



## Research article

## Environmental synergies in decentralized wastewater treatment at a hotel resort

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## ABSTRACT

Climate change and water scarcity are clearly related environmental problems, making them global environmental issues. Accordingly, the water cycle management deserves a revision in its approach, integrating the concept of circular economy within an efficient and sustainable management of water resources and the design of wastewater facilities. In this sense, newly engineered decentralized facilities have emerged as a viable option for the treatment of segregated wastewater flows. The design has not only integrated the wastewater treatment function, but also resource recovery, such as water reclamation for agricultural and irrigation activities, fertigation, fertilization and energy sustainability. Based on these premises, the concept of decentralized wastewater management deserves the same degree of attention and development that has so far been reserved for conventional centralized management systems. Therefore, this paper proposes a progressive substitution of the business-as-usual scenario or centralized system by applying a small-scale wastewater management scheme performing a more efficient resource and water recovery in a medium-sized 4–5-star resort hotel. The spotlight was a membrane technology for the anaerobic digestion of the blackwater instead of the greywater treatment. A favorable environmental profile was found for the decentralized scenario under two circumstances: a large system boundary including the beneficial environmental impacts of the products and, based on the results obtained from a sensitivity analysis, an energy demand for the operation of the AnMBR lower than  $2 \text{ kWh}\cdot\text{m}^{-3}$ . The global warming potential results (around 9%) were even for such high demand and much larger benefits were obtained for other impact categories (94% for SOD and 98% for LU). Nevertheless, the operation (gate-to-gate approach) of these on-site recovery facilities is far from being optimized and further research should follow to decrease the 39.8% difference in the global warming potential between decentralized and centralized systems.

## 1. Introduction

The tourism industry is one of the key sectors of the Spanish economy, with a relevance of 12.4% of the Gross Domestic Product (GDP) in 2019 and a total number of hotel establishments of 14600 in 2020 (INE, 2021). In an environmental context determined by climate change and water stress, water is an essential resource in many tourism activities (Forero-Ortiz et al., 2020).

Factors such as the scale and degree of complexity of treatment facilities, the climate of the area, the water management and water saving strategies and the nature of services provided govern the highly variable water demand per tourist (Chen et al., 2013). In particular, the hospitality industry uses large amounts of freshwater to clean towels and linen and some of them offer leisure facilities such as swimming pools, spas and golf courses, in addition to its use in the irrigation of

landscaped areas and cleaning facilities. Tirado et al. (2019) have estimated a water consumption of  $208\text{--}594 \text{ L}\cdot\text{guest}^{-1}\cdot\text{night}^{-1}$ , for one-to five-star hotels in Mallorca, respectively, values that are in line with other references (Becken, 2014; Ridoutt et al., 2018). This high-water consumption far exceeded the average of  $144 \text{ L}\cdot\text{person}^{-1}\cdot\text{day}^{-1}$  estimated for domestic activities (Gutierrez-Escolar et al., 2014).

Water consumption can be minimized with technological advances in water saving. These include lower-flow taps, more efficient irrigation systems and low-flush toilets, among others. There are also other more advanced technological solutions, the most widespread would be based on water pressure regulation systems, water leak detection and the use of rainwater for irrigation (Tirado et al., 2019; Popely and Moreno-Melgarejo, 2020). Social awareness and education for water conservation are leading measures at the societal level, but with long-term effects, as all voluntary changes in user behavior are not

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immediate.

Wastewater generated in touristic resorts must be treated before being discharged into the environment. However, the effluent quality may exceed the legislative limits when the influent flow exceeds the design capacity of the wastewater treatment facility. This situation is very typical in tourist areas where there is seasonal population growth (Borboudaki et al., 2005). In coastal urban areas, the overflow is directly discharge into the seawater instead of being treated the contamination not only affect to the environment but also to the public health (affecting bathing areas) and the image of the city (Martínez-Gomariz et al., 2021; Al Aukidy and Verlicchi, 2017; Gabarda-Mallorquí et al., 2016).

A qualitative and quantitative leap forward in water management corresponds to the recovery of water after treatment. Depending on the use of reclaimed water, special attention must be paid to water quality to avoid risks to the environment and human health and to comply with current legislation on the reuse of reclaimed water. Stream segregation in greywater and blackwater can provide differentiated treatment options to enhance process efficiency (Murat Hocaoglu et al., 2010; Paulo et al., 2013). In addition, greywater contamination by faecal pathogens is avoided and blackwater streams are highly concentrated in organic load allowing for nutrient and energy recovery (Belser-Baykal, 2019).

In this context, newly designed small-scale wastewater treatment facilities, also called decentralized systems, can be implemented in highly touristic developments to support existing centralized plants, but also to comply wastewater sustainability criteria: water recovery, energy self-sufficiency and recovery of nutrients (such as phosphorus, nitrogen and potassium) for the production of bio-based fertilizers. While decentralized greywater treatment and water reuse in hotels is not a new concept, on-site blackwater treatment and resource recovery is an underexploited topic in a hotel residential context (Atanasova et al., 2017; Chai et al., 2012; Gual et al., 2008; March et al., 2004), being aborced so far by one publication: Lansing et al. (2017) have proposed the implementation of an anaerobic digestion system followed by soil infiltration as decentralized sewage treatment in a hotel.

Therefore, this study has been built around a decision-making background to decide the most environmentally friendly wastewater treatment option for a resort. The benchmark of centralized-decentralized wastewater treatments proposed by other authors such as Santana et al. (2019) has been completed by incorporating the decentralization of wastewater (WW) through on-site treatment with membrane technology. Environmental impacts have been quantified and hotspots have been identified for a small-scale installation implemented in a medium-sized 4 and 5-star hotel. Special attention has been paid to nutrient recovery and energy consumption in blackwater treatment. Reclaimed water, nutrient recovery and energy supply have been addressed both separately and together with the application of various system boundaries according to the multifunctionality of the system. In addition, a discussion has been proposed regarding the applicability of fertilizers obtained from the BW treatment.

## 2. Research methodology

### 2.1. Goal and scope definition

The environmental profiles of centralized, decentralized and/or hybrid configurations of wastewater treatment implemented in a 4–5 stars hotel have been compared. The Life Cycle Assessment (LCA) described in ISO 14040/44:2006 was the methodology followed for such purpose. The paradigm shift in the wastewater sector towards greater resource recovery has resulted in multifunctional wastewater treatment facilities that no longer only treat wastewater, but also recover nutrients, energy and reclaimed water (Larsen, 2018). Therefore, the analysis proposed in this paper advances the objectives of wastewater treatment in different configurations (see Section 2.2.2) for an attributional LCA modelling, whereby the impacts of input-output flows are estimated according to the functional unit (FU) of the system, i.e., the flow of

wastewater to be treated in units of  $\text{m}^3 \cdot \text{d}^{-1}$  (Ekvall et al., 2016). The multifunctionality has been addressed by four different system boundaries related to the wastewater treatment function only, the combination of wastewater treatment and resource recovery activities, the wastewater treatment function with water-saving measures and finally a boundary where all the previous functions of the system are well represented.

This environmental assessment was combined with a discussion related to legislative issues and expected problems (Section 3.1). The reclaimed water produced in the designed small-scale scheme (with and without water saving measures) was compared to European and Spanish legislative thresholds, which imposes the quality of the water for several applications.

### 2.2. Description of the hotel and wastewater treatment scenarios

#### 2.2.1. Hotel characteristics

The modelling of a scenario considering an average four- and five-star hotel has been proposed to comparatively evaluate the environmental loads of the different alternatives of grey and black wastewater treatment. According to data from the Spanish National Institute of Statistics (INE) and in relation to the type of accommodation and number of beds per hotel category, a total of 140 rooms has been estimated. Data from the Eurostat database (2021) have registered 1780 hotels with 100–249 rooms in 2019, which represents 9.04% of the total number of Spanish hotels. About 61.59% of hotels have less than 25 rooms and only 3.55% are large enough to offer 250 rooms. A number of 54 staff is required for an annual average of 182 guests per night. The average annual bed occupancy is 60.12%, with rooms for 1, 2 and 3 persons, so the maximum occupancy level is  $2.16 \text{ guests} \cdot \text{night}^{-1} \cdot \text{room}^{-1}$ .

