CEI_{EE}.

Fig. 3 shows a very good circularity index for the scenarios in which the indicators of the circular economy have the highest possible values (see Scenario 4), which is normal. The value of the circularity index is all the greater as the technological equipment in the sewage treatment plant allows the reduction of energy consumption, the reuse of treated water in human activity, the reuse and recycling of sewage sludge as a raw material or material. The lowest circularity index was obtained in Scenario 3, where the treated water is not reused, the sludge is not recycled and reused, and the degree of coverage of energy consumption from renewable energy sources has a very low value.

Table 7

Circularity index considering the contribution of CEI_{EE}

Scenario	1	2	3	4
CEI_{WP}	0,9	0,9	0,9	0,9
CEI_{DM}	1	0	0	1
CEI_{EE}	1	1	1	0,8
CEI_{RU}	0	0	0	1
CEI_{AD}	0	1	0	1
CEI_{EG}	0,5	0,6	0,3	0,5
CEI_{RC}	1	0	0	1
$\boldsymbol{ICIn}$	**0,63**	**0,5**	**0,32**	**0,88**

Table 8

Circularity index without the contribution of CEI_{EE}

Scenario	1	2	3	4
CEI_{WP}	0,9	0,9	0,9	0,9
CEI_{DM}	1	0	0	1
CEI_{RU}	0	0	0	1
CEI_{AD}	0	1	0	1
CEI_{EG}	0,5	0,6	0,3	0,5
CEI_{RC}	1	0	0	1
$\boldsymbol{ICIn}$	**0,57**	**0,42**	**0,2**	**0,9**

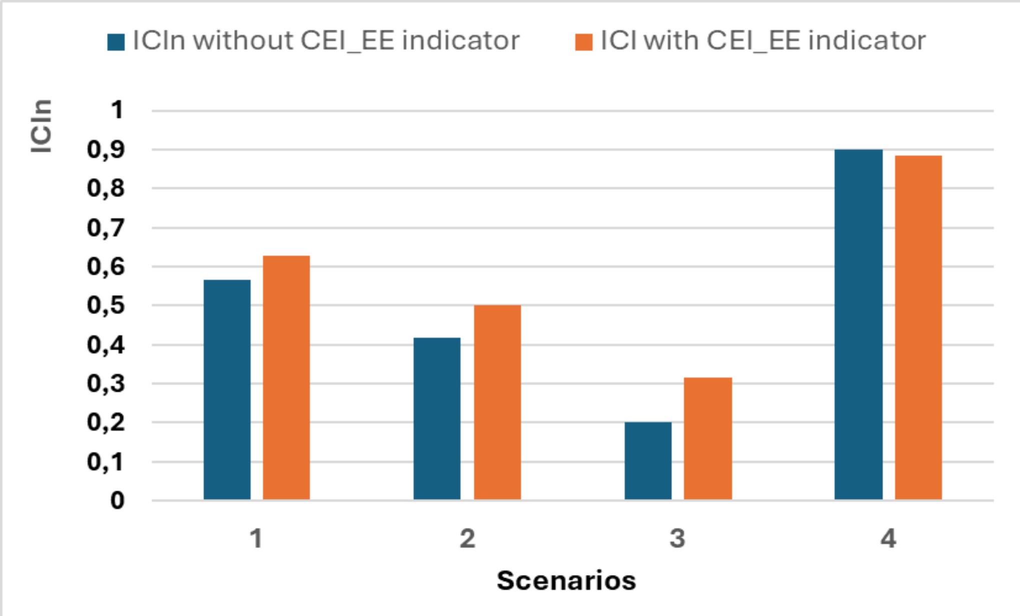

Fig. 3. Circularity index evolution for all four Scenarios (x -axis)

Regarding the use or not of the CEI_{EE} indicator, it can be observed that the trends in the graphic representation are preserved even if we do not consider the CEI_{EE} but the values of the circularity index are lower, with the exception of Scenario 4 in which giving up the CEI_{EE} an improvement of the index is obtained by 0.02% compared to the situation in which CEI_{EE} is considered in Scenario 4.

5. Conclusions

In this paper, a calculation of the circular economy indicators and the circularity index is proposed for a municipal wastewater treatment plant. A work methodology existing in the specialized literature was used, which was adapted to the case study proposed in the paper, namely the Constanta Nord wastewater treatment plant WWTP_CTN. For the values of the WWTP_CTN parameters (average flow rate of wastewater, average flow rate of resulting sewage sludge, electricity consumption in the treatment process and water quality indicators obtained from the treatment process) *CEI* and ICI_n were calculated in the case of the four proposed scenarios.

From the results obtained, an improvement of the circularity index was observed for the scenarios that considered the use of the 3Rs green principles (reduce, reuse, recycle) in the technological process of WWTP_CTN.

