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Full length article

Assessing the ISO hierarchy validity in circular wastewater treatment life cycle assessments: A Portuguese case study

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ABSTRACT

This study evaluates the validity of ISO hierarchy in handling multifunctionality in life cycle assessments of circular wastewater treatment plants (WWTPs). The case study focuses on retrofitting a WWTP to produce Kaumera biopolymer, a potential substitute for sodium alginate. Various multifunctionality handling approaches—system expansion, zero-burden, economic, and mass allocations—were applied and various functional units were selected to calculate environmental impacts. The global warming (GWP), mineral resource scarcity (MRSP), and fossil resource scarcity (FRSP) indicators were examined. The results indicate that Kaumera offers significant environmental benefits (40 %–99.9 %) in GWP, MRSP, and FRSP compared to sodium alginate. System expansion provides a comprehensive assessment, making it the preferred approach. Economic allocation yields closer results to system expansion than other approaches, while zero-burden and mass allocation show 88–93 % and 100 % improvements, respectively, leading to misleading conclusions. We suggest that ISO should prioritize economic allocation over mass allocation in wastewater treatment studies.

1. Introduction

Historically, urban wastewater was viewed as a hazard, necessitating treatment to mitigate impacts on human health and the environment. Wastewater treatment plants (WWTPs) focused on ensuring effluent quality to meet environmental discharge standards. In recent years, however, the wastewater treatment sector has been increasingly embracing a circular economy (CE) approach, recognizing wastewater as a source of water, energy, and nutrients (Puchongkawarin et al., 2015; Wang et al., 2023). This transition to circular practices in the wastewater treatment sector results in WWTPs recovering secondary materials and, consequently, providing more functions from a Life Cycle Assessment (LCA) perspective. This study contributes to the field by demonstrating how the ISO hierarchy for managing multifunctionality can be effectively applied when retrofitting WWTPs to promote circularity.

The CE concept aims to minimize pressure on natural resources, while creating sustainable growth and jobs, and supporting EU's 2050 climate neutrality target. In a CE, the value of products and resources is maintained within the economy for as long as possible, and waste generation is minimized (Directorate-General for Environment, 2024). Therefore, sustainability tools are used to analyze expected environmental, societal and economic benefits of the transition to a more CE. Among these benefits, only the environmental benefits are solely assessed with one tool, the LCA.

WWTPs are central to advancing CE goals due to their ability to transform waste into valuable resources. WWTPs can become "bio-factories" that recover energy and materials from wastewater, providing a higher-quality water effluent and extending beyond traditional metrics, such as Biological Oxygen Demand and Total Suspended Solids (Furness et al., 2021). The transition to a CE transforms WWTPs into multifunctional systems due to resource recovery, energy management, and removal of emerging contaminants (Corominas et al., 2020; Padilla-Rivera et al., 2016). WWTPs that employ the aerobic granular sludge technology reduce their energy and chemical needs compared with conventional technologies, while recovering biopolymers (Tavares Ferreira et al., 2021). The latter can replace market materials, such as sodium alginate, and its postprocessing makes it ideal for various

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applications, such as a coating material for slow-release fertilizers, a biostimulant in agriculture, a fire retardant, or a curing agent for concrete (Royal HaskoningDHV, 2019). Due to these advances, conventional assessment approaches may not accurately represent the environmental impacts of multifunctional WWTPs, creating a need for appropriate approaches in LCA studies (Corona et al., 2019).

LCA is a tool standardized by ISO (International Organization for Standardization, 2006a, 2006b) for assessing the environmental sustainability of products or waste treatment systems. According to ISO 14, 040:2006 (International Organization for Standardization, 2006b), a product system is defined as: "A collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product". ISO 14,040:2006 does not explicitly define waste treatment as a standalone term but it is considered as part of the broader framework of a product system. In this context, waste treatment refers to processes or systems that manage waste streams to recover materials or energy, or to dispose of them with minimum environmental impacts. When a modelled system serves multiple functions, it becomes challenging to determine how to distribute environmental impacts among those functions. According to ISO 14,044:2006 (International Organization for Standardization, 2006a): "The study shall identify the processes shared with other product systems and deal with them according to the stepwise procedure presented below". This issue is called multifunctionality, it is the most debated issue in LCA (Tsalidis and Korevaar, 2020), and this "stepwise procedure" is called the ISO hierarchy concerning multifunctionality. Multiple functions in waste treatment systems stem from the end-use of recovered materials. The ISO presents a three-level hierarchy approach to handle multifunctionality (International Organization for Standardization, 2006b):

1. Avoid allocation by sub-division (specifying sub-processes per co-product) or apply system expansion (expanding the functional unit to represent all functions);
2. Apply allocation following the underlying physical relationships of multiple functions;
3. Apply allocation based on other relationships (e.g., economic values).

However, this hierarchy may limit the use of mass allocation (Step 2) in circular wastewater treatment systems. This is because the input flow, commonly regarded as the functional flow (wastewater) (Corominas et al., 2020), is highly diluted with water. Additionally, the treated wastewater outflow released into the environment has no economic value, the recovered sludge is wet (Wang et al., 2024) and typically provided free of charge to local farmers, and other secondary recovered resources constitute only a negligible fraction of the input flow.

So far, LCA studies focusing on resource recovery from wastewater do not always follow the ISO hierarchy for handling multifunctionality or select a multifunctionality handling approach arbitrarily to model waste treatment systems that promote circular economy practices. Therefore, our study investigates whether the ISO hierarchy remains valid in LCA studies of WWTPs recovering resources and which multifunctionality handling approach best assesses the transition from a linear to a circular economy. The main objectives of CE include mitigating climate change, limiting biodiversity loss, decreasing virgin resource consumption, boosting economic growth, and creating jobs (European Parliament, 2023). To this end, the LCA conducted in this study involves an existing WWTP retrofitted to recover Kaumera biopolymer.