The wastewater flow of the hotel has been estimated under the assumption that guests stay in the building throughout the day. Mass balances were performed for two water consumption patterns according to the implemented water saving measures in toilets:  $4.5 \text{ L} \cdot \text{flush}^{-1}$  as detailed in Directive 2016/611 and  $9 \text{ L} \cdot \text{flush}^{-1}$  (Gao et al., 2019). Table 1 shows the information of the water consumption of the toilet bowls and wastewater production rate for both patterns. Furthermore, the composition of black wastewater was estimated from data reported by Jönsson et al. (2005) and Larsen et al. (2013) and then verified with other literature references and raw data. For example, Tervahauta et al., (2013) and Rose et al., (2015) have provided the generation rate of different human excreta waste streams such as feces, urine and toilet paper per capita and day both as volume and weight. Accordingly, the average volume of feces should be in the range of  $0.053\text{--}0.265 \text{ L} \cdot \text{person}^{-1} \cdot \text{d}^{-1}$  being  $0.1 \text{ L} \cdot \text{person}^{-1} \cdot \text{d}^{-1}$  the most common figure and the volume of urines as  $0.8\text{--}2.45 \text{ L} \cdot \text{person}^{-1} \cdot \text{d}^{-1}$  with  $1.4 \text{ L} \cdot \text{person}^{-1} \cdot \text{d}^{-1}$  as average value.

The results obtained were also like those of an office building system with decentralized wastewater treatment in the context of the Run4Life project, where reclaimed water from greywater treatment has been used to refill toilets. The composition of the black water considered within the framework of the Run4Life project is the following:  $1200 \text{ mg} \cdot \text{L}^{-1}$  TSS,  $1300 \text{ mg} \cdot \text{L}^{-1}$  COD,  $170 \text{ mg} \cdot \text{L}^{-1}$  TN and  $17 \text{ mg} \cdot \text{L}^{-1}$  TP for  $3\text{--}4.5 \text{ L} \cdot \text{flush}^{-1}$  toilets and was similar to that considered for the analysis (Table 1).

Hand basin, bath/shower and laundry are the sources of grey water in the hotel. Relevant information related to amount of laundry per room, flowrates and usage of shower and tap water and room cleaning times was taken from Styles et al. (2015), which led to grey water production of  $12.35 \text{ m}^3 \cdot \text{d}^{-1}$  and  $31.89 \text{ m}^3 \cdot \text{d}^{-1}$  for the scenarios with and without water saving measures.

The composition of grey wastewater was estimated from data provided by Noutsopoulos et al. (2018) based on the characterization of different household greywater sources (bath shower, sink, kitchen, laundry and dishwasher). In addition to the wastewater production rates and composition, Table 1 also includes other information on the

**Table 1**  
Characterization of the hotel wastewaters.

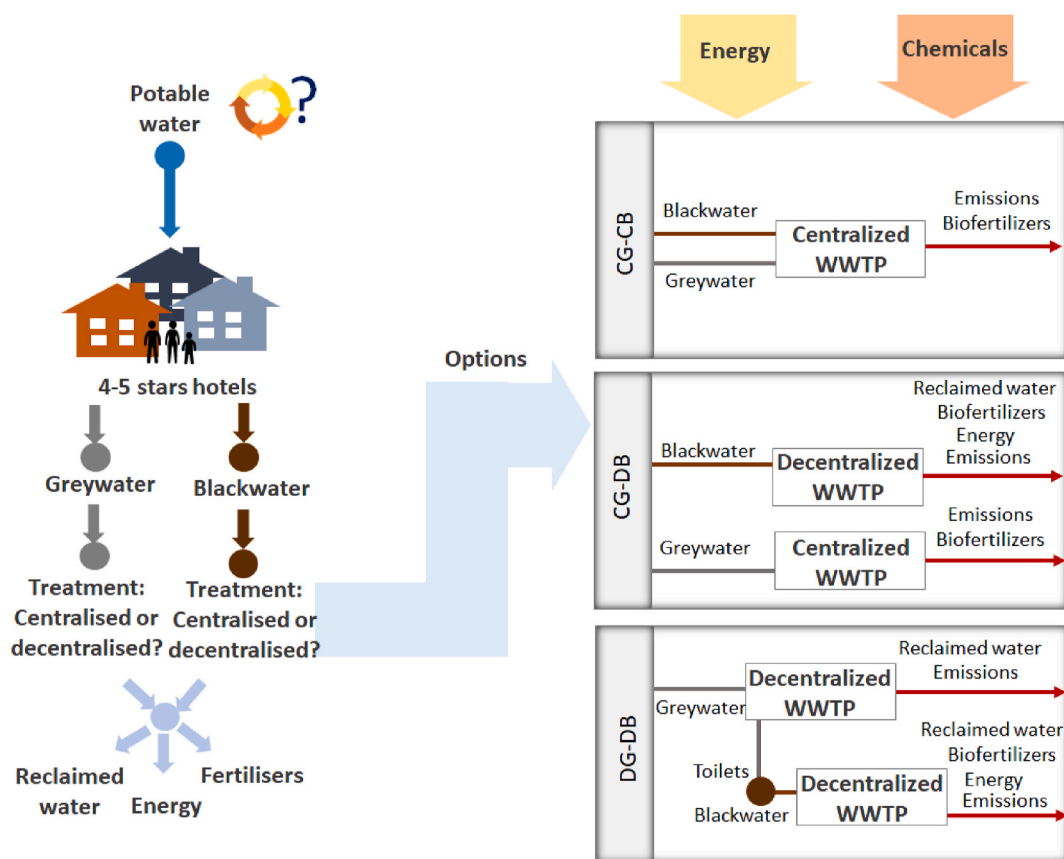
Physical Characteristics/Sources	GW				BW				BW with GW reclamation in toilets	
	Bath/shower	Hand basin	Laundry	Mixture	Feces	Urine	Toilet paper	Mixture	Reclaimed GW	Mixture
<b>With water saving measures</b>										
<b>Flow</b>										
Water consumption (m <sup>3</sup> .d <sup>-1</sup> )	7.64	2.74	1.96	12.35	–	–	–	8.06	8.06	8.06
Production rate (L.d <sup>-1</sup> )	7644	2744	1960	12348	25.87	330.40	0.236	8420.50	–	8420.50
<b>Composition</b>										
TSS (mg.L <sup>-1</sup> )	80.27	86.01	1131.84	248.46	209854.01	8571.43	6.80.10 <sup>6</sup>	1171.52	20.03	1190.70
COD (mg.L <sup>-1</sup> )	432.23	421.43	4214.29	1030.16	282846.72	9285.71	8.80.10 <sup>6</sup>	1479.82	51.90	1529.52
TN (mg.L <sup>-1</sup> )	2.84	2.32	14.81	4.63	13686.13	6571.43	0.00	299.89	0.37	300.24
TP (mg.L <sup>-1</sup> )	0.10	1.38	2.65	0.79	3649.64	642.86	0.00	36.43	0.25	36.67
<b>Without water saving measures</b>										
<b>Flow</b>										
Water consumption (m <sup>3</sup> .d <sup>-1</sup> )	16.38	9.91	5.60	31.89	–	–	–	17.39	17.39	17.39
Production rate (L.d <sup>-1</sup> )	16380	9912	5600	31892	25.87	330.40	0.236	17744.50	–	17744.50
<b>Composition</b>										
TSS (mg.L <sup>-1</sup> )	37.46	23.81	396.14	96.20	209854.01	8571.43	6.80.10 <sup>6</sup>	555.94	7.75	563.53
COD (mg.L <sup>-1</sup> )	201.71	116.67	1475.00	398.86	282846.72	9285.71	8.80.10 <sup>6</sup>	702.23	20.09	721.92
TN (mg.L <sup>-1</sup> )	1.33	0.64	5.18	1.79	13686.13	6571.43	0.00	142.31	0.14	142.45
TP (mg.L <sup>-1</sup> )	0.05	0.38	0.93	0.31	3649.64	642.86	0.00	17.29	0.10	17.38

characteristics of the segregated streams of the hotel such as the composition of the black water from the toilets filled with reclaimed water.

