Heliyon 9 (2023) e17587

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Impact of water as raw material on material circularity - A case study from the Hungarian food sector

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ARTICLE INFO

Keywords:
Circular economy
Poultry processing
Water footprint
Material circularity indicator
CE indicator prototype
Life cycle assessment

ABSTRACT

Measuring circularity is necessary to prove the feasibility of transforming linear technologies into circular ones. However, most of the circular economic researches consider water only as a medium. Food industry processes are excellent examples of systems that are hard to break free from linearity, albeit not impossible. This paper explores solutions to include water in circularity calculations using a Hungarian poultry processing plant as a case study. Two circular economic indicators, the questionnaire-type Circular Economy Indicator Prototype (CEIP) and the product-centric Material Circularity Indicator (MCI and MCI') and the Water Footprint were examined in detail and modified to fit the needs of assessing circularity with water included as raw material. The calculations were supported by Life Cycle Assessment (LCA). The impact on circularity and the environment were quantified by considering different reuse scenarios. As the results of CEIP show, including water reuse in the technology or recycling for irrigation could increase the indicator values from low to medium-high level of circularity. However, the level of improvement highly depends on the amount of water used. LCA highlighted the significant environmental effects of packaging (<2% of product mass) and the relative benefits of recycling and reuse. The MCI' values (including water as raw material) increased from 0.171 to 0.848 when water demand was reduced by 50% and 100% reused within the processes. This led to a reduction of 76% in the environmental effect. On the other hand, Water Footprint analysis showed that 99% of the water is incorporated in the product itself; therefore, technological water consumption should be treated separately from broiler breeding. The results show that a fairly linear process can be directed towards circularity. However, environmental benefits are not guaranteed with higher circularity points, and recycling may lead to unexpected results.

1. Introduction

Establishing circular economy (CE) has gained importance in recent years, owing to the positive economic (and environmental) impact of technology loops [1]. Circular economy was first mentioned in publications in 1977 [2]. In 2008, the first law on the circular economy was adopted in China [3]; after that, in 2015, the European Union issued an action plan for member states [4].

However, humanity is only at the beginning of the process, with various types of setbacks: on a global scale, 9.1% of the raw materials were used in a circular manner [5] but fell to 7.2% in 2023 [6]. Several practical solutions show that the circular economy and Industry 4.0 (I4.0) are inseparable [7]. In creating a cycle, supply chains are interconnected, which motivates the creation of

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https://doi.org/10.1016/j.heliyon.2023.e17587
Received 9 May 2023; Received in revised form 20 June 2023; Accepted 21 June 2023

industrial symbiosis [8], thereby improving the circularity of critical areas, for example, the food industry [9]. By linking the supply chain and the circularity, efficiency can be improved from an environmental, economic and social point of view [10], thus getting closer to meeting Sustainable Development Goals (SDG) [11].

Priority areas of circular economy studies focus on food waste [12], plastics [13], critical raw materials [14], construction waste [15] and materials from biological sources [16]. Nonetheless, water is an ancillary topic in the circularity assessment and is mostly associated with agriculture-related topics based on the bibliometric research of Santeramo [17].

Usually, water is treated as a medium in the processes, and while it gets contaminated during production and has to be treated, neither the source nor the fate of the used water is considered in the circularity assessment of the products. The authors believe that a system can only be truly circular if water reuse is propagated along with other material reuse strategies. However, to achieve that, the methodologies for circularity calculations should pay attention to water as a resource, especially when water is an integral part of the product itself. The food sector is a good example of products with relatively high water contents that are inherently single-use.

Four different methods were used to understand the role of water in circularity assessment and to provide pathways towards circularity in a Hungarian poultry processing plant with regard to water use besides solids. Two circularity indicators were chosen besides carrying out a simplified life cycle assessment and calculating the water footprint of the examined plant. An important aspect was for the indicator calculations to be reproducible and have sufficient complexity for multi-level analysis [18].

The structure of the paper is the following: In section 2, a literature review is provided about the technical means of achieving circularity, focusing on water reuse and the food sector and the scope of the research is summarised based on the literature findings. Section 3 gives an overview of the used data and methods, while section 4 describes the results of the calculations.

2. Literature review

2.1. Technical efforts of a more circular economy

By analysing the interconnectedness [19], it becomes apparent that the different technological areas cannot be treated separately; yet various obstacles hinder reaching a circular economy [20]. Some are inevitable (laws of thermodynamics), and others can be overcome by resolving theoretical, practical, political and ideological discrepancies [21]. Barriers depending on the size of the companies, the industry and the customer base must be determined individually in each case [22] before defining priorities and responsibilities [23]. Moving away from the linear economic model is especially challenging for the food industry [[24,25]], primarily due to the strict consumer protection regulations. On the other hand, even in the meat industry, there are options to introduce loops, for example, by producing biogas from manure and thus reducing greenhouse gas emissions [26]. In the food industry, the steps of effective waste processing and recycling are the main focus of the cycle [27], such as how animal by-products unfit for human consumption can become forage [28].

Circularity can also be achieved regarding water consumption, besides other material flows; the term coined for creating a closed water cycle in an industrial setting and thus reducing freshwater use is Zero Liquid Discharge (ZLD) [29]. It is also a viable option for the agricultural processing industry; for example, wastewater was reused safely in meat production and processing technology to create a closed water cycle within the farm [30]. Another study showed the membrane separation process as a valuable water recycling tool [31], with three examples of water with low contamination levels (milk processing, meat processing, and bottle washing). Poultry processing wastewater from bird washer and chiller (with cca. 1100 and 900 mg/l chemical oxygen demand (COD), respectively) were successfully treated using 30 kDa polyethersulfone membranes resulting in 75–95% COD removal showing great potential for water reuse purposes [32]. Reusing reclaimed water for irrigation is also an option, but contaminants of emerging concerns call for caution [33].

2.2. Measuring circularity

A successful transition to a circular economy is aided by analysing activities [34] from both economic and environmental points of view. Change is needed on the lower levels to improve the global circularity value, for which different level indicators are available [35,36]. However, one should remember that micro-level indicators only lead to partial solutions and focus exclusively on economic aspects [37].

Circular Economy Indicator Prototype (CEIP) [38] is a straightforward method suitable for product comparison and preliminary analysis, encouraging decision-makers to turn to circularity without giving a painstakingly detailed picture of the technology. The questions may lead to higher variability due to the perceived ambiguity of how the questions should be interpreted [39], but this can be compensated by completing the questionnaire in a workshop manner. Brändström and Saidani [40] pointed out that CEIP tends to provide lower circularity scores than other methods but gives a good overview of the actual state.