2. Overview of LCA studies for resource recovery in retrofitted WWTPs

Sfez et al. (2019) applied LCA to investigate whether the share of the environmental burden of consumer products should be allocated to recovered resources from wastewater. The authors found that allocating or not allocating part of the virgin resources used from consumer goods to the recovered resources greatly affects the potential of recovered resources to compete with benchmark products in terms of biotic and abiotic resources, fossil fuels, metal ores, minerals, and water resources.

In addition, out of nine LCA studies on wastewater treatment systems that assessed secondary resource recovery, only five LCA studies applied a multifunctionality handling approach, such as substitution or system expansion, but no explanation was given on the selected approaches. In particular, studies (Estévez et al., 2022; Gowd et al., 2023; Malila et al., 2019) that applied substitution did not mention explicitly the approach in the text, but presented negative environmental impact scores. In contrast, two studies contradicted ISO by avoiding handling multifunctionality in their LCA systems with several functions and reported environmental benefits when existing wastewater treatment systems are expanded to recover resources, even though this expansion results in greater energy and material needs for the system. Mayor et al. (2023) and Lehtoranta et al. (2022) reported environmental benefits for Global warming because their functional unit was fertilized soil due to the recovery of materials and one year of operation, respectively. Table 1 presents various parameters and results of nine LCA studies on wastewater treatment systems with secondary resource recovery. Most studies indicated a decline in performance for Global warming, Mineral resource scarcity, and Fossil resource potentials when compared with WWTPs before retrofitting or reference WWTPs with or without handling multifunctionality. Recovered resources consisted of struvite, biogas, compost, and nitrogen-rich or phosphorus-rich fertilizer, and in eight LCA studies multiple resources were recovered.

Table 1
Parameters and relative results of similar LCA studies; negative percentages show improvement.

Study	Recovered resources	Multifunctionality approach	GW [a]	MRS [b]	FRS [c]
(Malila et al., 2019)	Soil enhancer, Fertilizer	Substitution	No change	–	–
(Mayor et al., 2023)	Struvite, NH_4NO_3	–	−24 %	–	34 %
(Tian et al., 2020) [d]	Electricity, Heat, Bio-char, Bio-oil	–	10–210 %	–	−10-+90 %
(Lam et al., 2022)	Struvite, Phosphates	System expansion	−7-+8 %	–	–
(Gowd et al., 2023)	Struvite	Substitution	−34 %-+180 %	400 % - 1800 % lower	−0.38 % - +64 %
(Estévez et al., 2022)	Nitrogen fertilizer, Reclaimed water, Biogas	Substitution	−65 %	–	−75 %
(Morsy et al., 2020) [d]	Treated sewage sludge, Biogas	–	+17 %	–	+20 %
(van Zelm et al., 2020)	$(NH_4)2SO_4$, NH_3, H_2S0_4	System expansion	–	–	–
(Lehtoranta et al., 2022)	Compost	–	−24 %	–	–

[a] Global warming
[b] Mineral resource scarcity
[c] Fossil resource scarcity.
[d] these studies regarded retrofitting WWTPs.

3. Methods

3.1. Case study

The assessment considers the transformation of the Faro-Olhão WWTP to a Kaumera Nereda® Gum recovery facility (Fig. 1). Kaumera Nereda® Gum is a biopolymer extracted from aerobic granular sludge which can be used for numerous applications (Royal HaskoningDHV, 2019). The Kaumera Nereda® Gum will hereafter be referred to as Kaumera. A perquisite to recover Kaumera is that a Nereda® system is used for biological nutrients removal in the mainline. The Nereda® system is the first aerobic granular sludge technology applied at full-scale. It provides system's advantages regarding treatment performance, energy-efficiency, cost-effectiveness, and alginate-like exopolysaccharides from aerobic granular sludge (AGS) can be extracted (Pronk et al., 2017). The existing Nereda® process at Faro-Olhão WWTP treats approx. 6123,498 m^3/y and produces approx. 2388 tons of sludge which is a waste because it has a negative financial value. The wastewater treatment sub-system (Fig. 1. B) and the Kaumera production sub-system (Fig. 1. A) are described below.

The wastewater enters the plant, where it is pre-treated by sieving and degritting (Fig. 1. B). Then, wastewater flows to the Nereda® process where a liquid effluent and the activated granular sludge (AGS) are produced. The AGS from the Nereda® process is transferred to the sludge treatment stage, consisting of a gravity thickener and a mechanical centrifuge. After thickening, the sludge exits the wastewater sub-system (B5 in Fig. 1) and enters the Kaumera production sub-system. The wastewater treatment sub-system consumes chemicals, including sodium hydroxide, sodium hypochlorite, sulfuric acid, and polyacrylamide, as well as grid electricity. The Kaumera production sub-system (sub-section (B) in Fig. 1) includes two reactors and two centrifuges. Kaumera production involves four key steps: (1) Potassium hydroxide is added to the extraction reactor, where the biopolymer is chemically extracted from the AGS at a high temperature (80 °C). (2) The mixture from the extraction reactor is sent to a centrifuge for solid-liquid separation, with the liquid fraction redirected to the head of the Nereda WWTP. (3) The biopolymer is then transferred to the precipitation reactor, where sulfuric acid is used to precipitate the biopolymer. (4) The resulting mixture is moved to the second centrifuge, where the Kaumera gel is separated from the precipitated biopolymer, with the waste directed back to the head of the Nereda WWTP.