2.2.2. Description of the treatment scenarios and system boundaries

Centralized, hybrid and decentralized wastewater treatment scenarios have been considered in the framework of different system boundaries according to the selected wastewater treatment schemes (Fig. 1).

2.2.2.1. Focus on wastewater treatment. Wastewater produced in hotels is generally pumped to centralized wastewater treatment facilities to reduce pollution caused by effluent discharge and to comply with legislation. However, decentralized facilities are also suitable for hotels for on-site resource recovery purposes, when centralized facilities are at the limit of their capacity, avoiding the connection to a large sewer network infrastructure. The benchmarking between these two wastewater management options has been established for a gate-to-gate perspective. The centralized facility corresponds to a small-medium



**Fig. 1.** Scheme for the definition of the system boundaries and treatment configurations. CG-CB: Centralization of grey water & centralization of black water; DG-DB: Decentralization of grey water & decentralization of black water; CG-DB: Centralization of grey water & decentralization of black water.

scale facility of about 13500 persons equivalent and 6360 m<sup>3</sup>·d<sup>-1</sup> maximum design flow. The treatment is characterized by a pre-treatment step with sand clarification, grease removal, screening and filtration. Secondary treatment includes a biological reactor with addition of iron chloride and settling. The tertiary treatment is based on ultraviolet (UV) irradiation. Sludge treatment comprises thickening, dewatering and storage and the sludge is finally transported for composting (Lorenzo Toja, 2017). The environmental impact of energy consumption from the operation of pumps, instruments and lighting was also taken into account. In summary, all black and grey water produced from the hotel was pumped to the centralized configuration for the treatment of both streams (CG-CB).

The CG-CB treatment option has been compared to the decentralized treatment for greywater and blackwater (DG-DB) when implementing water use reduction measures in the hotel. The greywater treatment in this configuration consists of an aerobic membrane bioreactor (AMBR) equipped with a denitrification unit, an aeration blower, a membrane blower and pumps for sludge recirculation and discharge. The reclaimed water is disinfected with 2 mg·L<sup>-1</sup> free chlorine provided by the addition of sodium hypochlorite during storage (Atanasova et al., 2017). The anaerobic membrane bioreactor (AnMBR) is the main equipment of the decentralized blackwater treatment. The AnMBR technology is a promising technology for wastewater treatment as the low load is compensated by the low hydraulic retention time (HRT) at which it is possible to operate the anaerobic reactor, being able to reach high solid retention times (SRT) that allow the anaerobic removal of organic matter even at low temperatures (Abdelrahman et al., 2021). Given the high quality of the effluent obtained with AnMBR technology (almost free of suspended solids and pathogens), its direct use in the field to supply nutrients recovered from the water (N and P) to crops would be feasible (Harb and Hong, 2017). Accordingly, the solid digestate from the AnMBR can be used as organic biofertilizer for green areas and the effluent, after disinfection with UV-LED, as liquid biofertilizer. The biogas produced is fed to a cogeneration unit for electricity and heat. Fig. 2 illustrates the configuration described above.

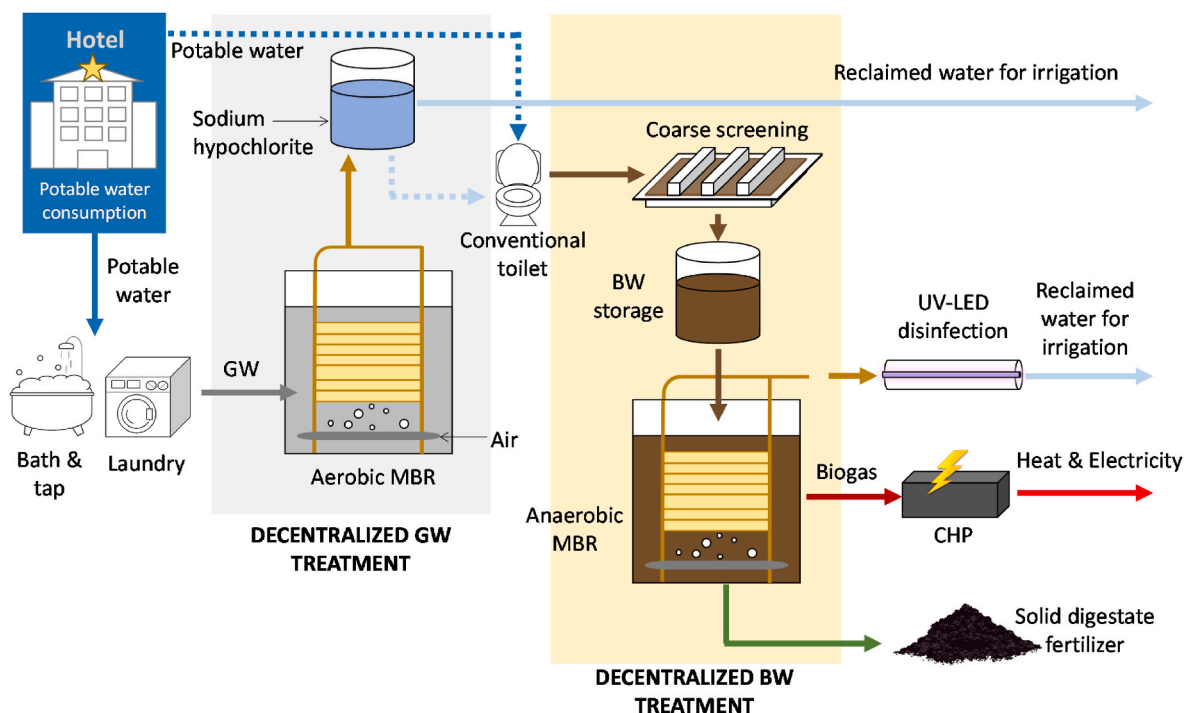


Fig. 2. Decentralized grey water and black water (DG-DB) treatment scheme. BW: Blackwater; CHP: Combined Heat and Power; GW: Greywater; MBR: Membrane Bioreactor; UV-LED: Ultraviolet Light Emitting Diode.

2.2.2.2. *Coupling wastewater treatment and resource recovery.* The previous approach only analyses the environmental profile (individual and comparative) of wastewater treatment. However, the impacts are only related to the wastewater treatment technologies and not to the products generated. Therefore, the assessment of the environmental profiles including the production of bioenergy and biofertilizer can only be performed opening the scope and widening the system through a system expansion (Moretti et al., 2020). However, different amounts of marketable/useful products were obtained from the CG-CB and DG-DB treatment options. The mass and energy quantities of final products between the centralized and decentralized scenarios must be balanced to make a meaningful and fair comparison. For this purpose and based on the lower production rates of the centralized option, the counterpart production processes of three flows (mineral fertilizers, electricity and thermal energy) have been included. In this way it is possible to balance the quantities of the final products between the centralized and decentralized scenarios. The equivalent mineral fertilizer production in the CG-CB system was estimated with average substitution ratio for biofertilizers (around 60% for nitrogen and 60% for phosphorus) for the excess of products based on the information provided by Ashekuzzaman et al. (2021), De Notaris et al. (2018) and Hijbeek et al. (2018).