One of the most commonly used methods to calculate the degree of circularity in more detail, ignoring economic values but focusing on the product's life, is the Material Circularity Indicator (MCI) [41]. It requires detailed knowledge of products and material flows, resulting in time-consuming but reliable methods for evaluating existing products. It does not consider the environmental impacts of the product; thus, connecting LCA and MCI was suggested to show ways of improving circularity while mitigating environmental impacts [42]. MCI is popular in a variety of industries. It was found that broiler farming and slaughtering have more linear than circular qualities [43]. A combined analysis of life cycle assessment (LCA) and MCI showed that the number of recycling in the case of three-layer plastic packaging materials has incremental environmental benefits. However, two rounds of recycling gave the highest MCI value [44]. Corona et al. [45] found that circularity and climate change goals may not overlap for lignin-based asphalt production. In the construction industry, a combination of methods (cradle-to-cradle life cycle assessment with predictive building systemic circularity indicator) is used where material MCI is the first step in calculating the system circularity [46,47]. Because MCI do not consider water as a raw material, they both were modified to include water usage and recycling in the calculations as opposed to Kakwani & Kalbar [48], who used the logic of the MCI and developed the Water Circularity Indicator to assess water usage separately from other material flows.

Water Footprint (WF) [49] is a widely used method to calculate direct and indirect water used as it focuses on the amount of water used, which can be obtained through production data. Its advantage is that many scientific sources and experimental data are available, but in contrast to most indicators, it concentrates on the entire life cycle and does not consider circularity. Combined use of LCA and WF [50] is proposed for a detailed understanding of sustainable water consumption in both blue and green water categories. The authors made an effort to include water reuse in the calculation, thus slightly shifting the methods towards handling circular solutions.

The above-mentioned methodologies provide information in a static way. Life Cycle Assessment, on the other hand, considers the connections between individual processes within the boundaries of a system through the whole life cycle of a product or technology in a comprehensive manner and includes water mass balances [51]. As it focuses on mapping the environmental impacts, it can serve as a basis for both water footprint [52] and circularity calculations [53], but the methods are not interchangeable. Rocchi et al. [43] attempted to simultaneously assess life-cyle environmental impacts and material circularity in agricultural systems, but water was not included in the material flow. Rufí-Salís et al. [54] found that MCI had certain limitations at the system level when examining ways to improve circularity in urban agriculture since including water in the material flow zeroed down the MCI value. They suggested combining LCA and MCI to understand the environmental and circularity aspects of a system [54].

2.3. Scope of the research

Based on the assessment of the various indicators, one methodology cannot provide a complete and exhaustive assessment of the performance of a technology or a product of an organisation. Nonetheless, using an aggregate indicator that gives fact-based information on the current state and impacts of strategic decisions is convenient for decision-makers and helps mainstream the circularity approach. From this point of view, not considering water as a raw material in circularity calculations is a shortcoming of the circularity indicators. This is especially so when water becomes a part of the product, such as food products. However, even if water only serves for cleaning or heating, it can be reused within the technology or outside the boundaries of the facility, as shown in the literature review section. Leaving out a substantial material flow such as water means dismissing the immense potential of creating a technological loop that water reclamation and reuse would mean.

Therefore, besides an LCA, the two chosen circularity indicators (CEIP and MCI) were modified to handle the water use, disposal and reuse together with other material flows. This is a different approach to what Kakwani & Kalbar [48], who created a separate indicator for the water line using the algorithm of the MCI. Additionally, WF was calculated because it is traditionally used to evaluate water use in various technologies. However, it was adjusted to break away its linear approach of water, and recycling can be considered within the footprint calculation.

The test case was a Hungarian poultry processing company using the data from two consecutive years. The company was a great candidate for the analysis as they were carrying out multiple investments to improve the efficiency and sustainability of their poultry processing plant. One of them was to build a wastewater treatment plant as a first step to reduce their environmental impacts. The authors were involved in the research and development phase of the project, which gave them access to detailed data as well as the knowledge and opinion of various experts and decision-makers.

The LCA helped highlight the environmental effects of suggested scenarios, while the modified circularity indicators could direct the attention towards circularity pathways in an inherently linear industry. A comparison between the original and modified indicators and a discussion of the disadvantages and benefits of the applied various methods were conducted using six scenarios. Such a comprehensive, multifaceted analysis of the poultry processing industry has not been carried out to the best knowledge of the authors.

3. Materials and methods

On the way to achieving the circular goal, it is worth examining the current valuation methods and technological steps in all areas of the economy. Less flexible areas should also be considered to get information on the shortcomings and limitations of the indicators.

Not all of the examined indicators were suitable for calculating the circularity of poultry processing in their original form, but they could be suitable with minimal transformation. The questionnaire-type CEIP considers the circular design guide developed by the Ellen MacArthur Foundation for the physiological stages of products [55]. This method is suitable for a quick survey (interview) to identify vulnerabilities in the circularity. In addition, it was used to identify additional points of connection to the circularity. For more detailed calculations, MCI was selected, which is a product-centric circularity indicator. The calculation can be performed if the product properties and material flows are known. However, it does not consider the biological cycle, despite it playing a crucial role in forming circularity.

WF calculation [56] was used to assess the water profile along the product chain. This method covers certain technological steps not included in circular economic indicators. WF is typically used for linear analysis; this manuscript is modified to include recycling. The LCA was carried out to assess the environmental impacts and understand the relevance of water as an item on the material list.

3.1. CE indicator prototype

CEIP [38] examines the performance of the product per the principles of the CE. Nine professionals, who relate to the concept of circularity due to their profession or interest, were interviewed during its design so that it can be closer to the needs of the decision-makers. It calculates circularity based on the answers to questions concerning the fate of the product. The structure of the indicator is related to the steps of the product life cycle.

- Design/Redesign (Q1-Q3)
- Manufacturing (Q4-Q5)
- Commercialisation (Q6-Q8)
- In Use (Q9-Q12)
- End of Use (Q13-Q15)

For each life cycle category, there are main and supplementary questions that have to be answered. Most questions are single-choice; sometimes, the answer should be a percentage value. The score for questions is pre-defined in the manual with the values of the individual answer options. The product rating can be calculated by Equation (1).

$$\text{Product Rating} = \left(\sum \text{scored points}\right)/\left(\sum \text{available points}\right) \tag{1}$$

The maximum is 152 points, but if the question does not apply to the product, the total score can be reduced to 120. Once the table based on the available information is completed, the evaluation of the product is defined according to the following categories.

- $0 \leq$ Poor ≤ 0.2
- 0.4 $0.2 <$ Fair $\leq$
- 0.6 $0.4 <$ Good $\leq$
- $0.6 <$ Very Good ≤ 0.75
- $0.75 <$ Excellent ≤ 1

More detailed instructions on the calculation procedure can be obtained from the original methodology [38].

Interviews with the poultry processing company management and wastewater treatment experts involved in the development project were completed to understand the current state of water management and the gaps in their approach that could obstruct water reuse. Water reuse strategies were considered based on the literature covering state-of-the-art water resource recovery solutions. Based on the gathered information, four questions considering water as raw material were added to the production part (numbering follows the original method).

