DOKTORAL (PHD) THESIS

RESEARCH ON THE REALISATION OF A CIRCULAR (WATER) ECONOMY

Author:
Réka Harasztiné Hargitai
Doctoral School of Chemistry and Environmental Sciences

Supervisor:
Dr. Viola Somogyi
associate professor

University of Pannonia
Sustainability Solutions Research Laboratory

Veszprém
2025

Introduction and objectives

One of today's biggest challenges is to achieve sustainability in all economic sectors while using resources efficiently. The Circular Economy (CE) offers an approach that reduces the use of natural resources and keeps them in a closed system. Circularity has been successfully implemented in many industrial sectors and is now being applied to the transformation of activities that previously would have been unthinkable in any form. Municipal wastewater treatment has already become partially circular thanks to sludge recycling and renewable energy use. Industrial actors, such as poultry processing, are also looking for ways to optimise water use, while the difficulty of recycling the waste produced is a challenge. However, their effluents can be treated using efficient methods to the extent that they can be recycled.

The implementation of the circular economy in water-intensive industries is a less researched area, so I focused my research on the feasibility, measurement and environmental impacts of the water cycle, using poultry processing and municipal wastewater treatment as examples. Circular economy calculations, popular in the literature, do not treat water as a feedstock, while linear water footprint calculations ignore the pathways of the cycle. However, by integrating the water cycle into the calculations, a more accurate picture of water-intensive industries can be obtained. Life Cycle Assessment (LCA) highlights the environmental impacts of industrial processes. In the case of purified water reuse, it points to the method that ensures maximum recycling with the least impact. By applying the methods in parallel, it is possible to select more sustainable water technology solutions.

Based on the above, I have identified the following research objectives:

1. Performing and modifying circular economy calculations
2. Perform and modify water footprint calculation
3. Carrying out life cycle analysis to support the cycle calculations
4. Conduct a life cycle analysis to demonstrate the impact of wastewater treatment technologies on water reuse

Applied methods

On the way to achieving the circular goal, it is worth examining current assessment methods and technological steps in all areas of the economy, including less flexible areas, to gain information on the shortcomings and limitations of these methods. To develop the water cycle, I have examined two case studies: a poultry processing plant and a municipal wastewater treatment plant. Data was collected through personal interviews, process documents and automated control systems. Missing data was collected from Ecoinvent and Sphera databases and literature sources.

I analysed in detail the water and energy demand of the main steps of poultry processing - slaughtering, boiling, cutting, packaging - and the generation of by-products and waste in terms of water cycle and environmental impact, using data from two years (2018 and 2019). The daily amount of product and waste generated from the two broiler types (Ross-308 and Cobb-500) showed significant differences in terms of water and material use. Depending on the type of product produced, additives of varying composition are used, as well as packaging materials made of plastic, wood and metal. The daily water demand of the plant, which is highest during boiler house and boiling, varies depending on the number of cuts. The pre-treatment of the wastewater generated is already started on site. The assessment of the environmental impact of the use of chemicals (e.g. sodium aluminate, polyelectrolytes) in the treatment of wastewater was also part of the assessment. The system boundaries considered in the analysis of the scenarios are illustrated in Figure 1.

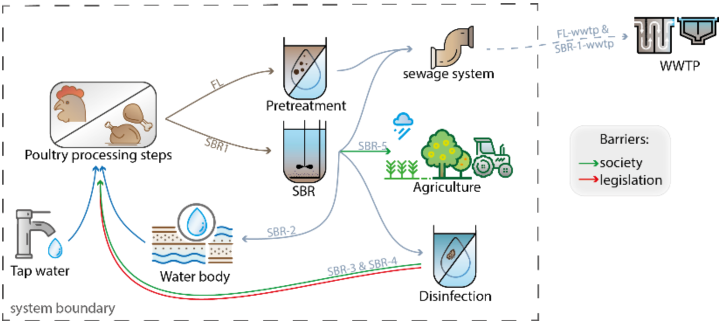

Figure 1. System boundaries in the Life Cycle Assessment of a poultry processing plant [edited by the author]