2.2.2.3. *Wastewater treatment with a focus on reclaimed water.* This approach builds on the premise of the wastewater treatment but with an extension of the system to cradle-to-gate processes. Considering that the centralized-decentralized approach has already been addressed previously for conventional toilets, the centralized scenario has not been included in this section which addresses how toilet design can affect environmental performance. In this section, the emphasis has been put on comparing the environmental effects of some water reduction measures filling toilets with reclaimed greywater and reuse of greywater for irrigation purposes.

2.2.2.4. *Going for the big picture: Integrating water and resource recovery with wastewater treatment.* The last rearrangement of the system boundaries incorporates altogether the environmental benefits

associated with the outcomes of the previous alternatives. CG-CB and DG-DB scenarios are compared, then, with a cradle-to-gate boundaries where the impacts from the products are also relevant. In addition, a new hybrid wastewater management system called CG-DB (centralized greywater treatment-decentralized blackwater treatment) was also assessed and compared to the other treatment options. CG-DB treats segregated wastewater streams but only the greywater is pumped to a centralized facility, as usually done, while the blackwater is treated in-situ. Although the composition of the greywater differs from the typical mixed domestic wastewater treated in centralized plants, the environmental impacts were assumed to be proportional to the treatment of an equivalent flow of mixed wastewater. The flowrate of the hotel blackwater is small enough to result in a transition state from centralization to decentralization of 0.70%. This a transition state is below 8%, and thus the centralized facility does not require the implementation of structural changes to cope with unfavorable carbon/nitrogen ratios and hydraulic constraints. A total of 12 hotels in the area with similar characteristics would cause changes in the design of the centralized facility for a hybrid treatment option. [Morandi et al. \(2017\)](#) and [Morandi and Steinmetz \(2019\)](#) have demonstrated the benefits and drawbacks of the transition from centralized to decentralized schemes. Future LCA studies should incorporate the environmental impacts of the newest centralized treatment options for higher transition states and its possible energetic benefits. Nevertheless, the above-mentioned assumption was considered admissible in this manuscript for the quantification of impacts of the hybrid wastewater treatment.

### 2.3. Life cycle inventory analysis

The Life Cycle Inventory (LCI) analysis involves the collection of data to quantify the input and output flows for the different sub-systems within the framework of the system boundaries. Data collection will consider data from actual data, estimated data from mass balances and equipment design and operation as well as background data in the case of generic processes associated with energy production, chemicals, transport, etc. available in the Ecoinvent v3.0.0.1 database. [Table 2](#) shows the summary of the inputs and outputs of the life cycle inventory for the different treatment options (considering the four scenarios in [Section 2.2.2](#)).

The LCI of decentralized wastewater treatment options is mainly based on mass and energy balances considering the information provided in [Table 1](#). The quality of the effluents after treatment is optimal when using the AMBR and AnMBR systems. Blackwater sludge has a significantly lower amount of heavy metals compared to manure and other mineral fertilizers; however, little information has been found on the reuse of greywater sludge in agriculture ([Tervahauta et al., 2014](#); [Melesse et al., 2018](#)). Greywater sludge was assumed to be a waste according to the recommendations of [Eriksson and Donner \(2009\)](#) and [Eriksson et al. \(2010\)](#) while the nutrient content of sewage sludge allows its valorisation as a solid biofertilizer to be considered. Greywater waste was estimated at  $7.50 \text{ L}\cdot\text{m}^{-3}$  of influent to the AMBR ([Atanasova et al., 2017](#)) while biofertilizer is 1.21% of the blackwater input flow to the AnMBR ([Cashman et al., 2018](#)). The expected removal efficiencies in both MBR are summarized in [Table 3](#).

The AnMBR produces biogas with a methanization ratio of 75% and a major composition of methane (80%),  $\text{CO}_2$  (19.9%) and other trace components such as  $\text{H}_2\text{S}$  ([Hu et al., 2020](#)). The biogas is used to generate electricity and heat in a Combined Heat and Power (CHP) system with an efficiency of 42.5% for heat and 37.5% for electricity ([Omer, 2017](#)).

Direct and indirect emissions are related to the aerobic and anaerobic MBR and the CHP unit. [Tsushima et al. \(2014\)](#) and [Mannina et al. \(2018\)](#) has estimated the  $\text{N}_2\text{O}$  emissions from the AMBR. Apart from these emissions, the AMBR also releases  $\text{CO}_2$  and  $\text{N}_2$  to the atmosphere. Carbon dioxide is formed from the oxidation of the organic compounds which can be removed from the influent with aeration or by retention in the membrane. Therefore, the organic load of the influent is removed in

**Table 2**

Life cycle inventory per functional unit ( $\text{m}^3\cdot\text{d}^{-1}$  of GW & BW) (fourth approach).

	CG-CB	CG-DB	DG-DB
<b>Inputs from Technosphere</b>			
<b>Materials</b>			
Potable water (L) - Consumption in hotel	982.83	982.83	594.55
NaClO (5%) (g) - Storage	–	–	0.39
NaClO (5%) (g) - cleaning	–	1.46	1.46
Polyelectrolyte (g)	0.34	0.20	–
$\text{FeCl}_3$ (40%) (g)	10.10	6.00	–
Diesel for composting (L)	$1.36\cdot 10^{-4}$	$8.09\cdot 10^{-5}$	–
Transport of residues (kg·km)	$6.38\cdot 10^{-2}$	$3.79\cdot 10^{-2}$	–
Landfill (kg)	2.55	1.52	–
Transport of sludge to composting (kg·km)	8.17	4.86	–
Transport of polyelectrolyte (kg·km)	$2.24\cdot 10^{-4}$	$1.33\cdot 10^{-4}$	–
Transport of $\text{FeCl}_3$ (40%) (kg·km)	$1.01\cdot 10^{-2}$	$6.00\cdot 10^{-3}$	–
Nitrogen mineral fertiliser (g)	84.09	–	0.93
Phosphorus mineral fertiliser (g)	18.68	–	2.59
Irrigation water ( $\text{m}^3$ )	0.996	0.59	–
<b>Energy</b>			
Electricity (kWh) - Tap water pumping	0.20	0.12	0.12
Electricity (kWh) - Wastewater pumping	0.44	0.26	–
Electricity (kWh) - Decentralized GW treatment	–	–	0.80
Electricity (kWh) - Decentralized BW treatment	–	–	0.80
Electricity (kWh) - Pre-treatment centralised facility	$9.45\cdot 10^{-2}$	$5.62\cdot 10^{-2}$	–
Electricity (kWh) - Secondary treatment centralised facility	0.35	0.21	–
Electricity (kWh) - Tertiary treatment centralised facility	$2.83\cdot 10^{-2}$	$1.68\cdot 10^{-2}$	–
Electricity (kWh) - Sludge treatment centralised facility	$3.44\cdot 10^{-2}$	$2.05\cdot 10^{-2}$	–
Electricity (kWh) - other activities in centralised facility	$2.09\cdot 10^{-2}$	$1.24\cdot 10^{-2}$	–
Electricity (kWh) - composting in centralised facility	$6.58\cdot 10^{-3}$	$3.90\cdot 10^{-3}$	–
Electricity production (kWh)	0.59	–	–
Heat production (kWh)	0.67	–	–
<b>Outputs to the Technosphere</b>			
Sludge waste (L) - AMBR/Centralised facility	0.03	0.02	4.46
Treated water (L)	982.83	594.55	–
Reclaimed water (L)	–	388.28	594.55
Biofertilizer (g)- Nitrogen	3.00	84.73	84.73
Biofertilizer (g) - phosphate	7.26	20.44	20.44
Electricity (kWh)	0.00	0.59	0.59
Heat (kWh)	0.00	0.67	0.67
<b>Outputs to the Environment</b>			
<b>Emissions to air</b>			
$\text{CO}_2$ (kg)	0.25	0.47	1.02
$\text{N}_2\text{O}$ (mg)	224.80	133.66	27.50
S (mg)	–	268.86	268.86
$\text{CH}_4$ (g)	6.66	9.34	5.38
<b>Emissions to water</b>			
COD (g)	17.50	–	–
$\text{BOD}_5$ (g)	5.33	–	–
TN (g)	2.42	–	–
TP (g)	1.00	–	–

**Table 3**

Aerobic and anaerobic MBR removal efficiencies (%).