The reference system regards a conventional form of producing alginate biopolymer from seaweed (Langlois et al., 2012), with or without the wastewater treatment sub-system (Fig. 1. B) depending on the applied multifunctionality handling approach.

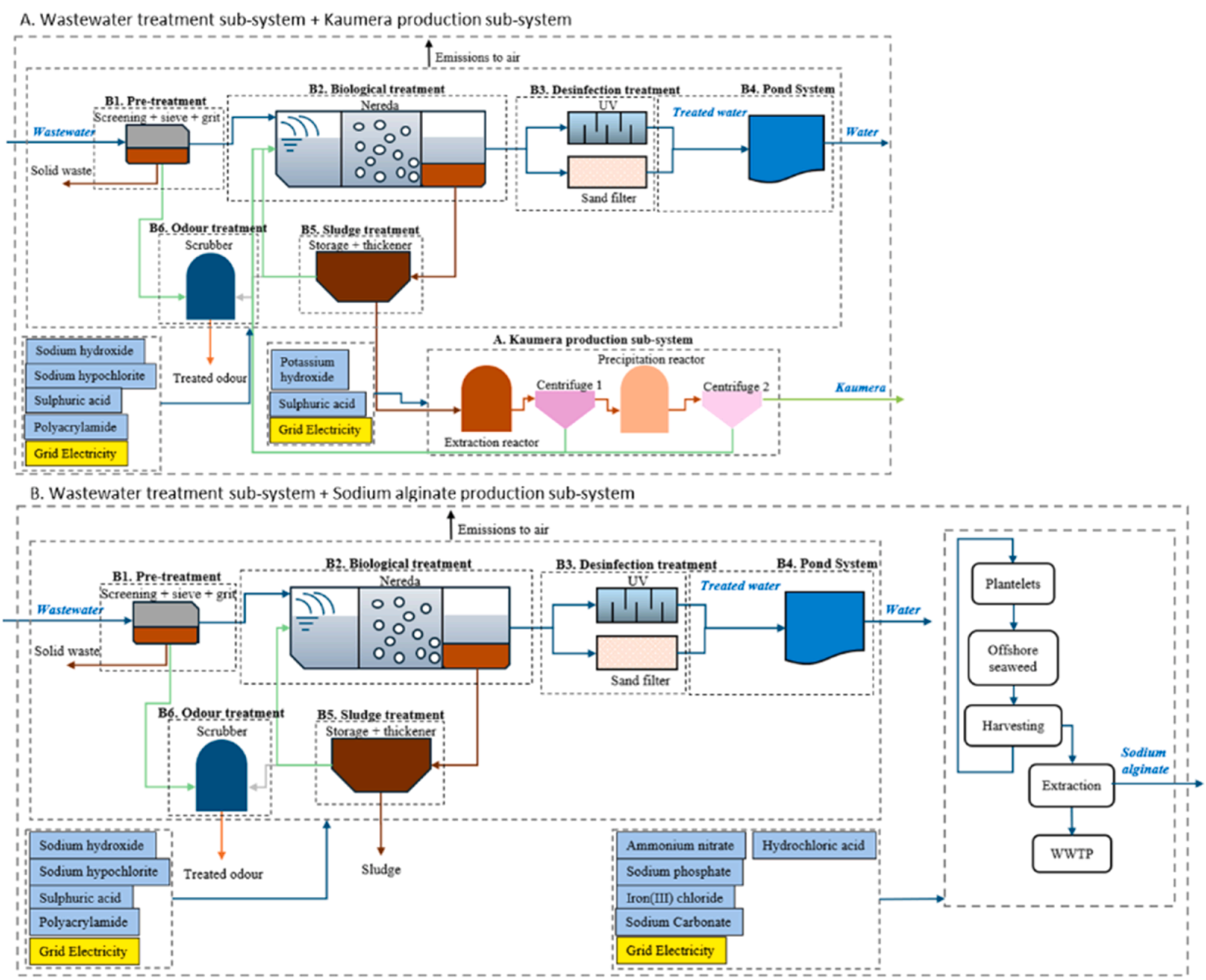

Fig. 1. A: The original system with processes comprising the Kaumera production sub-system and the existing wastewater treatment sub-system; B: The reference system with processes comprising the sodium alginate production sub-system and the existing wastewater treatment sub-system.

3.2. Life cycle assessment

3.2.1. Goal and scope

3.2.1.1. Goal. The goal of WWTP system is twofold: to treat wastewater and produce Kaumera biopolymer. According to ISO's hierarchy for handling multifunctionality (International Organization for Standardization, 2006b), these functions must be managed appropriately. The chosen approach for handling multifunctionality impacts the definition of the functional unit. Two different functional units were considered, based on the applied multifunctionality handling approach:

One year of operation: This functional unit is used when system expansion is applied. It regards the treatment of 6123,498 m^3 of wastewater and the production of 312 tons of Kaumera on dry basis. In this scenario, the original system encompasses the entire WWTP operation, covering both wastewater treatment and Kaumera production. The reference system includes the wastewater treatment sub-system and sodium alginate production (de Koning et al., 2023; Langlois et al., 2012).

One kg of Kaumera: This functional unit is used when the Kaumera sub-system is isolated, employing approaches like zero-burden, mass allocation, or economic allocation. Under this condition, the focus is solely on Kaumera production, with the reference system covering sodium alginate production from seaweed. One kg of Kaumera replaces one kg of sodium alginate (de Koning et al., 2023; Langlois et al., 2012).