In the case of the wastewater treatment plant, I looked at its continuous improvement in line with industry standards. With a nominal capacity of 18 000 m³/day, the plant receives municipal and industrial wastewater from several municipalities, so due to its size, long time series and sufficiently detailed data were available. The analysis was carried out for the period 2015 to 2022, divided into distinct periods according to technological development, excluding overlapping technological changes. Wastewater treatment consists of several steps: mechanical pretreatment, primary and secondary sedimention, biological treatment (anaerobic, anoxic and oxic stages) and sludge treatment. The biogas produced at the plant is recycled in the form of electricity and heat, and the biogas surplus is incinerated. The energy demand for aeration, the use of chemicals for sludge treatment, the quality and quantity of sludge and treated water produced are all important factors in the environmental impact. The system boundaries considered in the analysis and the scenarios considered are illustrated in Figure 2.

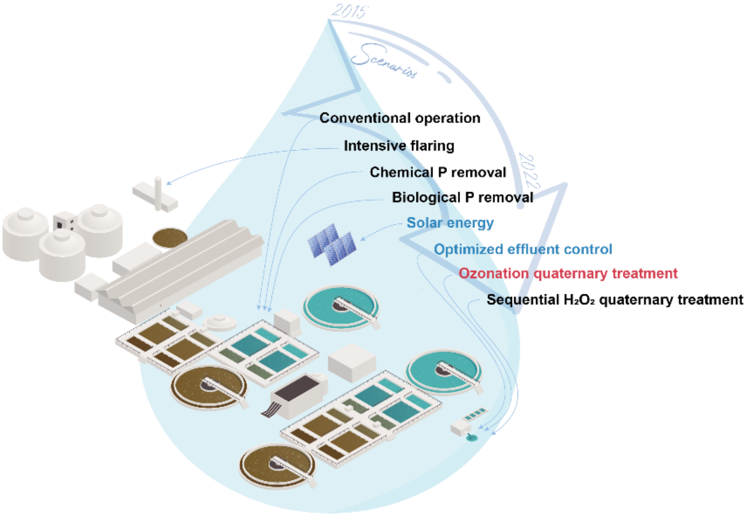

Figure 2. System boundaries in the Life Cycle Assessment of a municipal wastewater treatment plant [edited by the author]

I have reviewed the circular economy indicators in the literature, with an eye to how water as a raw material can be integrated into the calculations. I have used two indicators to calculate the material circulation, with values between 0 (linear) and 1 (circular) indicating the degree of circulation. The CE Indicator Prototype (CEIP) is a questionnaire-based method that assesses product performance in line with the principles of the circular economy, taking into account all stages of the product life cycle (design, production, trade, in-use, after-use). The Material Circularity Indicator (MCI) is designed for industry, focusing on the origin of raw materials, the fate of waste and the usefulness of the product. It focuses on the materials incorporated into the product, but can also be complemented by material losses. Both methods measure the cycling of material flows, so I have recalculated the cycling by modifying CEIP and MCI to include water in the list of materials. I also approached the calculation of the water cycle from the direction of a linear water indicator, the Water Footprint (WF) calculation. This method takes into account the direct and indirect water quantities incorporated throughout the life cycle of the product, which can be categorised into blue, green and grey water footprints. The method allows for comparisons between different technologies in terms of water use, but does not take into account the amount of water recycled. Therefore, in the modification I integrated water cycle paths into the calculation to get a more accurate picture of water use. To verify the calculations and their modifications, I performed a "Cronbach alpha" uncertainty analysis.

The water circularity calculations approached from both directions do not in themselves show the really significant consequences of the water cycle, so I have also supported the calculations with Life Cycle Assessment. The analysis was carried out according to standard specifications (ISO 14040:2006, ISO 14044:2006) using Sphera (GaBi) software. I used the ReCiPe method for the LCA to complement the circular economy calculations and for the comparative analysis of the technological improvements of the wastewater treatment plant. The positive or negative value of the impacts defined by this method reflects different environmental impacts that are a consequence of the activity or product under study. By understanding the environmental impacts, it is possible to compare recycling methods, focusing on quality as well as quantity. To assess the environmental impact of the wastewater treatment plant, I also used the Effluent Quality Index (EQI), which shows the direction of environmental impact in terms of the quality of the treated water discharged.