Reactor Type	Parameter	Value	Source
Aerobic membrane bioreactor (AMBR)	COD	95	<a href="#">Atanasova et al. (2017)</a>
	TSS	92	<a href="#">Fountoulakis et al. (2016)</a>
	TN	92	<a href="#">Atasoul et al. (2007)</a>
	TP	69	<a href="#">Fountoulakis et al. (2016)</a>
Anaerobic membrane bioreactor (AnMBR)	COD	93.5	Run4Life project
	TSS	99.2	<a href="#">Musa et al. (2018)</a>
	TN	12	Run4Life project
	TP	20	Run4Life project

the AMBR with a high overall throughput: 95% of COD (12% is related to the membrane filtration) (Atanasova et al., 2017; Fu et al., 2008). CO<sub>2</sub> emissions were calculated from the stoichiometry of oxidation reactions using theoretical COD conversion factors (Dionisi et al., 2018), as detailed in Eq. (1), where the organic matter is represented by C<sub>5</sub>H<sub>7</sub>O<sub>2</sub>N.



Nitrogen compounds can be removed by assimilation in biomass and end up in excess MBR sludge or by nitrification-denitrification. Although a N removal efficiency of 92% is expected, only 24.5% is assimilated by the sludge (Atasoy et al., 2007; Fu et al., 2009).

On the other hand, the estimation of the methane losses due to its absorbance in the liquid effluent can be estimated with the Law of Henry. Considering that the permeate is saturated in methane and its solubility in water at 20 °C, it is assumed that 5% of methane is released to air. There can be limitations due to a supersaturation of the methane leading to an increase of the methane concentration up to 6.9 times higher than the equilibrium conditions, but also new technologies (such as degassing membranes for methane recovery) have emerged trying to desorb CO<sub>2(g)</sub> and CH<sub>4(g)</sub> and to reduce the carbon emissions from the AnMBR effluents (Crone et al., 2016; Rongwong et al., 2017; Sanchis-Perucho et al., 2020). For modelling purposes, equilibrium conditions were assumed in this study and the emissions associated with the AnMBR are represented by a percentage of the biogas losses. Emissions in the CHP system were estimated according to the Fuel Analysis Method of the Environmental Protection Agency (EPA, 2016) based on the fuel carbon content of the biogas.

Regarding energy balances, information was taken from Banti et al. (2020) for energy consumption in greywater treatment, while a sensitivity analysis was performed based on literature data for blackwater treatment. Based on the information in Table 4, aerobic MBR systems operate for an energy consumption of 0.5–11.5 kWh·m<sup>-3</sup> and anaerobic MBR demands around 0.03–5.77 kWh·m<sup>-3</sup>.

The energy comparison between MBR reactors is not an easy task. The power requirement depends for each case on factors such as the degree of dilution of the wastewater, the scale, the type of reactor, the layout, the use and location of the membrane and the operational strategy (Krzeminski et al., 2012). In addition, the auxiliary equipment considered may be different (sludge collection in settling tanks, digester mixer, feeding pump, sludge recycle pump, permeate pump, blower and chemical cleaning facilities) (Yamashita et al., 2019). The optimization

of each of these parameters and the selection of the appropriate membrane technology is essential to reduce the environmental impact. Atasoy et al. (2007) have reported power requirements for aerobic submerged MBRs of 1.70 kWh·m<sup>-3</sup> and 2.30 kWh·m<sup>-3</sup> for grey and blackwater. An energy consumption of 3–7.3 kWh·m<sup>-3</sup> has been reported for side-stream MBR reactors (Seib et al., 2016). Santasmasas et al. (2013) presented values of 2 and 2.9 kWh·m<sup>-3</sup> for laboratory-scale reactors treating of approximately 1.2 and 3.4 m<sup>3</sup>·d<sup>-1</sup>. Values as high as 9.6 and 6.5–64.8 kWh·m<sup>-3</sup> were achieved for the treatment of wastewater under psychrophilic temperatures (Wang et al., 2018). Based on the diversity shown before, the sensitivity analysis provided in this manuscript is intended to raise awareness between licensors and to make the newest technologies competitive with the current very energetically optimized centralized systems.

#### 2.4. Life cycle impact assessment

The Life Cycle Impact Assessment (LCIA) transforms the elementary flows of the life cycle inventory of wastewater treatment processes into environmental impact contributions that are assessed in the interpretation stage of the LCA results. Although the LCIA is composed of five different stages (selection, classification, characterization, normalization and weighting), only those considered as mandatory were selected in this manuscript (Hauschild and Huijbregts, 2015). The estimation of environmental impacts was carried out considering the ReCiPe 2016 Midpoint and Endpoint methods V1.03 World (2010) and the SimaPro v9.0 software as calculation tool. A time balance perspective (the Hierarchy approach) was chosen. The midpoint impact categories considered in this study were freshwater eutrophication (FE), marine eutrophication (ME), global warming (GW), stratospheric ozone depletion (SOD), fossil resource scarcity (FRS), water consumption (WC), terrestrial ecotoxicity (TET), marine ecotoxicity (MET), freshwater ecotoxicity (FET) and terrestrial acidification (TA). The endpoint impact categories were Human Health (HH), Ecosystem quality (EQ) and Resource Scarcity (RS), which were obtained from an aggregation process of the midpoint impact categories mentioned above. Normalization and weighting factors were used to estimate a single score result expressed in millipoints (mPt).

### 3. Results and discussion

#### 3.1. Water and fertilizer quality and possible applications

Water reclamation in a hotel is restricted by the European and Spanish legislative framework regulating the composition of effluents for reuse purposes. The UE Regulation 2020/741 imposes some quality limitations for the reuse of reclaimed water in agriculture, although no minimum requirements are included for green areas. On the other hand, the Spanish Royal Decree 1620/2007 of 7 December 2007, which establishes the regulations applicable to the reuse of water and the quality standards for reclaimed water, complies for urban and recreational uses. Some maximum admissible values have been established for intestinal nematodes, *E. coli*, TSS and turbidity. Table 5 presents the characteristics of the reclaimed water with and without the application of water saving measures (as already explained in Section 2.2.1).

The recovery of the hotel blackwater of the hotel seems to be an arduous task with multiple constraints for each of the products obtained: the effluent or liquid fertilizer with a high concentration of nutrients (N and P) and the solid fertilizer. The Council Directive of 21 May 1991 concerning urban wastewater treatment aims to protect the environment against the adverse effects of uncontrolled wastewater discharges, that is why impediments are found for the reclamation of AMBR permeate and the direct discharge into fields is only considered with a further treatment for nutrient removal or recovery. However, and under the concept of circular economy, N and P are perceived as bio-based products and thus the actual water and resource recovery frameworks

**Table 4**  
Energy requirements of aerobic and anaerobic MBR expressed in kWh·m<sup>-3</sup>.

Reactor Type	Value	Source
Anaerobic membrane bioreactor (AnMBR)	0.08–0.35 <sup>(1)</sup>	Lei et al. (2018)
	0.03–5.7	Song et al. (2018)
	<0.675	Zhen et al. (2019)
	0.1–2.6	Wu and Kim (2020)
	0.4	Galib et al. (2016)
	4.78 <sup>(1)</sup>	Bair et al. (2015)
	0.09–5.4	Wang et al. (2018)
	0.04–1.35 <sup>(1)</sup>	Medina et al. (2020)/Shin and Bae (2018)
	0.22–0.27	Jiménez Benitez et al. (2020)
	0.8 and 0.03–5.77	Martin et al. (2011)
Aerobic membrane bioreactor (AMBR)	1.87–3.91 and 0.05–0.13	Seib et al. (2016)
	1.07	Arias et al. (2019)
	6.10	Chong et al. (2013)
	0.68	Bailey et al. (2020)
	1.40 <sup>(1)</sup>	Krzeminski et al. (2012)
	2.00 <sup>(1)</sup>	Krzeminski et al. (2012)
	3.0–6.0 <sup>(2)</sup>	Grundestam and Hellström (2007)
	3.0–11.5 <sup>(1)</sup>	Verrecht et al. (2012)
	0.5–2.5	Lazarova et al. (2012)
	2.0	Martin et al. (2011)

Notes: (1) Small scale reactors (2) Energy for MBR and reverse osmosis.