3.2.1.2. Scope. The scope of the system is cradle-to-gate, from the inflow of wastewater into the WWTP, to the production of Kaumera. Processes upstream of the wastewater inflow are not considered because urban wastewater has no positive market value (Ijassi et al., 2021) and upstream processes are not expected to be affected by wastewater management options (European Commission et al., 2011). However, the

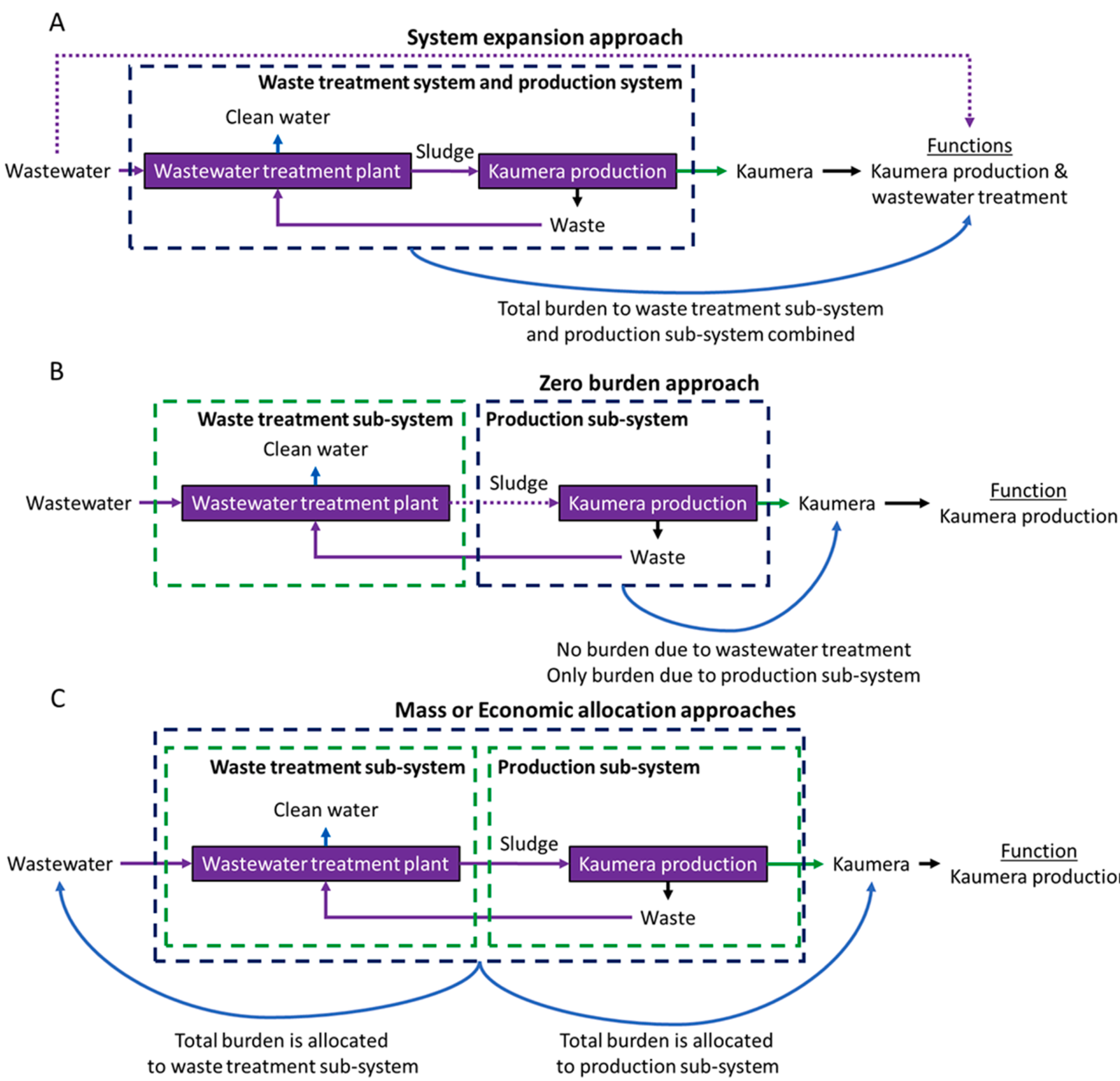

Fig. 2. Illustration of system expansion (A), "zero-burden" (B), and mass and economic allocation (C) (blue dashed lines regard what is considered according to each approach, dotted arrows regard physical separation of processes).

literature considers this design as "cradle-to-gate" instead of "gate-to-gate" (Kumar and Verma, 2021).

Approaches for Handling Multifunctionality: System Expansion, Zero-Burden, Mass Allocation, and Economic Allocation

Three different approaches to handling multifunctionality and their combinations were analyzed and compared. Fig. 2 illustrates these multifunctionality handling approaches applied to assess the environmental impact of the WWTP system and its sub-systems. Table 2 outlines the allocation factors for each approach, illustrating how the environmental burden is distributed across different sub-systems.

System Expansion: This approach does not distribute the environmental burden among functions but considers the combined impacts for both wastewater treatment and Kaumera production. Its focus is to evaluate the environmental performance of treating 1 m^3 of wastewater and recovering Kaumera, compared to treating 1 m^3 of wastewater and producing sodium alginate from seaweed. System expansion offers a broader perspective by including the combined burdens across the full scope of WWTP operations.

Zero-Burden Approach: In this approach, only the Kaumera production processes are considered for the environmental assessment, disregarding the wastewater treatment sub-system. This isolation allows for a focused evaluation of Kaumera production and its comparison with sodium alginate production from seaweed.