- Q16 - Is there a water use statement? (2 + 15)
- Q17 - Is there a water reduction plan? (10 + 5)
- Q18 - Is there wastewater reusing/recycling? (2 + 15)
- Q19 - Is there a system in place for rainwater retention and recovery? (5)

Bonus points were given for water recycling (Q16) if water usage was known, weighted by 10%. In addition, plans to reduce water use (Q17) were evaluated, and points to the existing system for savings were given. Penalty points (−2) were applied if water use increased compared to the previous year. Besides recycling, great emphasis was placed on the fate of wastewater (Q18). The current Hungarian food industry regulations do not support wastewater recycling, but it can also be used for other purposes, which are equally valuable. Therefore, the purpose of recovery was distinguished, such as communal, technological, and irrigation reuse. Pre-treatment and future wastewater recovery plans were rewarded with low scores. The fourth question (Q19) similarly ranks rainwater retention as water recirculation.

After reviewing the original questions, another question was included for the “Design/Redesign” lifecycle to describe the product to the raw material ratio.

- Q20 - What is the weight ratio of the product produced to the raw materials used? (3 + 2)

Several categories were defined: “Up to 50%", “50% < x <80%", “80% < x < 95%", and “95% or more”. The direction in which it changed was evaluated compared to the previous year. For performance below 50%, a penalty point (−1) was applied, as was a deteriorating product-feedstock ratio with a negative score (−2). The penalty points were introduced to incentivise the protection of water resources and to start the conversation on the importance of water reuse.

Additions increase the maximum available score to 194 for the case study (taking into account all questions, 211 points are available).

3.2. Material circularity indicator

MCI is a micro-level indicator and is designed for industrial uses. It focuses on the origin of materials, the fate of waste, and product usefulness. The method is described in Ellen MacArthur Foundation & Granta Design [41]. An absolute linear product would be made from virgin raw materials and disposed to a landfill after use. In contrast, products containing 100% secondary raw materials can be considered circular. Most products are found between these extremes, so the MCI was given a value between 0 and 1, where 0 means linearity and 1 means circularity. The methodology is based on the following assumptions.

- does not consider the material recovered from waste recycling returning to its place of generation,
- the quality of recycled materials is assumed to be the same as the raw material,
- no loss occurs during waste collection,
- material flows do not connect to biological cycles,
- the mass of the input material flow is equal to the mass of the output material flow (no consumption, incineration), so the mass of the product is constant.

The mass of unusable waste leaving the material streams is divided by the total mass flow to obtain the Linear Flow Index (LFI). LFI ranges from 1 to 0, where 1 is the fully linear flow, and 0 is the fully restoring flow. By changing the composition, the linear material flow can be influenced, for example, by reducing the virgin feedstock (V, kg) or improving waste recycling (CR, %) and reuse (CU, %), resulting in increased circularity. Material Circularity Indicator of the product (MCI_p) can use the linear flow index and the utility (X). Essentially, the value for a linear product would be 0.0; however, due to the utility factor ($f(X) = 0.9/X$), 0.1 is the baseline to allow the comparison of different linear products. The Modified Material Circularity Indicator (MCI') integrates material losses into the equations, i.e., the calculations are performed on all materials and wastes used for the product.

In the original methodology, water is considered a medium; therefore, it does not affect the material flow. The authors modified the calculation to consider water as a material stream (in kilograms), and it was included among the raw materials.

3.3. Water footprint

The WF calculations can be performed at a micro-, meso- and macro level; for a product, one or more consumers, a geographical region or a nation. Mapping the water usage of an organisation has several benefits. For example, the management will be provided with pointers to improve quality while reducing costs, and the environmentally friendly profile can help access a new customer base.

WF has three main parts: green, blue, and grey water footprint. The Green Water Footprint (WF_{green}, L/kg product) can be applied in practice for agricultural and forestry products, where estimating the internal (rain) water content is significant. Evaluating the water content helped assess the effects and costs of rainwater use. The Blue Water Footprint (WF_{blue}, L/kg product) is contained more easily measurable water from surface and subsurface sources. Evapotranspiration is included evaporation during storage, transport, processing, collection, and neutralisation. The backflow may occur in another catchment or a different period (for example, alternation of dry and rainy periods) and, therefore, should not be used in the same period. The maximum blue water footprint is referred to the amount of water currently available for which no more can be used. Its reduction can be achieved spectacularly in agriculture by reducing consumer losses, while in the industry, it depends on the recycling and reuse associated with the activity performed.

The purpose of the Grey Water Footprint (WF_{grey}, L/kg product) is to express the degree of water contamination by specifying the quantity of water required to dilute the effluent to the background concentration (c_{hat}, mg/L). WF_{grey} can be reduced through pollution prevention, recycling and treatment. The water demand was calculated for one year per kg of product for the three footprints.

The water requirements are summed to calculate the Water Footprint of the product (WF, L/kg product). The indicator shows the current direct and indirect water use status; it does not estimate future quality. Water recycling before discharge is not considered an option in the calculation; therefore, water-saving solutions after treatment cannot be accounted for with the WF methodology. While it is a quantitative method, the WF does not show the critical role of water in production or the effects of other factors (for example, pests, employment, energy use, and weather). The procedure is described in more detail in the user manual [49].

WF was modified to include water reuse in the indicator. The water footprint calculation was also carried out for one average product. The composition of green, blue and grey water footprints was calculated. The following simplified formula (Equation (2)) represents the summary:

$$WF_{PP}=WF_s + WF_p + WF_b + WF_{tw} + WF_e + WF_{ww} \quad (2)$$

WF_{PP} [m^3/kg] means the total water footprint of the poultry processing plant, which compares the amount of total water used to the weight of all products. The water footprint of the technological raw materials (Table 2) consisted of 3 parts: the water demand of spices (WF_s), packaging materials (WF_p) and broilers (WF_b). The technological water footprint was provided by the water consumption of the technology (WF_{tw}), the energy use (WF_e) and the wastewater dilution water volume (WF_{ww}).

3.4. Life cycle assessment

Life cycle assessment was carried out using the Life Cycle Assessment Product Sustainability (GaBi) Software [57], version 10.6.1.35, following the steps identified in the ISO 14040 standard [58]. System boundaries and involved processes were defined to fit the data requirements of the indicators. This led to a simplified description of the plant compared to what the software and LCA, in general, would allow, but the priority was to provide a solid base for the comparison of results and methods. Data that could not be collected from the case study directly was used from the Sphera software's own and the Ecoinvent database. Seven sustainability metrics were chosen to evaluate the different scenarios based on their relative importance. Five were used from the Environmental Footprint package (EF, version 3.0): climate change (CC), ecotoxicity freshwater (EFP), land use (LU), Resource use fossils (RU-f) and Water use (WU). In addition, freshwater consumption (FC) was calculated according to ReCiPe and global warming potential (GWP) was determined per the CML 2001 methodology.