**Table 5**

Reclaimed water from black and grey water treatment and maximum admissible values for water applications.

Parameter	Reclaimed GW (WWSM)	Reclaimed GW (NWSM)	Reclaimed BW (WWSM)	Reclaimed BW (NWSM)	Urban green areas irrigation	Golf courses irrigation	Ornamental water
TSS (mg·L <sup>-1</sup> )	20.03	7.75	9.64	4.50	<20 <sup>(1)</sup>	<20 <sup>(1)</sup>	<35 <sup>(1)(2)</sup>
COD (mg·L <sup>-1</sup> )	51.90	20.09	100.64	46.20	125 <sup>(2)</sup>	125 <sup>(2)</sup>	125 <sup>(2)</sup>
TN (mg·L <sup>-1</sup> )	0.37	0.14	267.45	126.77	<2 <sup>(2)</sup>	<2 <sup>(2)</sup>	<2 <sup>(1)(2)</sup>
TP (mg·L <sup>-1</sup> )	0.25	0.10	29.70	14.00	<15 <sup>(2)</sup>	<15 <sup>(2)</sup>	<15 <sup>(2)</sup>
Intestinal Nematodes (egg·10L <sup>-1</sup> )	–	–	–	–	<1 <sup>(1)</sup>	<1 <sup>(1)</sup>	–
Escherichia Coli (CFU·100 mL <sup>-1</sup> )	–	–	9–52	–	<200 <sup>(1)</sup>	<200 <sup>(1)</sup>	<10,000 <sup>(1)</sup>
Turbidity (NFU)	16.96	8.78	10.03	6.61	<10 <sup>(1)</sup>	<10 <sup>(1)</sup>	–

Notes: (1) Royal Decree 1620/2007, (2) Council Directive of 21 May 1991. WWSM: With water saving measures; NWSM: No water saving measures. Table 5 also summarises the maximum permissible legislative values for the intended uses of reclaimed water: irrigation of green areas, irrigation of golf courses and ornamental water bodies such as ponds. The flow of reclaimed greywater in a hotel with water saving measures is 2.6 times lower than that of a hotel without measures. However, the water quality when considering the same removal efficiencies in the AMBR for both cases is better for higher water consumption due to dilution of pollutants. The water complies with the standards and can be used as irrigation water. The reclaimed wastewater also has good quality with respect to TSS and turbidity. The latter has been estimated from the correlation between TSS and turbidity provided by Bersinger et al. (2015). Reclaimed greywater has characteristics that overcome quality and risk barriers and has therefore been easily included within the circular economy concept (Sauvé et al., 2021; Vuppiladadiyam et al., 2019). Hence, the literature has focused on the stand-alone analysis of greywater treatment in hotels instead of blackwater treatment. Examples include Estelrich et al. (2021), Sayegh et al. (2021) and Dwitiya et al. (2021).

need to evolve (Reynaert et al., 2021). In sustainable decentralized systems, the complexity of the installation must be compensated by environmentally viable nutrient recovery. Each treatment layer involves the consumption of other resources (such as electricity), which indirectly affects the environment (due to its production processes). Therefore, a possible solution is the direct recovery of the effluent from the anaerobic membrane system in order to recover resources. In consequence, fertigation management practices should be designed to avoid nutrient leaching and to protect sensitive areas where there is potential of groundwater contamination (Helmecke et al., 2020). Besides, specific analysis should be performed for a certain hotel to monitor the cumulative contaminants not retained by the membrane or biodegraded.

Regarding to the application of the biosolids to the soil, Colli-vignarelli et al. (2019) have reported a lack of consensus within the scientific literature on the drawbacks of their use. Organic chemicals and pathogens (included in the legislation) and heavy metals are currently of most concern. However, the presence of other emerging contaminants detected in very low concentrations makes the decision-making procedure even more difficult. PFASs were detected in sludge from centralised treatment of domestic and industrial wastewater and therefore after applications on soils ended up in groundwater (Coggan et al., 2019; Johnson, 2022). PFAS were found in consumer products such as textiles, cosmetics and other everyday products (Kotthoff et al., 2015). However, their traceability in segregated wastewater streams for application in decentralized treatment systems is still very limited. Siloxanes are other micropollutants in similar circumstances and greatly affect the valorisation of highly concentrated organic streams. They accumulate in sewage sludge and landfills, but their behaviour in small-scale systems with stream segregation has not been explored (De Arespacochaga et al., 2015). Antibiotics are other contaminants of concern that are removed by biodegradation and sorption, but their concentration in sludge also depends on the physicochemical characteristics and the rate of use in sludge.

The key to build environmentally friendly solutions with an absolute minimum impact is to find a balance between the effects coming from direct and indirect discharges considering not only Spanish regional data but also more local ones. Therefore, the techno-environmental analysis included in this manuscript has been constructed as a general conceptual case study, considering a mass cut-off around 5% (not including micropollutants), with the aim of recovering resources. Thus, focusing on nutrient recovery from blackwater in the AnMBR, it is estimated that the 812 kg N·year<sup>-1</sup> and 90 kg P·year<sup>-1</sup> retrieved from the decentralized wastewater treatment can be used for the fertilization

of 3 ha of a golf course with an average need of 190 kg N·ha<sup>-1</sup>·year<sup>-1</sup> or 6.1 ha of a garden lawn demanding 95.4 kg N ha<sup>-1</sup>·year<sup>-1</sup> (Bock and Easton, 2020; Ihtisham et al., 2020; Ashekuzzaman et al., 2021). Accordingly, decentralized blackwater treatment can pose an opportunity for hotels with considerable land area.

### 3.2. Comparison between treatment scenarios

The centralized water treatment plant considered in this study for comparison with an innovative decentralized system has an energy consumption of about 0.53 kWh·m<sup>-3</sup> of treated water. In addition, and due to the sewer network infrastructure (87.99 km), the consumption per pumping of wastewater amounts to 0.44 kWh·m<sup>-3</sup>. For a gate-to-gate analysis (Focus on wastewater treatment approach, Section 2.2.2), this consumption represents the largest environmental impact of the system assuming around 40–45% of the impacts in most categories. The exceptions are GW (19%), SOD (4%) and FE (13%) as in these cases the largest impact comes from emissions to air and water. Therefore, GW and SOD are mainly affected to air pollutants such as CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> and FE is influenced by water contaminants such as COD, TN, TP and TSS. Secondary treatment accounts for 37% of the environmental impact. Energy (88–98%) is the input with the highest burden on the environment, while transport (<0.023%) and production (2–12%) of ferric chloride are practically negligible.