Economic and Mass Allocation: These approaches distribute the environmental impacts across sub-systems, with allocation factors based on economic values or mass. Economic allocation uses expected market price for Kaumera (e.g., 2.5 €/kg), resulting in varying distribution scenarios. In addition, mass allocation is applied to the original system or only to the Kaumera production sub-system. In the latter case, a combination of mass allocation and zero-burden approach is used, assuming that the AGS requires further treatment before disposal, thus isolating the Kaumera production sub-system into two distinct functions: sludge treatment and Kaumera production. In these cases, isolated Kaumera production is compared with sodium alginate production from seaweed (Langlois et al., 2012).

3.2.1.3. Impacts. Circular economy systems are expected to yield environmental benefits compared to linear economy systems by reducing reliance on pristine natural resources. These benefits can be assessed through various environmental impact indicators, such as Global Warming Potential (GWP), Mineral Resource Scarcity Potential (MRSP), and Fossil Resource Scarcity Potential (FRSP). In this study, the ReCiPe2016 Life Cycle Impact Assessment method (H) (Huijbregts et al., 2017) was used at the midpoint level to evaluate these impacts, providing a standardized framework to assess the environmental performance of circular systems against traditional linear economy models.

3.2.2. Inventory

Table 3 presents the inputs, outputs, and environmental releases of the wastewater treatment and Kaumera production sub-systems. Process-level data for wastewater treatment sub-system, such as Nereda, sludge treatment, etc. was not available. Therefore, the wastewater treatment sub-system was modelled as a black box, i.e., it was represented by an input-output relationship. This study employs several functional units; thus, the values of the inputs, outputs, and environmental releases are normalized by one year of operation, as shown in Table 3 with ranged values for sensitivity analysis, which is the functional unit of system expansion. The names of employed dataset from Ecoinvent v3.10 can be found in Table S1 and the inventory for the sodium alginate production from seaweed of the reference system (Fieler et al., 2021; Langlois et al., 2012) can be found in Table S2 of the Supplementary Material.

Assumptions:

1. Food production systems and cosmetics production systems were excluded from this study, even though they are the main sources of urban wastewater (Sfez et al., 2019) because wastewater has no positive market value. The application of CE is expected to mainly affect the packaging and production methods and not the contents of products that become wastewater. For instance, fruits, vegetables, and meat do not change in terms of nutritional values due to the application of CE principles in their production systems;
2. All the carbon in the wastewater was assumed to be biogenic. Therefore, direct CO_2 emissions in the wastewater treatment sub-system (B) are not accounted for by the global warming indicator.

Table 2
Allocation factors by approach and sub-system.

Approach/Sub-system	Wastewater treatment	Kaumera production
Economic allocation	87.3 %	12.7 %
Mass allocation	99.97 %	0.03 %
Zero-burden [a]	–	100 %
Zero-burden & Mass allocation [a]	–	100 %
System expansion	100 %	

[a] the two sub-systems are separated.

Table 3
Life cycle inventory values (on wet basis excluding electricity values) of the WWTP normalized by one year of operation, with percentage ranges considered in sensitivity analysis.

Input	Amount	Unit	Output	Amount	Unit
Wastewater treatment sub-system					
Wastewater	6123,498	m^3	Activated granular sludge	5205	ton
Sodium Hydroxide	54.4	ton	Clean water	6113,616	m^3
Sodium Hypochlorite	549.4 ± 10 %	ton	Biogenic CO_2	4766	ton
Sulfuric acid	3.43	ton	N_2O	2.17 ± 10 %	ton
Polyelectrolyte [a]	15.62	ton			
Electricity [a]	3874 ± 10 %	MWh			
Electricity [b]	2783	MWh			
Kaumera extraction reactor					
Activated granular sludge	5205	ton	Alkaline Sludge	5215	ton
Potassium hydroxide	10.51	ton			
Electricity	116	MWh			
Centrifuge (1)					
Alkaline Sludge	5215	ton	Centrifuged Alkaline Sludge	2608	ton
Electricity	100 ± 10 %	MWh	Alkaline Sludge Residue	2608	ton
Acidification tank					
Centrifuged Alkaline Sludge	2608	ton	Acidified sludge	2610	ton
Sulfuric acid	2.05	ton			
Electricity	10 ± 10 %	MWh			
Centrifuge (2)					
Centrifuged acidified sludge	2610	ton	Kaumera gel	1566	ton
Electricity	16 ± 10 %	MWh	Acidified sludge residue	1313	ton

[a] only used in the existing WWTP (i.e., reference system for system expansion approach).
[b] only for retrofitted WWTP due to lower dewatering needs for AGS.

4. Results and discussion

This study examines which multifunctionality handling approach best assesses the transition from linear to circular economy in wastewater treatment, focusing on recovering secondary materials. The case study involves a WWTP retrofitted to produce Kaumera from AGS. To confirm whether the existing WWTP sub-system with the Nereda®

technology delivers environmental performance comparable to conventional urban WWTPs, the GWP indicator was used because it is a key measure recommended for conventional WWTPs (Corominas et al., 2020). The GWP score for the retrofitted system is approx. 0.28 kg CO_2 equivalent per m^3 of wastewater input. This score is in the lower range of carbon footprints of conventional urban WWTP which range between 0.24 and 0.7 kg CO_2 equivalent per m^3 (Gowd et al., 2023; Pasciucco et al., 2023; Rashid and Liu, 2020). The use of Nereda® technology reduces carbon emissions and minimizes chemical usage (Nancharaiah and Sarvajith, 2019), suggesting that it contributes to the environmental benefits of retrofitting WWTPs. These findings also allow for the comparison of various multifunctionality handling approaches.