The combined use of the three methods allowed me to assess the material and water flows as a complex system, thus identifying intervention points that contribute to the sustainable development of the water cycle. The strength of the methodological approach is that the impacts of water cycle development can be measured across different water-intensive industries, contributing to improved resource efficiency and sustainable water use.

THESES

I. I have established that **for technologies with high water consumption, the circularity of water as a material flow cannot be determined without taking its flow into account. Therefore, methodological adjustments are necessary. The approach I propose enables the quantification of the water cycle** and contributes to more water- and material-efficient product design.

I.1. I have demonstrated that **the CEIP calculation method underestimates the degree of circularity for consumer products**. The "Commercialisation", "In Use" and "End of Use" life cycle stages do not receive any points, which lowers the value of circularity. However, the indicator does consider areas that cannot be described purely through material flows, such as product design and improvements in the raw material–product–waste ratio.

I.2. **I have integrated water, as a raw material, into the CEIP calculation**. By introducing questions regarding water flows, the linear value increased from 0.171 (2018) to 0.212. Reducing water consumption, reusing water, and using recycled packaging materials can increase the circularity value up to 0.392.

I.3. I have demonstrated that **the MCI method captures the transition between linear and circular states in consumer products**. The methodology is suitable for analyzing the performance of consumer products over time, while considering return loops and product lifespan compared to competing industrial players.

I.4. **I have integrated water, as a raw material, into the MCI calculation**. For the year 2018, considering water led to a decrease in the MCI value from 0.493 to 0.485. When including losses, the value dropped from 0.567 to 0.171. By minimizing these losses, a circularity value of 0.848 can be achieved.

Related publication: 3

II. I have demonstrated that **with the modifications I propose, the traditionally linear Water Footprint (WF) calculation becomes suitable for measuring the water cycle**. The modified calculation accounts for the water volumes embedded during the life cycle of poultry processing products, as well as recycled water flows resulting from reuse.

II.1. **I confirmed the linear nature of poultry processing using the water footprint calculation**. Producing 1 kg of poultry product requires 3.99 m^3 (2018) and 4.24 m^3 (2019) of water, of which 99 % is attributed to broiler rearing. The remaining 1 % includes raw materials, technological water use, transportation, and energy consumption.

II.2. **I modified the indicator to measure the water cycle, applying two reuse targets: technological and irrigation reuse**. The savings are not reflected in the total water footprint, since the water used during broiler rearing is not recyclable, and its water demand cannot be reduced without compromising product quality.

II.3. I concluded that **in the case of the modified water footprint indicator, the focus should be on material flows that do not affect product quality**. Technological reuse resulted in a 29.28 % (2018) and 33 % (2019) reduction, while reuse for irrigation purposes achieved a 15.79 % and 17.8 % decrease, respectively.

Related publication: 3

III. I have established that **life cycle assessment, when supplemented with modified literature-based indicators and applied in parallel, can provide a comprehensive view of the extent of water circularity and its environmental impacts**. Through their combined application, I demonstrated that **the proposed water reuse methods in a poultry processing plant increase environmental burdens and, overall, do not support the improvement of circularity values**.

III.1. I demonstrated that **declining quality increases environmental impacts while circularity decreases**. The human health impact of the default flotation scenario rose from 98.17 DALY (2018) to 105.66 DALY (2019), while the MCI value decreased from 0.485 to 0.476 when water was considered.

III.2. I demonstrated that **the use of an in-house wastewater treatment facility reduces environmental impacts**, resulting in a 30.66 % saving in metal depletion. As a result of this transition, the human health impact decreased from 98.17 DALY to 97.85 DALY in 2018.

III.3. I demonstrated that **energy consumption and the effects of biological processes are significant factors that circular economy indicators tend to neglect**. Energy determines endpoint impacts: 19.36 % for human health, 8.96 % for natural environment, and 98.25 % for resource scarcity. The biological dimension is also relevant when the type of material flow is marked as “material entering nature”.

Related publications: 2, 3

IV. I have established that **technological developments in municipal wastewater treatment contribute to sustainable water protection in the long term, even though the transformations I examined may increase environmental burdens in**

the short term. The results of the analysed developments can support the environmentally friendly modernization of wastewater treatment technologies applied in industrial settings.