3.5. *Uncertainty analysis*

"Cronbach's Alpha" analysis [59] was performed to verify the calculations and their modifications. It is the most commonly used indicator of internal consistency, which calculates the uncertainty of the methods using the following equation (3):

$$\alpha = [n/(n-1)]*(1-\Sigma V_i/V_t) \tag{3}$$

where n is the number of items, i represents an item, V_i is the variance of item scores, and V_t is the total variance of overall scores. The Cronbach's alpha (α) coefficient ranges between 0 and 1. The more consistent the items will be with each other if it is closer to 1. On the other hand, it should be taken into account that the α is even higher with the more extended tests. Based on Taber [60], α can be considered adequate from 0.7 in most cases, but there were sources where 0.4 was already sufficient. In these tests, α had to have a minimum value of 0.6 to be accepted.

3.6. *Data collection*

Poultry processing requires a high level of raw materials, which must not contain reused or recycled materials due to strict regulations concerning products for human consumption. Essentially, the life of a chicken goes linearly from the egg to one's plate. Therefore, the possibilities for intervention are minimal; the demand for packaging material, the generation of animal by-products, and the incredible energy and water consumption can be considered to improve the environmental goals.

The data from a Hungarian poultry processing plant were used for the analysis. The calculations were performed for one reference product; the main steps and their relationship to the indicators are illustrated in Fig. 1. The essential element of the production is the chicken as "raw material". Delivered broiler chickens are reared under strict conditions and are characterised by low infection. They are fed with controlled, domestic broiler feed, free of antibiotics and animal proteins.

Nevertheless, there is a varying amount of loss in the livestock that can be considered waste in the analysis. Each year, two types of broilers of different sizes and yields are hatched in different proportions. The company documents the initial number of rearing units in the hatchery rather than the types of daily delivered broilers. Thus the processed ratio of Ross-308 and Cobb-500 received by the processing plant is unknown, which can cause a discrepancy in WF calculation due to their different rearing times and feed consumption [61]. Water used for broiler feeding (feed production, drinking water, cleaning) is only included in the LCA analysis due to the nature of the database and the WF calculation; the modified circularity indicators only consider water use within the gates of the poultry processing plant.

In addition to broiler, spices and packaging are considered production materials. The average WF value of spices was taken from the work of Mekonnen and Hoekstra [62]. Packaging materials can change depending on product type, each having unique WF values [63]. Plastic foils, foil bags, and absorbent pads are used. Average WF values were used for plastic packaging materials of unknown composition [64]. Materials used with known WF values were polyethene [65], high-density polyethene (HDPE, [65]), polypropylene [66] and low-density polyethene (LDPE, [67]). Wood-based materials include labels (paper), twine, wooden pallets, and paperboard. The composition of their WF is diverse; for wooden pallets, data from Sishodia et al. [68], for twine by Mekonnen and Hoekstra [69] were applied. At the same time, for all other information on wood packaging material, Schyns's work [70] was used. Clips are used in

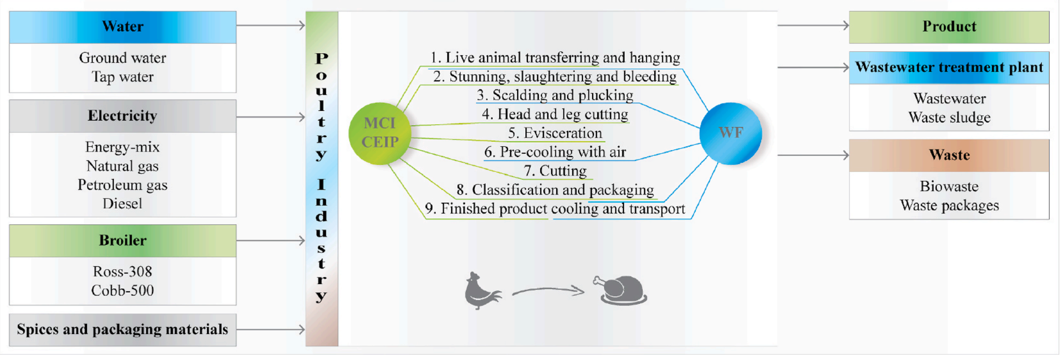


Fig. 1. Poultry processing steps as used in the different indicators.

small quantities during production; WF values of aluminium-based clips [71] were used.

The production processes operate with high water demand (Table S1), so water was also considered raw material. The two largest consumers are the boiler house (about 40%) and scalding, for which sterile water is used. The water demand varied between 340 and 700 m^3/day, depending on the number of cuts. First, water extracted from two wells is used to supply the technological steps; the missing quantity is met with tap water. Then, both streams undergo further treatment. In 2019, 1.3 times more water consumption was measured compared to 2018 due to changes in production processes.

In 2018 and 2019, 85.3% and 80.4% of the water demand left the plant as discharged wastewater. The difference is due to the evaporation caused by high temperatures and dehumidifying effect of the installed air purification equipment. In addition, processed meat takes up 2–3% water to prevent the finished product from drying out, which is essential for customer satisfaction. Wastewater goes through flotation and flocculation processes at the poultry processing plant and is further treated in a municipal wastewater treatment plant. For the calculation of WF_{grey}, the limit value of the discharge of municipal wastewater into surface water [72] and the latest (2015) measurement data of the affected surface water [73].

More than 80% of electricity and natural gas is used in production processes; the rest is used to supply buildings. Motor gasoline and diesel are used 100% during transportation. Electricity is bought from a supplier; thus, an average composition was used for the calculation: 5% coal, 12% renewable energy, 33% nuclear energy, 42% natural gas and 9% imported energy of unknown composition [74]. The WF values for fuel were used by Staples et al. [75]; for other energy forms, data were taken from Hadian and Madani [76].

The waste side includes animal by-products, provided for broilers arriving as carcasses and animal body parts generated next to the ribbon unfit for human consumption. Unused (residual) packaging materials are also wasted, taking a 5% loss into account. In the case of recycling efficiency, the data of the external partner [77] was taken into account.

4. Results and discussion

The calculations were performed for the two indicators and the two supporting methods, considering the design of the technology and the available data. An average was considered because the material flows are not documented separately for each product. The MCI methodology recommends selecting reference products; however, an average product can also be defined for the calculations. CEIP, WF and LCA are similarly flexible, though the latter is more suitable for detailed analysis of the environmental impacts. The original and modified calculations were always performed individually and labelled the same for comparability. The following cases were considered for the calculations performed according to the original methodologies.

- N: current operating mode,
- NP: 100% recycled packaging materials are used.

Scenarios examined for calculations supplemented the element of the material list with water, a larger analysing range to understand the modifications in more detail.