4.1. Assessment through the system expansion approach

Fig. 3 presents the normalized environmental impact results when the system expansion approach was applied to compare the entire retrofitted WWTP system with the current WWTP and sodium alginate production. The non-normalized environmental impact results of all ReCiPe2016 impact indicators are shown in Table S3. The wastewater treatment sub-system (B) is common in both systems, but no polyelectrolyte is used by the retrofitted WWTP (original system), and the latter dewaters, to a lesser extent, the produced AGS. Therefore, any difference between the two systems is mainly expected to originate from the Kaumera production and sodium alginate production processes, as well as lower electricity consumption in the dewatering process of AGS. Moreover, Fig. S1–2 show that the wastewater treatment sub-system (B) dominates (between 91 % and 94 % contribution). The system expansion approach is recommended by the ISO hierarchy if sub-division is not considered feasible. However, Kaumera production is based on the Nereda process, which has already been employed in the existing WWTP (Fig. 1). Therefore, sub-division of the retrofitted WWTP system into wastewater treatment and Kaumera production sub-systems is not feasible. The results of the system expansion may also provide a guide for evaluating the results of other multifunctionality handling approaches (Fig. 3).

Wastewater treatment and Kaumera production resulted in GWP benefits when compared with current WWTP and sodium alginate production. These benefits are approx. 40 % when compared to the reference system in the case of system expansion. The system expansion approach accounts for all inputs, outputs, and environmental releases in one year of operation. The input that dominated the GWP score was indirect emissions due to electricity generation which contributed approx. 57 % of the total score (see Fig. S1). Direct emissions of N_2O (for wastewater treatment) and indirect emissions from sodium hypochlorite consumption were the largest following contributors (34 % and 10 %, respectively). Furthermore, the wastewater treatment sub-system (B) consumes almost 10- times the amount of electricity of the Kaumera production sub-system (A), which contributes to approx. 6 % to the GWP score. Last, the chemicals used by the Kaumera production sub-system have a negligible contribution (approx. 0.3 %) to the GWP score.

Mineral resource scarcity concerns the extraction and consumption of minerals and metals. Wastewater treatment and Kaumera production resulted in MRSP benefits when compared with current WWTP and sodium alginate production. These benefits are approx. 22 % when compared to the reference system. The contribution analysis of MRSP is very similar to that of GWP, but contributing direct emissions do not occur for MRSP (see Fig. S3). The input that greatly dominates the MRSP score is electricity (for the wastewater treatment) which contributes approx. 58 % of the total score. Sodium hypochlorite, sodium hydroxide and electricity (for Kaumera) contributed approx. 31 %, 3 %, and 7 %, respectively. Last, the chemicals used by the Kaumera production sub-system (A) had small contribution to the MRSP score (approx. 1.2 %).

Fossil resource scarcity refers to the extraction and consumption of fossil fuel. Wastewater treatment and Kaumera production resulted in FRSP benefits when compared with current WWTP and sodium alginate production. These benefits are approx. 51 % when compared to the reference system in the case of system expansion. The contribution analysis of FRSP is very similar to that of GWP, but contributing direct emissions do not exist for FRSP (see Fig. S1). The input that dominates the FRSP score is electricity (for wastewater treatment), which contributes approx. 79 % of the total score, with sodium hypochlorite being the second-largest contributor of approx. 11 %. Sodium hydroxide and electricity (for Kaumera production) contributed approx. 1 % and 9 %, respectively. Last, the chemicals used by the Kaumera production sub-system made a negligible contribution (<0.5 %) to the FRSP score.

4.2. Assessment through the economic allocation, zero-burden, and mass allocation approaches

Fig. 4 presents the normalized environmental impact results for economic allocation, zero-burden, and mass allocation approaches, comparing the Kaumera production sub-system (A) with sodium alginate production. The non-normalized environmental impact results of all ReCiPe2016 impact indicators are shown in Table S4. Figs S3-S5 shows that the wastewater treatment sub-system (B) has a significant impact, accounting for 91 % to 94 % of the results, depending on the environmental impact category.

The production of Kaumera yields GWP benefits compared to sodium alginate across all applied multifunctionality handling approaches, ranging from approximately 74 % to 99.9 %. Allocation-based approaches distribute the GWP between both sub-systems, and mass allocation provides the most significant benefits, because it distributed 0.03 % of the total impact to Kaumera production, followed by economic allocation at Kaumera prices of 2.5 €. Combining the zero-burden with mass allocation results in approx. 90 % GWP benefits.

Among the allocation approaches, economic allocation only attributes a notable portion of the wastewater treatment sub-system to the

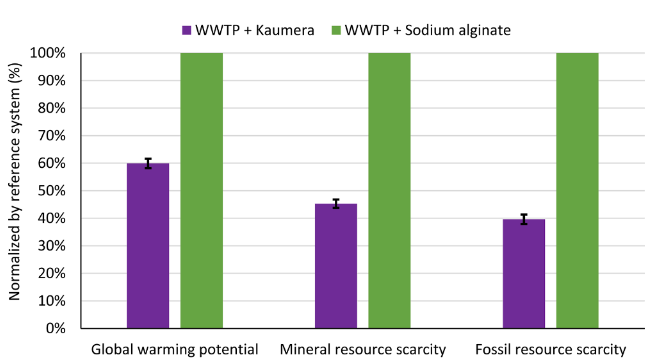

Fig. 3. Global warming, Mineral resource scarcity, and Fossil resource scarcity results with system expansion, FU = 1 year of operation.

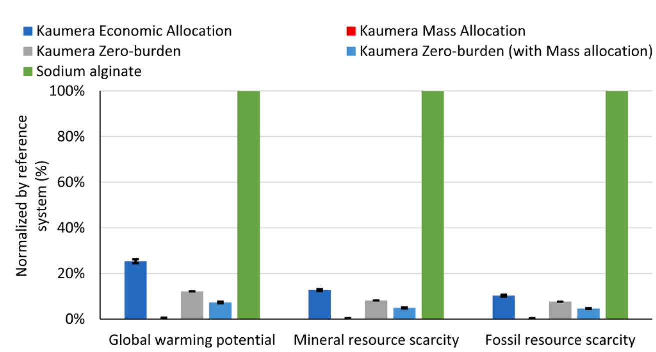

Fig. 4. Global warming, Mineral resource scarcity, and Fossil resource scarcity results with multifunctionality handling approaches, FU = 1 kg of product.