IV.1. I demonstrated that **optimizing biogas utilization can bring the plant closer to achieving energy neutrality**, as the yield was increased from 1.35 kWh/m^3 to 1.98 kWh/m^3, which can be further improved by optimizing the homogeneous sludge fed into the digester. However, the implementation of flaring hinders achieving this goal, as it affected seven impact categories (FD, FC, FEc, HTPc, IR, LU, TA), even when significantly reduced.

IV.2. I demonstrated that **reducing chemical use effectively contributes to lowering environmental impacts**. Following changes in aeration demand, energy-related impacts (CC, FPMF, PhOFe, PhOFhh, OD, TEc) initially increased by 23 %, then decreased by 12.91 %. Additionally, chemical use in the sludge line was reduced by 26.20 %.

IV.3. I demonstrated that **increasing the use of solar panels does not guarantee the achievement of energy neutrality for the wastewater treatment plant**. The energy produced per 1 m^3 treated water was only 0.06 kWh from solar panels, significantly less than the 0.42 kWh from biogas. Due to seasonal fluctuations in solar energy production, additional energy input is needed, while the solar park increased land use by a factor of 2.6. Purchased electricity was 5.17 times the capacity of the existing solar system, meaning complete replacement with solar energy is not feasible due to land limitations.

IV.4. I demonstrated that **optimized wastewater regulation increases treatment efficiency, but it comes with environmental costs**. Thanks to the ideal nutrient ratio (100:10.07:1.08), 96.33 % phosphorus removal was achieved. However, due to increased sludge production, the chemical demand rose, which was reflected in metal depletion, increasing from $6.54 \cdot 10^{-1}$ kg Cu eq. to $8.10 \cdot 10^{-1}$ kg Cu eq.

Related publication: 1

V. I have determined that **the implementation of quaternary treatment** – especially in the case of energy-intensive technologies – **further increases environmental burdens, which does not support the reuse of treated water**. However, I have also demonstrated that **with appropriate technology selection**, such as sequential H_2O_2 treatment, **these impacts can be significantly mitigated, making reuse feasible**. This aligns with policy and regulatory directions that define wastewater treatment plants as key actors in urban and industrial water cycles.

V.1. I demonstrated that **the increased energy consumption associated with ozonation-based quaternary treatment negatively affected environmental impacts to varying degrees**. It showed significant influence across six impact categories (CC, FPMF, LU, PhOFe, PhOFhh, and OD) and yielded the worst values in 11 impact categories among all scenarios. The most significant drawback was the loss of freshwater eutrophication benefits (0.48 kg P eq./FU) previously achieved through earlier developments.

V.2. I demonstrated that **sequential H_2O_2 quaternary treatment is a viable alternative for treated water reuse**. Its more favourable environmental impact is partly due to lower energy consumption, as the technology relies directly on renewable energy. When normalized between 0 and 1, the impact values outperform both intensive flaring (7.) and ozonation (8.), highlighting the relative advantages of sequential H_2O_2 treatment and supporting its suitability for treated water reuse.

Related publication: 1

LIST OF SCIENTIFIC PUBLICATIONS

Publications related to theses

Scientific Articles in international refereed journals

1. **Harasztiné Hargitai Réka**, Sebestyén Viktor, Volf Balázs, Somogyi Viola: Life cycle assessment of technological shifts in municipal wastewater treatment plants, HUNGARIAN JOURNAL OF INDUSTRY AND CHEMISTRY (0133-0276): 53 (2). (Elfogadó nyilatkozat alapján a várható megjelenés: 2025 december)
2. **Harasztiné Hargitai Réka**, Sebestyén Viktor, Somogyi Viola: Potential water reuse pathways from a life cycle analysis perspective in the poultry industry, JOURNAL OF WATER PROCESSING ENGINEERING (2214-7144 2214-7144): 64 p. 105577. Paper 105577. (2024), https://doi.org/10.1016/j.jwpe.2024.105577
3. **H-Hargitai Réka**, Somogyi Viola: Impact of water as raw material on material circularity - A case study from the Hungarian food sector, HELIYON (2405-8440): 9 7 Paper e17587. (2023), https://doi.org/10.1016/j.heliyon.2023.e17587