- W: current operating mode,
- WP: 100% recycled packaging materials are used,
- W50: 50% of wastewater was recycled back into the natural water cycle,
- W100: 100% of the generated wastewater was recycled back into the natural water cycle,
- WM: maximum circularity value available (100% recycled packaging materials are used, and 100% of wastewater was recycled back into the natural water cycle),
- WR: 100% of wastewater was recycled back into the natural water cycle and 50% less water consumption.

4.1. *Calculation of "CE indicator prototype"*

Two cases were examined using the original methodology that does not include waterline data. In the calculations, two questions did not apply to the product type.

- *"Is the product lighter than its previous version?"*– 2 point

Table 1
CEIP results for 2018 and 2019 - case N.

Lifecycle	Score	Available	Rating	Ranking
Design/Redesign	5	25	0.200	Poor
Manufacturing	17	25	0.680	Very Good
Commercialisation	0	15	0.000	Poor
In Use	0	35	0.000	Poor
End of Use	0	35	0.000	Poor
$\sum$	22	135	0.163	Poor

- *"Is there a rental option for the product?"*– 15 point

Therefore, the maximum score available was 135. There is no difference in the maximum score, as the product type is the same for both years and different cases.

Case N (Table 1) received a circularity value of 0.163 (Poor). Thus, the results show that the examined product is linear by nature, as one would expect from a consumer product. Circularity can only be detected at the production line; the packaging material recycling (NP case) reached 2 points more in the "Commercialisation" category; consequently, the value of CEIP increased to 0.178 (by 0.015).

The CEIP methodology is not flexible enough; comparing the production years showed no difference. The fundamental problem is that only positive cases can be distinguished; deteriorating quality is not considered. It is a negative trait because, in the case study, the increase in production is followed by an increase in water consumption, indicating declining performance. From a consumer product point of view, life cycle stages are more difficult to interpret because the "in use" and "end of use" stages are strongly linked to biological cycles. The 70 points, thus unattainable, push the product in a linear direction.

Meanwhile, the manufacturing stage corresponds to 18.5% of the available points, insufficient to reach the cyclical or "good"/"very good" status even with a full score. This supports the statement of Brändström & Saidani [40], who also found that CEIP underestimates circularity values. The results are illustrated in Fig. 2.

Integrating the new questions made comparing years with different characteristics possible, and the results show differences based on material flows and water use. As a result, for 2018, the values were higher but still in the Poor category; 2019 performed even weaker, considering the N and NP cases.

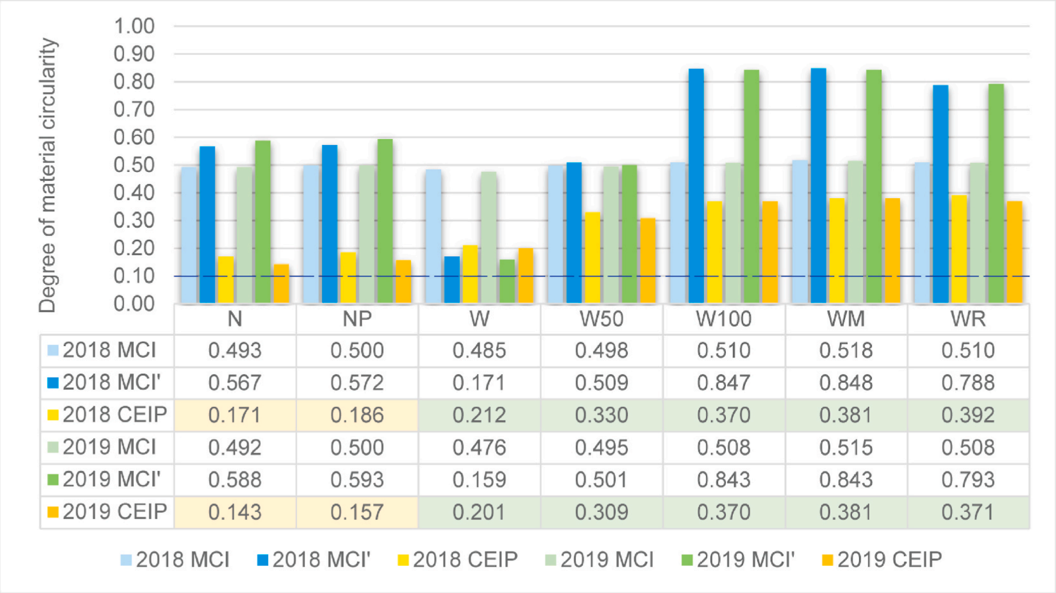
The negative change in production can be illustrated, making it more challenging to jump out of the linear range in both W and WP based on the data for 2019. The recycling of packaging materials shows a minimal increase in the WP and WM cases, as observed with the original methodology. Including water in the material flow improves the rate of circularity, and recycling also causes significant improvement, but more is needed to achieve a 'good' evaluation.

Considering a decrease of 2 points (e.g. penalty because of increased raw material use without increased productivity compared to the previous year), the circularity values are 4.63% lower considering the 2018 values and 5.91% for 2019. In contrast, an increase of 8 points would improve the values by 19.44 and 22.04% for 2018 and 2019, respectively. This suggests a higher sensitivity of the parameters after normalisation than only considering the total achievable points.

The indicator became suitable for waterline analysis and comparing different years with the modification. Nevertheless, it is not suitable to track continuous development but rather to determine pathways with which circularity can be achieved; it can be used as a preliminary study. As with the original methodology, the modified version is more appropriate for comparing different products. One has to bear in mind that CEIP underestimates circularity, but it can emphasise the need to move from a linear economic approach.

4.2. Calculation of material circularity indicator

MCI calculations were carried out based on the experience of CEIP. In addition, because broiler processing has a high demand for feedstock and only a portion of them is incorporated into the product, the effect of material losses was examined, adding water to the



	N	NP	W	W50	W100	WM	WR
2018 MCI	0.493	0.500	0.485	0.498	0.510	0.518	0.510
2018 MCI'	0.567	0.572	0.171	0.509	0.847	0.848	0.788
2018 CEIP	0.171	0.186	0.212	0.330	0.370	0.381	0.392
2019 MCI	0.492	0.500	0.476	0.495	0.508	0.515	0.508
2019 MCI'	0.588	0.593	0.159	0.501	0.843	0.843	0.793
2019 CEIP	0.143	0.157	0.201	0.309	0.370	0.381	0.371

Fig. 2. The value of MCI and CEIP for different cases (CEIP values with "Poor" ratings are shown with a yellow background, and "Fair" ratings are with a green background. The comparison limit of 0.1 is marked with a blue dashed line.)

list of inputs. The results are illustrated in Fig. 2.