Kaumera product (see Fig. S3). When using economic allocation with Kaumera, the ratio between the GWP from Kaumera production and GWP from wastewater treatment was 6.4 %. The primary source of GWP in the wastewater treatment sub-system is electricity consumption, followed by direct N_2O emissions and sodium hypochlorite dosing.

In addition, electricity was the main contributor to the GWP of the Kaumera production sub-system (A), and the contributions of sulfuric acid and potassium hydroxide were negligible. However, mass allocation results in the lowest allocation factor for the Kaumera production sub-system (A) (approx. 0.03 %), resulting in the allocation of almost the entire GWP score to the wastewater treatment sub-system. The zero-burden approach by default excludes the wastewater treatment sub-system (B), thus, the electricity consumption of the Kaumera production sub-system (A) mainly contributes to the GWP results. Last, the zero-burden approach in combination with mass allocation, further allocates a part of the GWP score of the Kaumera production sub-system to the acidified sludge residue. This combination also results in electricity consumption being the main contributor, as in the case of solely applying the zero-burden approach. The latter shows that if one focuses exclusively on the Kaumera production sub-system (A), electricity consumption by the Kaumera sub-system processes is a hotspot for GWP. However, if an allocation approach is followed, then the allocation factors shift the attention also to other inputs to the system, such as direct emissions from sodium hypochlorite and electricity (consumption by the wastewater treatment processes), because the wastewater treatment sub-system (B) is more intensive in terms of chemical dosing and energy consumption than the Kaumera production sub-system (A), and greater revenues are generated by wastewater treatment than selling Kaumera.

Mineral resource scarcity potential (MRSP) concerns the extraction and consumption of minerals and metals. Kaumera production results in MRSP benefits when compared with sodium alginate production, for all multifunctionality handling approaches applied (Fig. 3). Similar to the GWP results, all multifunctionality handling approaches resulted in mineral resource scarcity benefits ranging between approx. 87 % and 99.97 %. In addition, as in the case of the GWP, the results are more beneficial when mass allocation is applied, followed by the zero-burden approach with mass allocation, zero-burden approach, and economic allocation for the Kaumera biorefinery.

Although electricity is a major contributor to GWP, its generation does not employ large amounts of minerals and metals when compared to chemical production. Nevertheless, electricity consumption by the wastewater treatment subsystem (B) dominates the MRSP results when allocation was applied (approx. 58 %–82 %, Fig. S4), followed by sodium hypochlorite and sodium hydroxide. With all applied approaches, the MRSP results due to the Kaumera production processes were approx. 8 % of the MRSP results. The zero-burden with or without mass allocation showed that the main contributor to the MRSP results is electricity consumption (of Kaumera production sub-system), as in the GWP results.

The fossil resource scarcity concerns the extraction and consumption of fossil fuels. Kaumera production resulted in FRSP benefits when compared with sodium alginate for all multifunctionality handling approaches applied here (Fig. 3). Moreover, regarding the FRSP, all multifunctionality handling approaches follow the same pattern as MRSP. The FRSP results indicate benefits between approx. 90 % and 99.98 % in comparison to the reference case. These benefits are greater when mass allocation is applied, followed by results based on the zero-burden approach with mass allocation, zero-burden approach, and the economic allocation.

Fossil fuels are generally used to generate electricity and produce chemicals. Therefore, electricity is expected to contribute significantly to the FRSP results, as in the case of the GWP. This was found with economic and mass allocation approaches where electricity consumed by the wastewater treatment and Kaumera production sub-systems contributed largely to the FRSP results. Sodium hypochlorite and sodium hydroxide contributed to a smaller extent to the FRSP results (see Fig. S5), approx. 11 % and 1 %. These contributions are very similar to those in the case of GWP, but without the direct emissions of the wastewater treatment sub-system (B).

The Kaumera sub-system (A) consumes approx. 11 % of the total electricity consumption of the original system (Fig. 1). This was expected because the wastewater treatment sub-system is larger in terms of treating capacity than the Kaumera sub-system. Therefore, normalizing electricity and chemical requirements by output results in 1 kWh/kg Kaumera and 0.01 kg/kg Kaumera, respectively, for the Kaumera sub-system (A), and 0.455 kWh/m^3 clean water and 0.01 kg/m^3 clean water, respectively, for the wastewater treatment sub-system (B). These performance indicators show how much more efficient the wastewater treatment sub-system (B) is than the Kaumera treatment sub-system (A) due to scale and the fact that its technologies are robust and optimized for wastewater treatment.