Publications in national journals

4. **Harasztiné Hargitai Réka**, Somogyi Viola: Körkörösség mértékének számítási lehetősége és nehézsége az élelmiszeriparban, Hidrológiai Közlöny (0018-1323 2939-8495): 101 3 pp 75-84 (2021), Nyelv: Magyar, https://real-j.mtak.hu/15836/20/HK2021_03v2.pdf#page=76

Conference publications, with abstracts only

5. **Harasztiné Hargitai Réka**: Életciklus-elemzés alkalmazása a vízkörforgás felé vezető úton, XIX. LCA Konferencia - „Kihívások és lehetőségek az LCA és a Körforgásos Gazdaság területén", Konferencia helye, ideje: Budapesti Gazdasági Egyetem, 1055 Budapest, Markó u. 29-31., 2024. november 11-12., Nyelv: Magyar
6. **Harasztiné Hargitai Réka**: Körforgásos (víz)gazdaság megvalósításának vizsgálata, In: Zsirka Balázs, Domokos Endre PE/MK/KMI/Környezetmérnöki Intézeti Tanszék (szerk.), Green Solutions 2019 Conference, Konferencia helye, ideje: Veszprém, Magyarország

2019.01.01. (Pannon Egyetem), p. 7. (2019), Nyelv: Magyar, ISBN: 9789633961414

Other scientific publications

Scientific Articles in international refereed journals

7. Viola Somogyi, Viktor Sebestyén, Zsófia Kovács, **Réka H. Hargitai**, Endre Domokos:Enhanced Pollution Removal with Heat Reclamation in a Small Hungarian Wastewater Treatment Plant, Journal of Sustainable Development of Energy Water and Environment Systems (1848-9257 1848-9257): 6 3 pp 494-504 (2018), Nyelv: Angol, https://doi.org/10.13044/j.sdewes.d6.0200

Publications in national journals

8. Dr. Somogyi Viola, **Harasztiné Hargitai Réka**, Pitás Viktória, Dr. Kárpáti Árpád, Horváth Dániel: Vágóhídi szennyvizek optimális tápanyag arányának megközelítése az előkezelés során, MASZESZ Hírcsatorna: 2022. 3. lapszám pp 56-67 (2022), Nyelv: Magyar, https://www.maszesz.hu/wp-content/uploads/2024/06/Vagohidi-szennyvizek-optimalis-tapanyag-aranyanak-megkozelitese-az-elokezeles-soran_dr.SomogyiV_HarasztineHargitaiR_PitasV_dr.KarpatiA.pdf

Conference publications, with abstracts only

9. Szabó István; Pitás Viktória, Bordós Gábor, Prikler Bence, **Harasztiné Hargitai Réka**, Micsinai Adrienn, Szoboszlay Sándor: Modellrendszer alkalmazása szennyvíztisztító telepek mikroműanyag forgalmának in vitro elemzésére, Konferencia helye, ideje: Zalakaros, Magyarország 2023.10.19. - 2023.10.20., Nyelv: Magyar
10. **Harasztiné Hargitai Réka**, Dr. Somogyi Viola: Circularity indicator development for a more flexible and comprehensive approach to assessing material, water and biological cycles in product development, Konferencia helye, ideje: Athén, Görögország 2023.06.07. - 2023.06.09., Nyelv: Angol
11. Somogyi Viola, Pitás Viktória, **Harasztiné Hargitai Réka**, Csizmadiáné Czuppon Viktória: Future of nature-based wastewater treatment solutions in view of water reuse strategies, In: "Danube Delta" National Institute for

Research Development, DELTAS AND WETLANDS, Konferencia helye, ideje: Tulcea, Románia 2023.06.05. - 2023.06.09., Nyelv: Angol