The difference between 2018 and 2019 comes from the absolute and relative differences between broilers and products made from them. In 2018, 19.24%, while in 2019, 23.82% of the delivered broiler were collected as animal by-products. Consumption patterns determine the amount of packaging and spices used due to the nature of the products, which also has a minimal effect on the indicator in both standard and material loss modes. All raw materials come from fresh sources according to current regulations. The computed MCI value showed an intermediate state, halfway between the linear and circular states. Further improvement cannot be expected, as 95.1% of the raw material incorporated in the product is a broiler, i.e., a linear raw material. The MCI' value is higher because those materials not incorporated into the product (e.g., animal by-products) can be recycled, thus increasing the degree of circularity.

From the point of view of the MCI' results, it is not motivating to recycle the 1.8% packaging content of the product, but it is worth considering for customer satisfaction. Some material streams (spices and broiler) are utilised as nutrients in the human body, but the calculations do not consider the biological cycle; instead, they function as a "simple object of use", which has decreased the value of circularity.

By including water as raw material in the material flow calculation, the MCI value changed by −1.53% points compared to the 2018 data and −3.26% points for the 2019 data. The total weight of the product remained almost unchanged (25 963 730 kg to 25 662 024 kg). However, the 3% water content was calculated both in the raw material and waste side, increasing the mass of unusable materials and raw materials. For both years, the technology got a value close to linear by supplementing the material loss. The material loss mode considers that more than 80% of raw materials used are water, significantly increasing the amount of non-recoverable waste (8%–46%).

Water recycling was further investigated to determine the sensitivity of the Material Circularity Indicator to recycled wastewater between 0% and 100% (W, W50, and W100 cases). With the original method, the MCI value shows a barely visible increase (max. +3.14%), directly related to the 3% water content in the product. On the other hand, when material losses are included, the maximum of MCI' is 0.848 (WM case). The reasons for not reaching the ideal value of 1 are the broiler and spice as raw materials and the evaporation loss during the technology (freshwater demand). Interestingly, the indicator is not positively affected by water savings. Therefore, an improving circularity value can be achieved by increasing the recycling rate despite its higher specific water consumption, which can be considered a weakness of the method.

From the point of view of meat processing, the time of use does not depend on the quality of the product, i.e., the intensity of application (f(X)) cannot be interpreted for a consumer product; nevertheless, the lower limit has to be defined. The original purpose is to allow completely linear products to be compared from 0 to 0.1. The more linear the examined state (Fig. 3), the greater the deviation can be achieved by modifying the lower bound. In the original calculation method, changing the lower limit to 0 and 0.05 caused a difference between 5.2% and 12.2% in the circularity value and considering the losses increases the sensitivity of the indicator. Setting the f(x) to very low values may discourage the evaluator as the circularity indicator would also be in the lower range. While it is essential for durable products due to the sensitivity of the examined technology and comparison with competitors, it is psychologically good to keep the linear product boundary at 0.1 for consumer products.

4.3. Calculation of water footprint

Water Footprint was chosen to carry out to understand the total water usage of the company better (including the water demand of the broiler production stage). It has a linear approach regarding water consumption, but modifications were carried out to include water reuse in the indicator. The water footprint calculation was also done for one average product (Table 2).

Spices and broilers are strongly tied to agricultural water use, so at least 80% of their water footprint is green water content. In

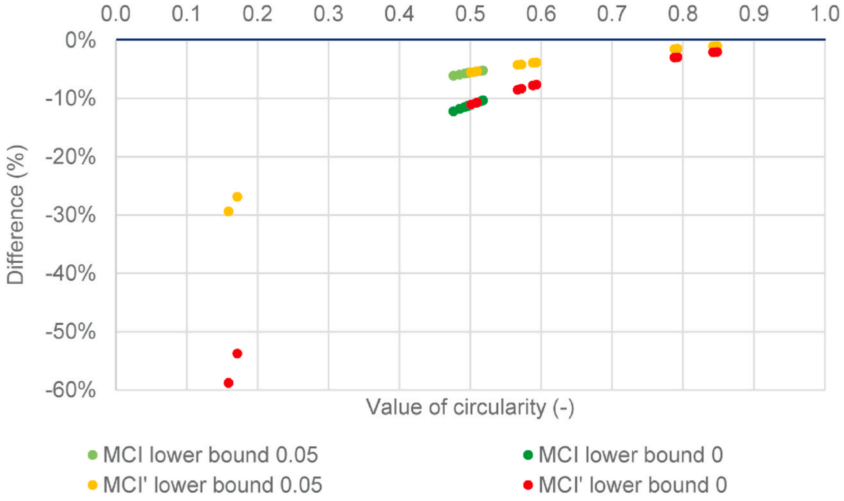


Fig. 3. The change in the value of the circularity depends on the lower bound.

Table 2
Calculated water footprint values of materials used in technology and technological steps.

		2018	2019
Spices	[m^3]	222 382	200 761
Packages	[m^3]	92 380	91 317
Broiler	[m^3]	102 875 301	107 816 382
Water	[m^3]	126 267	163 772
Wastewater	[m^3]	131 681	160 901
Energy	[m^3]	231 558	255 927

contrast, the water footprint of the packaging materials used in the technology consists of 70% blue water and 27% grey water.

The calculation of the water demand of the technology consists of several components. Direct water consumption is measured before the technology; this is the blue water footprint. 40% of the water goes to the boiler room, soaking/bathing and washing the products takes 20%, and scalding and plucking together is 14%. The technological transformation had a minimal effect on the number of cuts, while water use significantly increased the water footprint. The wastewater dilution water volume shows a 1.2-fold increase for 2019. A 1% increase in the processing of broiler chickens affected energy consumption by an increase of +10%.

The composition of the total Water Footprint is shown in Fig. 4. Examining the total WF value, the proportions of green, blue and grey water content did not change; all values increased by 5% compared to 2018. The reason is broiler processing, which increased by 2%; even before that, it was more than 99% of the water footprint. As a result, the 29.7% increase in water consumption of the technology relative to the total water footprint is barely noticeable.

The difference between the two years is clearly due to the total weight of the products and the change in water consumption. Without the broiler, the remaining 1% consists of 29.1% energy production, 25.3% spices, 17.4% wastewater discharge and 17.2% water consumption. Packaging materials account for 11%. The results show that WF cannot be significantly reduced due to the broiler. It is impossible to keep chickens on a water-poor diet because it leads to higher mortality and poor-quality meat, and for similar reasons, the water demand of the crops they consume cannot be reduced [78].

Scenarios of different water recycling options were considered for testing their effect on WF. For example, water recycled to technology reduces blue water demand, while water recycled for irrigation reduces broiler green water demand. In both cases, the wastewater minimises the value of the water footprint by demanding greywater. In terms of process water use and wastewater discharge, water recycled to the technology increases circularity, while irrigation reduces the load on the outlet side (Table 3). In contrast, the degree of circularity within the total WF is negligible, showing the importance of defining appropriate boundaries.