On the other hand, decentralized grey water treatment implies a total consumption of 0.80 kWh·m<sup>-3</sup> of grey and black water inflow to the DG-DB system if the data provided by Banti et al. (2020) were used for an aerated membrane system. Compared to the range of values presented in Table 4, this energy demand (1.37 kWh·m<sup>-3</sup> GW) is medium-low. The energy difference between the centralized and decentralized systems would then be 0.17 kWh·m<sup>-3</sup> for a black water treatment with zero energy consumption, which implies that, if the environmental profile were practically dependent on energy consumption, the improvement of this profile would be given by an efficient wastewater treatment with lower energy consumption than reported. Fig. 3A shows how for an energy consumption of the black water treatment of 0.2 kWh·m<sup>-3</sup>, the SOD and FE categories show an environmental improvement while the rest of the categories, excluding GW, are fairly equal to those of the centralized system. The difference found in GW is not only due to energy but also to the emissions to the atmosphere produced by the aeration systems (in CG-CB and DG-DB scenarios) and the valorisation of biogas in the DG-DB scenario. The direct emissions in CG-CB amount to 0.54 kg CO<sub>2-eq</sub>·m<sup>-3</sup> while the emissions in DG-DB amount to 1.15 kg CO<sub>2-eq</sub>·m<sup>-3</sup>. A higher energy consumption (around 0.8 kWh·m<sup>-3</sup>) within the

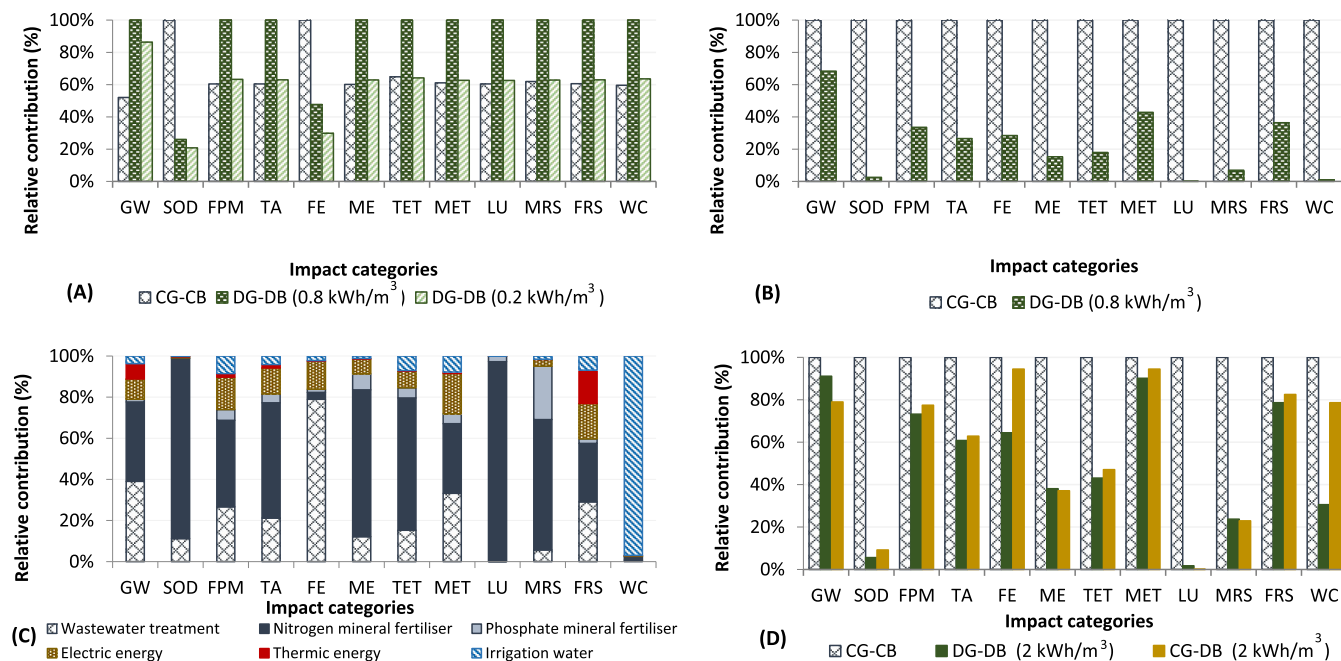


Fig. 3. Comparative profile of the (A) Focus on wastewater treatment, (B) Coupling wastewater treatment and resource recovery and (D) Integrating water and resource recovery with wastewater treatment perspectives and distribution of loads for the (C) Wastewater treatment with a focus on reclaimed water approach.

literature range of Table 4, provides an environmental profile of the decentralized system unfavorable (Fig. 3A).

However, it must be taken into account that the DG-DB water treatment system is not only designed for water treatment, but also for resource recovery. For this reason and considering the same functional unit, the system boundaries have been extended so that both processes allow the recovery/production of the same quantity of products (Coupling wastewater treatment and resource recovery approach, Section 2.2.2). Fig. 3C shows the distribution of environmental impacts in the centralized system. As this type of treatment is not designed for resource recovery, a higher input of resources is required from conventional production systems, including the production of mineral fertilizers, electrical energy, thermal energy and irrigation water. Nitrogen fertilizer production accounts for about 28–97% of the impacts, except in FE (3%) and WC (1.6%). The comparative profile of the CG-CB and DG-DB systems is drastically modified. For an energy consumption of 0.8 kWh·m<sup>-3</sup> for black water treatment in the AnMBR, the environmental profile is generally better.

The relationship between electricity consumption and environmental impact is directly proportional. Equation (2) exemplifies for the different system boundaries discussed so far how well the global warming category fits the lineal trend.

$$GW \text{ (kg CO}_2\text{-eq)} = 0.414 \cdot E + 1.492 \quad (2)$$

E is the electricity consumption of the DG-DB blackwater treatment. The greenhouse emissions (GHG) of the CG-CB scenario are 0.95 kg CO<sub>2</sub>-eq·m<sup>-3</sup> of treated BW and GW when the hotel has implemented water saving measures and for the boundaries of the first approach (see Fig. 1). The same emissions reach 2.43 kg CO<sub>2</sub>-eq·m<sup>-3</sup> when opening the scope to include the effect of the products on the environment. The energy consumption of the blackwater treatment should not exceed 2.27 kWh·m<sup>-3</sup> to ensure better performance of the decentralized treatment option.

Not only energy consumption but also water use are the main targets to decrease the environmental impact. The UE Commission Decision 2016/611 include some benchmarks of excellence in relation to water consumption. In this framework, a consumption of less than 140

L·night<sup>-1</sup>·guest<sup>-1</sup> is expected. The water requirement of this modelled hotel is 114.11 L·night<sup>-1</sup>·guest<sup>-1</sup> for a performance with water saving measures in the fittings (toilets, sinks and others) and 272.73 L·night<sup>-1</sup>·guest<sup>-1</sup> for a scenario without water saving measures but with grey water recovery for toilets. According to both approaches, the first option implies the treatment of 20.77 m<sup>3</sup>·d<sup>-1</sup> and the second one, 49.64 m<sup>3</sup>·d<sup>-1</sup>. However, care must be taken with the quality of the reclaimed water (see Section 3.1).

Water reclamation was analysed in the approach of Wastewater treatment with a focus on reclaimed water (Section 2.2.2). Two possible systems are compared in relation to the type of water consumed in the toilets for refilling: drinking water or reclaimed water. By reclaiming the treated water from the greywater produced in the hotel for flushing, the total water consumption is reduced from 20.41 m<sup>3</sup>·d<sup>-1</sup> to 12.35 m<sup>3</sup>·d<sup>-1</sup>. This comparison has resulted in a single score of 49.89 mPt for water reclamation and 65.59 mPt for drinking water consumption in the toilets.

Moreover, the HH endpoint impact category accounts for 80% of the overall impact while EQ and RS categories represent a 19% and 1%, respectively. Although these results were estimated for a conservative energy consumption (0.8 kWh·m<sup>-3</sup>) in the black water treatment, an energy demand of 0.2 kWh·m<sup>-3</sup> only reduces the environmental impact by about 5.8 and 7.7% for both systems, without and with water reclamation.