12. **Harasztiné Hargitai Réka**, Dr. Somogyi Viola: Víz- és szennyvízkutatások a körforgásos gazdaság kialakításához vezető úton, In: Hajdú Péter (Hajdú Péter Élelmiszertudomány) (szerk.), XXVI. Tavaszi Szél Konferencia 2023: Absztrakt kötet, Konferencia helye, ideje: Miskolc-Egyetemváros, Magyarország 2023.05.05. - 2023.05.07., p. 281. oldal. (2023), Nyelv: Magyar, ISBN: 9786156457233
13. Somogyi Viola, **Harasztiné Hargitai Réka**: Achieving Circularity in Wastewater Treatment Plants – Current State and Future Perspective, In: SPIL2021 Virtual Conference System, Konferencia helye, ideje: Brno, Csehország 2021.11.04. - 2021.11.05., p. SPIL21.0080. (2021), Nyelv: Angol
14. Somogyi Viola, Tetteh Ransford Okley, **Harasztiné Hargitai Réka**, Pitás Viktória: Challenges in poultry wastewater treatment under different temperature regimes, In: Book of Abstract, Konferencia helye, ideje: Svájc 2020.09.15. - 2020.09.17., Paper sciforum-034070. (2020), Nyelv: Angol
15. **Harasztiné Hargitai Réka**, Somogyi Viola: Integrálható-e a víz, mint alapanyag a körforgásos számításokba?, In: Magyar Víz- és Szennyvíztechnikai Szövetség Dr. Dulovics Dezső Junior Szimpózium – Absztarktfüzet, Konferencia helye, ideje: Online konferencia 2021.03.03. - 2021.03.04. (Magyar Víz- és Szennyvíztechnikai Szövetség), p. 27. 1 p. (2021), Nyelv: Magyar
16. **Harasztiné Hargitai Réka**, Somogyi Viola, Zebić Avdičević Maja, Domokos Endre: Membrán szűrés modellezése textilipari szennyvíz példáján keresztül, In: Magyar Víz- és Szennyvíztechnikai Szövetség Dr. Dulovics Dezső Junior Szimpózium, Konferencia helye, ideje: Budapest, Magyarország 2019.03.06. (Magyar Víz- és Szennyvíztechnikai Szövetség), Nyelv: Magyar
17. Somogyi Viola, Maja Zebic Avdicevic, **Harasztiné Hargitai Réka**, Domokos Endre, Ljubas D., Dobrovic S.: Modelling Ceramic and Polimer Ultrafiltration Membranes for Textile Dyeing Wastewater Treatment, In: Aleksandra Mudrovčić; Marko Ban (szerk.), 3rd SEE SDEWES Conference on Sustainable Development of Energy, Water and Environment Systems: Book of abstracts, Konferencia helye, ideje: Novi

Sad, Szerbia 2018.06.30. - 2018.07.03., pp 164-164 (2018), Nyelv: Angol, ISSN: 1847-7178

18. **H. Hargitai Réka**, Somogyi Viola, Domokos Endre: Körforgásos gazdaság jogi háttere és lehetőségei a víz szektorban, In: Absztrakt füzet, Konferencia helye, ideje: Debrecen, Magyarország 2018.10.11. - 2018.10.12. (Debreceni Egyetem Műszaki Kar), Nyelv: Magyar

Conference participation, with poster presentation:

19. Zebić Avdičević Maja, Somogyi Viola, Ljubas Davor; Domokos Endre, Dobrović S., **Harasztiné Hargitai Réka**, Varga Béla: Ultrafiltration of textile mercerization wastewater using ceramic membranes - modelling fouling and performance, In: 26th CROATIAN MEETING OF CHEMISTS & CHEMICAL ENGINEERS with international participation and 4th "Vladimir Prelog" Symposium: Book of Abstracts, Konferencia helye, ideje: Sibenik, Horvátország 2019.04.09. - 2019.04.12., p. 192. Paper P-B24. (2019), Nyelv: Angol
20. Somogyi Viola, Zebić Avdičević Maja, **Harasztiné Hargitai Réka**, Domokos Endre, Ljubas Davor, Dobrović S.: Modelling reactive dye removal by ultrafiltration ceramic membranes, In: 26th CROATIAN MEETING OF CHEMISTS & CHEMICAL ENGINEERS with international participation and 4th "Vladimir Prelog" Symposium: Book of Abstracts, Konferencia helye, ideje: Sibenik, Horvátország 2019.04.09. - 2019.04.12., p. 191. Paper P-B23. (2019), Nyelv: Angol