4.4. Results of life cycle assessment

Life Cycle Assessment was carried out using the same level of detail regarding the material flows details for the same scenarios defined for the indicators. The functional unit was chosen to be a 1 kg product. The results are shown in Fig. 5. While the broilers make up 95.1% of the product, their environmental impacts are less prominent. Instead, packaging materials and spices (4.9% of the product weight) provide the highest contribution in the baseline cases. Full recycling of packaging materials results in a reduction in all significant impact categories, such as a 99.5% reduction in the value of fossil resource use (RU$_f$) and an average of 87% decrease in freshwater Ecotoxicity Potential (EFP) value. However, due to the other two raw material types (spices and broiler), other categories barely reach the 11.11% reduction.

The importance of including water data in system analysis is clearly underlined in the LCA, though the results differ from the WF calculation. This is because most of the life cycle data was obtained from the software database. These data can be obtained from multiple levels (global, regional, etc.) and take into account the related life cycles. In contrast, WF used the global literature data [49], completed with the unique characteristics of the Hungarian case study. Case W showed an increase in the ecotoxicity category compared to the base scenario: for 2018, the increment of EFP was 62.5% and 76% for 2019. Regarding other impact categories, the change was less than 3.32% except for water use and freshwater consumption.

The real importance of involving water in the material flow is demonstrated by the impact categories related to water; a more than a thirty-fold increase of WU was experienced, and FC rose to 3.2 times the original value. Reusing the treated wastewater (W100) would

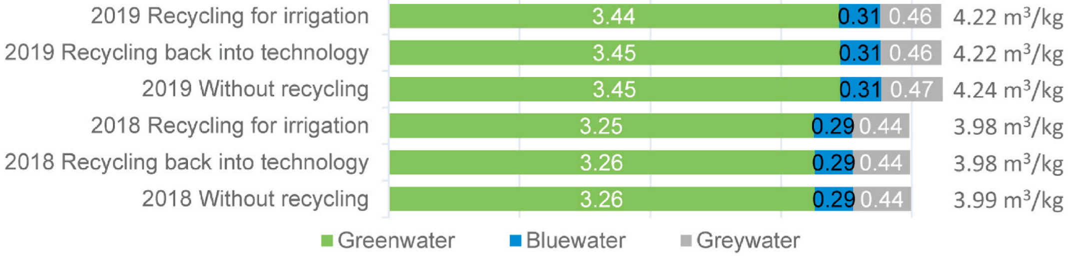


Fig. 4. Water footprint ratios based on 2018 and 2019 data.

Table 3
Changes in water footprint values for cases.

		Circularity	Technological cycle
2018	Without recycling	0	0
	Recycling back into technology	0.002	0.928
	Recycling for irrigation	0.001	0.510
2019	Without recycling	0	0
	Recycling back into technology	0.003	0.901
	Recycling for irrigation	0.001	0.496

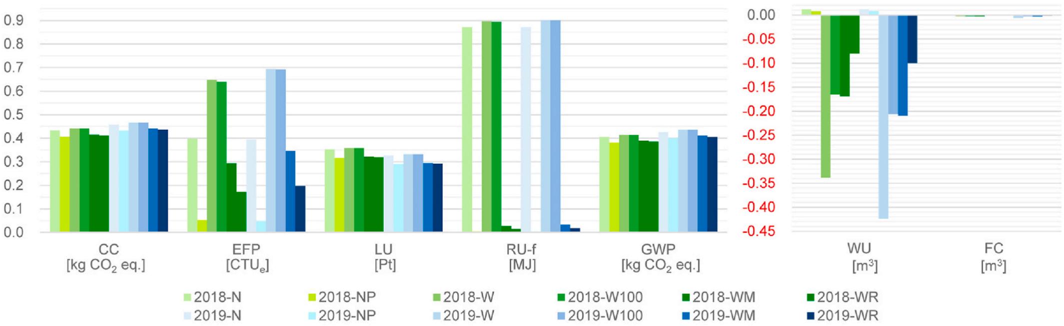
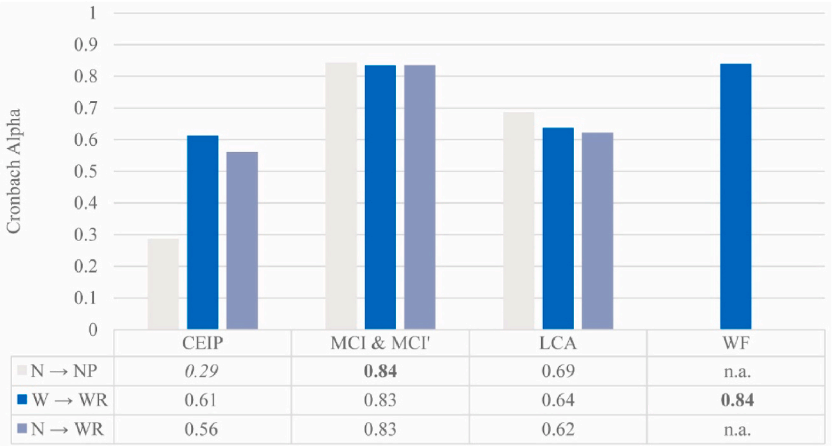


Fig. 5. Overview of the LCA results.

reduce WU and FC by 51%; achieving maximal circularity (WM) lowers the results by 50%. If the WR scenario is realised, the saving would be 76% due to the 50% reduced water consumption. The difference between the years is also significant for the scenarios including water because the change in 2019 due to the more wasteful production caused a 25% increase in the values of WU and FC compared to 2018.

4.5. *Uncertainty analysis*

Uncertainty analysis was carried out for the modified metrics to evaluate their validity and reliability using the Cronbach alpha method (Fig. 6). CEIP gives a higher α with the additional questions, but the life cycle stages that do not apply to consumer products (in use, end of use) clearly lower its values. Results of the different scenarios MCI and MCI' were analyzed together; for all cases, the reliability was calculated to be a rather high value (>0.83) considering ±5% water volume variation. The lower reliability of the LCA values is due to the different range of environmental impacts, which is only worsened by the fact that the WU and WF values (water use impact categories) appear in the negative range. WF is only interpretable in one case, which gives good reliability.



	CEIP	MCI & MCI'	LCA	WF
N → NP	*0.29*	**0.84**	0.69	n.a.
W → WR	0.61	0.83	0.64	**0.84**
N → WR	0.56	0.83	0.62	n.a.

Fig. 6. The value of Cronbach alpha (n.a. - not applicable).