It was also observed that in the methods of estimating the circularity index, both the technical evaluation elements and the economic ones must be considered. For this reason, a holistic and integral methodology to monitor, measure and estimate WWTP potential performance could be developed.

REFERENCES

[1] *M. von Sperling*, Basic principles of wastewater treatment, vol. 2, (Biological wastewater treatment series), Ed. IWA Publishing, 2007, https://www.iwapublishing.com/sites/default/files/ebooks/9781780402093.pdf.

[2] https://iwaponline.com/ebooks/book/791/Biological-Wastewater-TreatmentPrinciples, 2023.

[3] *L. D. Robescu L. D., F. Stroe, A. Presură, D. N. Robescu*, Wastewater treatment techniques, Ed. Technica, Bucharest, 2011.

[4] *A. Dereszewska, S. Cytawa*, Circular Economy in Wastewater Treatment Plants—Potential Opportunities for Biogenic Elements Recovery. Water **15**, 2023, https://doi.org/10.3390/w15213857

[5] *M. Smol*, Circular Economy in Wastewater Treatment Plant—Water, Energy and Raw Materials Recovery, Energies 2023, **16**(9), 3911; https://doi.org/10.3390/en160939111;

[6] *P. L. McCarty, J. Bae, and J. Kim*, Domestic Wastewater Treatment as a Net Energy Producer–Can This be Achieved? Environmental Science & Technology 2011 **45** (17), 7100-7106, DOI: 10.1021/es2014264

[7] https://www.europarl.europa.eu/topics/ro/article/20151201STO05603/economia-circulara-definitie-importanta-si-beneficii.

[8] https://www.europarl.europa.eu/doceo/document/TA-9-2021-0040_RO.html.

[9] *V. Ruxandu (Subțirelu), D. M. Cocârță, A. Badea,* The effect of sewage sludge on energy willow (SALIX VIMINALIS ”ENERGO) productivity, U.P.B. Sci. Bull., Series C, Vol. **79**, Iss. 2, 207-216, (2017), https://www.scientificbulletin.upb.ro>full988_137166.pdf.

[10] ***, Planul de acțiune pentru Strategia națională privind economia circular, HG 1172/21.09.2022, https://sgg.gov.ro/1/wp-content/uploads/2023/09/Planul-de-actiune-pentru-Strategia-nationala-privind-economia-circulara.pdf. (The action plan for the National Strategy regarding the circular economy, HG 1172/21.09.2022,)

[11] *A. V. Kiselev, E. R. Magaril, E. C. Rada*, Energy and sustainability assessment of municipal wastewater treatment under circular economy paradigm, WIT Transactions on Ecology and the Environment, **Vol 23**, pp 109-120, 2019, doi:10.2495/ESUS190101.

[12] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[13] *G. Moraga, S. Huysveld, F. Mathieux, G. A. Blengini, L. Alaerts, K. Van Acker, S. de Meester, J. Dewulf*, Circular economy indicators: What do they measure? Resour Conserv Recycl, 2019 Jul; **146**: 452-461. doi: 10.1016/j.resconrec.2019.03.045. PMID: 31274959; PMCID: PMC6559262.

[14] *M. Skare, B. Gavurova, V. Kovac*, Investigation of selected key indicators of circular economy for implementation processes in sectorial dimensions, Vol. **8.** Issue 4. 2023, DOI: 10.1016/j.jik.2023.100421

[15] *M. Saidani, B. Yannou, Y. Leroy, F. Cluzel*, How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework. *Recycling* 2017, **2**, 6. https://doi.org/10.3390/recycling2010006

[16] *B. Taşdoğan,* The circular economy approach to production inefficiency: a stochastic frontier analysis, Ankara Hacı Bayram Veli Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, **24**/2 (2022) 582-597, https://dergipark.org.tr/en/download/article-file/2353085.

[17] *I. Georgescu, J. Kinnunen, A.-M. Androniceanu*, Empirical Evidence on Circular Economy and Economic Development in Europe: A Panel Approach. Journal of Business Economics and Management. **23**. 199-217, 2022, 10.3846/jbem.2022.16050.

[18] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN.

[19] *D. Robescu, A. Presură, I. I. Panaitescu,* Modeling and simulation of biological anaerobic treatment of sludge resulted from wastewater treatment, 4th International Conference on Development, Energy, Environment, Economics (DEEE13), WSEAS, Paris, 2013.

[20] *I.-I. Panaitescu*, Managementul operaţional al unei staţii de epurare ape uzate orăşeneşti, Teza de doctorat, Univ. Politehnica București, 2014. (The operational management of an urban wastewater treatment plant, Doctoral Thesis, Univ. Bucharest Polytechnic, 2014.)

[21] *N. Ion, L. Mihăescu, G. Ionescu, E. Pop, G. P. Negreanu, C. A. Safta*, Analysis of energy consumption for neutralization of the wastewater treatment plants sludge, EU-Conexus EENVIRO Conference, 2024 (accepted).