4.3. Comparison with other studies

The current study's results differ from others because they revealed burdens for two impact categories, GWP and FRSP due to different methodological approaches. Tian et al. (2020) analyzed an existing WWTP and its retrofitted versions, focusing on various co-products, but without applying any multifunctionality handling approach. Their choice can lead to a less comprehensive assessment. Morsy et al. (2020) compared an existing WWTP with its expansion, which aimed to produce higher-quality effluent and sludge for agricultural use without considering multifunctionality handling. A deterioration in total environmental performance is expected when a monofunctional system is modified to provide several functions, due to the additional chemical and energy requirements of the additional functions. On the other hand, LCA studies that applied system expansion (Lam et al., 2022; van Zelm et al., 2020) or substitution (Estévez et al., 2022; Gowd et al., 2023; Malila et al., 2019) did not explain their decision for their followed approach nor reference the ISO hierarchy. Studies in Table 1 that compared WWTPs with nutrient recovery to conventional WWTPs demonstrated global warming benefits (Estévez et al., 2022; Lehtoranta et al., 2022; Mayor et al., 2023), similar to this study's outcomes. However, two studies reported both environmental benefits and burdens due to varying energy consumption and recovered nutrients. For instance, Gowd et al. (2023) indicated that a microbial fuel cell for wastewater treatment and nutrient recovery was more efficient than other traditional methods, due to lower energy consumption and higher nutrient recovery. Moreover, Lam et al. (2022) reported environmental burdens when the recovered nutrient was struvite, but environmental benefits when it was single superphosphate due to its agricultural application focus. These variations suggest that process optimization is crucial, and the recovered product can significantly influence expected environmental benefits. It highlights the importance of a comprehensive approach to assessing environmental impacts in WWTP retrofits.

5. Limitations and recommendations

One limitation is the exclusion from the system boundaries all life cycle stages upstream of wastewater production, such as cradle-to-WWTP gate food production systems and cosmetics production systems. Sfez et al. (2019) considered food and cosmetics production systems, and concluded that allocating their impact to wastewater treatment systems, while also allocating part of the impact of wastewater treatment systems to the food and cosmetics production systems results in the "fairest" approach. These authors also mentioned that this is a data intensive approach which may be interesting for policy makers. In this case, the reference system should also include the same food and cosmetics production systems both qualitatively and quantitatively. However, we argue that upstream production systems could be excluded because they have a completely different purpose (production and consumption of food and cosmetics) to secondary resource recovery. Last, the use of secondary resources from wastewater to food and cosmetics production systems is prohibited; thus, recovered nutrients cannot replace pristine nutrients, as in the case of metal recycling.

Another limitation is the decision that the system boundaries end at the WWTP exit (gate) and disregard the construction of infrastructure or equipment manufacturing. A full LCA of Kaumera should include the use stage, capital goods production, and end-of-life processes. Kaumera is a bio-based material with no expected adverse effects during use stage (Heijdens, 2021). However, if Kaumera is further treated to convert it to provide another function, such as becoming a fire-retardant, then the additional processes should be considered by the LCA. In addition, end-of-life impacts are insignificant over the operating lifetime of wastewater treatment infrastructure (Corominas et al., 2020), and construction affects to a small extent global warming, but the effect of equipment manufacturing can be higher regarding mineral resource scarcity due to metals (Morera et al., 2020). Last, a recent review (Byrne et al., 2017) stated that the construction phase should be considered when decisions for construction materials are important, and infrastructure having negligible operation and maintenance requirements.

These limitations suggest that a more comprehensive approach to system boundaries and upstream consideration might be required for LCAs in WWTP contexts. This would help avoid misleading conclusions and better represent the environmental impacts of a circular economy framework in wastewater treatment.

To address the limitations of the ISO hierarchy in LCA, future research should focus on expanding system boundaries to include upstream processes, such as food and cosmetics production. Studies should also consider infrastructure and equipment manufacturing, as well as end-of-life processes, to create a complete LCA for products derived from wastewater treatment systems. By ensuring comprehensive assessments and maintaining consistency in reference systems, researchers can achieve more accurate and holistic evaluations of environmental impacts in wastewater treatment contexts. Such a comprehensive approach could lead to better representation and understanding of environmental effects in a circular economy.

6. Conclusions

WWTPs are critical for a sustainable environment and circular economy. This study explored which approach for handling multifunctionality best assesses the transition from a linear to a circular economy in LCA studies of wastewater treatment, where secondary materials are recovered. Additionally, the validity of the ISO hierarchy for handling multifunctionality in these contexts was examined.

The results indicate that Kaumera production offers environmental benefits in GWP, MRSP, and FRSP, largely due to reduced energy and chemical consumption compared to sodium alginate production. However, further treatment of Kaumera could lead to a decline in these benefits if it is transformed into a product with a different function, requiring a new reference product. Given that the Nereda process is a prerequisite for Kaumera production, makes the sub-division approach impossible. Therefore, the system expansion approach is recommended for handling multifunctionality, as it provides a more holistic view by considering the entire operation of both the wastewater treatment and Kaumera production sub-systems. This approach, although more data-intensive, results in a more holistic representation of environmental impacts. The economic allocation approach results in environmental scores closer to system expansion, and depending on the price of Kaumera, its impact may rise. The price of 2.5 € per kg of Kaumera was communicated from the Kaumera producer, but it may change in the future. Other methods, such as mass allocation, show nearly 100 % benefits when Kaumera is compared to sodium alginate, which could result in misleading conclusions due to the large volume difference between wastewater and recovered materials.

In summary, for retrofitting WWTPs to support a circular economy, we found that system expansion is the most suitable approach, followed by economic allocation. Other approaches recommended by ISO, such as mass allocation, can lead to arbitrary decisions on allocating environmental burdens. The ISO hierarchy's final step should prioritize economic allocation over mass allocation, as the latter can distort environmental impact assessments.

CRediT authorship contribution statement

Georgios Archimidis Tsalidis: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Daniel Dias:** Writing – review & editing, Data curation. **Antonio Martins:** Writing – review & editing, Resources. **Vasileia Vasilaki:** Writing – review & editing. **João Miguel Ribeiro:** Writing – review & editing. **Evina Katsou:** Writing – review & editing, Supervision, Funding acquisition.

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. Only Antonio Martins is an employee at the wastewater treatment plant of the case study but he is not developing the Kaumera product.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108146.

Data availability

Data will be made available on request.

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