4.6. Comparison of methods

The results of the methods (Table 4 for the indicators and Fig. 5 for LCA) clearly show that by incorporating water consumption into the calculation, the position of poultry processing regarding circularity shifts considerably. All indicators show deteriorating performance for 2019 with adjustments, except MCI'. CEIP originally underestimates the level of circularity compared to the modified version, but its life cycle perspective gives a more comprehensive evaluation of the product. On the other hand, MCI describes an intermediate state because the indicator treats consumables the same way as durable goods. This turned out to be one of the shortcomings of the method. Instead of a "buy and throw away" approach, the calculation would need to provide the option to consider the biological cycle. On the other hand, LCA takes the material back to nature, providing a more nuanced picture of the environmental effects (but not the level of circularity). Leaving out and later adding the water flows in the LCA shows the immense impact water use can have on the outputs of a technology. This proves that the linear or circular nature of a system should only be assessed with involving water-related processes. Using the modified calculations, the radical drop of the MCI' indicator value shows the linear nature of the poultry processing technology in its current state, which is also in line with the result of CEIP.

The depth of analyses varies widely. CEIP is unsuitable for detailed comparisons; while MCI and MCI' allow tracking more subtle differences, it can also consider recycling the elements of the product after use. Since the sole function of the meat product is that it is consumed, recycling parts of the product was not included in the calculation. None of the versions includes quantifying the biological cycle (human consumption), though Rocchi et al. [43] modified the MCI method to include biological cycles. On the other hand, resource recovery from wastewater (e.g., fertiliser) could be incorporated.

While the different indicators might not be exhaustive, they are fairly simple to compute. Contrary to that, LCA cannot be performed as a quick overview analysis due to its complexity and vast data requirements. After setting up the inventory, though, it can serve various purposes, such as assessing the environmental effects of any technological intervention or facilitating circularity calculations by providing necessary data of different scenarios. While circularity indicators can be determined without setting up a life cycle model, combining the two approaches can help avoid the pitfalls of striving to create loops without considering the environmental costs.

The WF calculation results in very similar values for all examined cases because broilers correspond to up to 99% of the water involved in the calculation as green water. The difference between the years is entirely in line with the increase in raw material. From this perspective, water recycling could play only a minor role in mitigating the impact of the technology. In this sense, LCA serves a more nuanced picture as packaging material and spice water demand are distinguishable, as is the effect of recycling packaging or water.

Putting the broiler water use aside, the majority of water demand of the processing steps is blue water, as the technological lines require a large amount of sterile water, and 85% of it becomes greywater. Furthermore, as the water footprint of energy consumption was determined by the Hungarian electricity production rates (with a modest ratio of renewables), and the WF of renewable energy sources vary between 0.001 and 78.0 m^3/GJ [76], the overall WF will change as the energy mix shifts towards one or another energy source.

The linearity of the product is apparent; it cannot be changed due to the quality requirements of raw material production. With a focus on the technology water use, the result is similar to the other two indicators; with irrigation, an intermediate state (0.49–0.51) can be achieved, while with technological water recycling, almost full circularity can be achieved (0.9–0.92).

4.7. Limitations and suggestions for further studies

One of the biggest areas for improvement of the circularity indicators was that negative changes are not penalised, which may result in better circularity values despite using more resources. To overcome this, the authors added penalty points for increased water consumption as a test, and they suggest further modifying both CEIP and MCI to include penalty points where increased resource use is relevant.

Another issue with CE indicators is that they only consider the level of recycling and reuse but do not calculate the respective environmental impacts. Therefore it is suggested to carry out some environmental impact assessment of proposed changes in the technology.

Should the biological cycle be included in the calculation, the circularity of food products could be assessed in a more comprehensive way, and in other cases, resource recovery from wastewater could add to the level of circularity of any type of product.

Another of the drawbacks of MCI and MCI' is that neither includes energy in the calculation; therefore, energy consumption and potential recovery are not included in the circularity approach. Thus, if energy recovery in the wastewater treatment process or from the waste materials is achieved, it cannot be considered in the algorithm. If it were, that would cover all aspects of resource recovery and thus circularity.

5. Conclusions

With sustainable development in mind, circular economy in all industrial sectors must be pursued, though breaking free from the linear economy is challenging, especially in the food industry. One step towards that goal is to develop and use tools for monitoring circularity that can handle consumer goods and water as raw material beyond durable products.

The authors used a Hungarian poultry processing plant as a case study for understanding the constraints and monitoring circularity and sustainability using four different methodologies: two material circularity indicators (CEIP and MCI), the water footprint and LCA.

Table 4
Summary of the CEIP, MCI and MCI' calculations for the different scenarios.

		N	NP	W	WP	W50	W100	WM	WR
CEIP	2018	0.163 → 0.171	0.178 → 0.186	0.216	0.227		0.371	0.381	
	2019	0.163 → 0.143	0.178 → 0.157	0.186	0.196		0.351	0.361	
MCI	2018	0.493	0.500	0.485		0.498	0.510	0.518	0.510
	2019	0.492	0.500	0.476		0.495	0.508	0.515	0.508
MCI'	2018	0.567	0.572	0.171		0.509	0.847	0.848	0.788
	2019	0.588	0.593	0.159		0.501	0.843	0.843	0.793
WF	2018	3.99 m^3/kg					3.98 m^3/kg		
	2019	4.24 m^3/kg					4.22 m^3/kg		

The circularity indicators originally did not consider water as a raw material, giving a false interpretation of circularity in cases where water is incorporated into the end product. Unsurprisingly, the inclusion of water reduces the apparent circularity, thus better illustrating the linear nature of the food industry. The change in the indicator values is highlighted even more with the lifecycle assessment where water use was deliberately omitted for the baseline scenario realising a thirty-fold increase in the water use category. The modifications, such as the introduction of water as raw material in CEIP and MCI, the penalty points in the CEIP, and the reuse in the WF, provided a deeper insight into the challenges in moving towards circularity in poultry processing. LCA helped highlight the environmental effects of the examined interventions to improve the circularity of the case study.

None of the three indicators was initially designed for consumer products. Not all products can be broken down into their components and reused or recycled with technological solutions; natural processes need to be factored into the calculations, such as the bioavailability of a consumer product. Nevertheless, with slight modifications, they may become suitable for measuring circularity, including the water cycle. Circularity indicators proposed in this paper and by other authors have the potential to make circularity more visible rather than acting as a stand-alone decision-support tool. The results also emphasise the risk of using one single metric for assessing a product, because chasing higher circularity values may result in increased negative environmental impacts. However, the metrics should cover various circularity aspects if that route is chosen. The authors recommend further developing the indicators based on the results by integrating more elements, such as consumption patterns, water use, energy use, and biological and environmental conditions.

Author contribution statement

Réka H-Hargitai: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Viola Somogyi: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

All data generated or analyzed during this study are included in this published article and its supplementary information file.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been implemented by the TKP2021-NKTA-21 project with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the 2021 Thematic Excellence Programme funding scheme. The data were gathered in frame of Széchenyi 2020 under the GINOP-2.2.1-15-2017-00096 project.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2023.e17587.

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