The chosen boundaries have limited the study of this perspective to the environmental quantification of a decentralized wastewater treatment option with different water consumption strategies in the hotel. However, and as already discussed for the first approach of this study, the environmental impact of the products was not included. Therefore, a system expansion of the cradle-to-gate perspective was proposed to evaluate the reuse of the reclaimed water obtained after the greywater treatment for other possible applications. The reclaimed water has a quality composition that allows it to be discharged directly into the environment or to be reused for irrigation of different green areas such as gardens or golf courses. Therefore, the decentralized wastewater treatment configuration without greywater reclamation in the toilets has been expanded to incorporate these two other possible applications instead of toilet flushing. The environmental single score result of the

scenario with treated greywater discharge is 75.02 mPt, which is 1.22 time higher than the equivalent scenario with water recovery for irrigation.

Finally, the fourth approach (*Going for the big picture: Integrating water and resource recovery with wastewater treatment*) integrates all the previous analysis based on the results shown. Fig. 3D illustrates the comparative environmental profile of the centralized, decentralized and hybrid configurations. The DG-DB scenario has proven to be environmentally friendly for larger system boundaries when considering upstream and downstream processes and for an energy consumption of 2 kWh·m<sup>-3</sup> of water to be treated (GW and BW) in the black water treatment with AnMBR (around 5 kWh·m<sup>-3</sup> influent to the AnMBR). The DG-DB has a better environmental profile than the CG-DB treatment option in all categories except GW (13% reduction). Energy consumption, direct emissions and resource recovery are the main reasons. The centralised wastewater installation has lower energy consumption and direct emissions than the decentralized treatment, but resource recovery is worse. Direct emissions from centralised treatment are 0.54 kg CO<sub>2-eq</sub>·m<sup>-3</sup> (when greywater is assumed to have similar impacts as domestic wastewater) while direct emissions from decentralized greywater treatment are 0.85 kg CO<sub>2-eq</sub>·m<sup>-3</sup>. The production of bioproducts offsets the environmental impacts of the decentralized systems with a difference of 19 g P<sub>2</sub>O<sub>5</sub>·m<sup>-3</sup>, 84 g N·m<sup>-3</sup>, 0.59 kWh·m<sup>-3</sup> of electricity, 0.67 kWh·m<sup>-3</sup> of thermal energy and 0.996 m<sup>3</sup>·m<sup>-3</sup> of water for on-site irrigation. However, and when it comes to compare decentralized and hybrid systems, the profile changes. Decentralized blackwater treatment recovers most of the resources (nutrients and energy), except for reclaimed water, but centralised greywater treatment reduces energy consumption. Note that the energy demand in decentralized greywater treatment might be lower (Table 4) than the value assumed in this manuscript and therefore the environmental profile of full decentralization would become better. The relevant mid-point impact categories are also LU and WC. The production of mineral nitrogen fertiliser is responsible for the large difference between centralised and decentralized systems (Fig. 3C and D), while on-site reuse of reclaimed water from greywater treatment reduces the impact of DG-DB compared to CG-DB.

### 3.3. Centralized versus decentralized in LCAs for wastewater treatment

Interest in the centralized-decentralized benchmark has increased considerably in recent years within the life cycle assessment community that has addressed the wastewater treatment sector. Out of a total of 25 articles collected from 2012 to May 2022 (see supplementary material in Tables S.1 to S.4), 56% correspond to the period 2019–2022.

The study of wastewater treatment facilities in these publications has mainly focused on wastewater treatment in residential areas and only 20% of the studies have shifted the frame to other activities: 2 for office buildings or commercial areas (Leong et al., 2019; Hendrickson et al., 2015), 2 for hospitals (Igos et al., 2012, 2013) and 1 for hotels (Santana et al., 2019). In addition, in 12 of them only greywater and stormwater treatment has been decentralized, while blackwater treatment has been considered in 4 of the 25 articles. Within this context, the publications Estévez et al. (2022), Besson et al. (2021), Arias et al. (2020) and Romeiko (2020) with only two different treatment technologies (UASB and septic tank) can be highlighted.

The articles published in the decade 2012–2022 present very different characteristics. Not only are they technologically different, but they have been approached with different functional units, system boundaries, perspectives and impact assessment methods. The comparison has thus been made on the basis of the direction the results have taken: the environmental impacts were favorable for the decentralized system, they were worse or there was no clear categorization with respect to their environmental profile.

In this sense, 56% of the articles indicated a clear environmental improvement in the implementation of decentralized systems while 8% considered the opposite. Igos et al. (2013) have stated that the added

value of implementing a decentralized system for the treatment of micropollutants in wastewater is very low due to the volume of water treated. On the other hand, the conclusions reached by Jeong et al. (2018) for membrane bioreactors claim that the electrical energy input was the main hot spot of the system. Energy consumption seems to be the parameter that affects membrane systems the most within a very wide range of specific demand (as shown in Table 4) for both aerobic and anaerobic reactors. In this regard, this manuscript demonstrates for the limits of the system focusing solely on the operation of the facility, and in agreement with the results of Jeong et al. (2018), that the system is not environmentally friendly. However, the focus of this study is on resource recovery. Thus, the wider limits of the system demonstrate that a decentralized wastewater treatment with membrane technologies is more environmentally sustainable than a conventional one. For this reason, this publication is one of a series of articles that claim that decentralized systems improve the environment.

This beneficial environmental profile could be modified if the decentralized wastewater treatment facility supports the operation of a centralized system, avoiding overflow peaks. Clauson-Kaas et al. (2012) have shown that the energy consumption of a centralized facility operating with overflows is 5 times higher than that of decentralized facilities with lamella filtration and separation technologies. The remaining 36% of the articles have not categorized their environmental profile for the following reasons: a large technological difference (Mayer et al., 2021; Besson et al., 2021), dependence on the length of the wastewater transport network (Risch et al., 2021), scale effects (Santana et al., 2019) and dependence on the lifetime of the facilities (Hasik et al., 2017).

## 4. Conclusions and future challenges

Decentralized greywater treatment in hotels has so far been the most recurrent solution for wastewater treatment and water reclamation and has contributed to the reduction of the remarkable demand for tap water in tourist areas. However, closing the urban water cycle is only one of the many aspects of the circular economy concept. Resource recovery has to be included as a key objective in decentralized wastewater treatment with membrane technologies.

In the current context, the path developed in centralized plants, where an optimized approach to their treatment function can bring benefits beyond 39.8% in global warming potential, is valued. However, new decentralized facilities were designed with life-cycle thinking and have higher results for system boundaries that are not limited to the operation of the facility. The resource recovery scenarios with decentralized wastewater treatment proved to have favorable environmental results (around 9% for global warming) even for energy consumptions in the operation of the anaerobic membrane bioreactor system as high as 2 kWh·m<sup>-3</sup>. Indeed, the centralized wastewater facility represents between 0.8 and 79% (WC and FE) of the impacts and GW represents 39% when comparing centralized and decentralized scenarios for the production of the same amount of products (including non-renewables). It seems that the current centralization-decentralization competition will not only depend on a scale comparison, but also on other aspects related to the specificity of treatment (technology), operation, products and system boundaries considered by the LCA practitioner. Therefore, future challenges will be associated with the creation of databases from the measurement of gaseous emissions, the development of correlations for energy consumptions under different scales and the performance of LCA studies for circumstances of environmental-political concern. An example can be the comparison between normal operation and a wastewater treatment situation where the centralized facility has exceeded its capacity (due to heavy rainfall or population growth).

### Credit author statement

**Sofía Estévez:** Methodology, formal analysis, investigation, Writing - Original Draft, visualization; **María Teresa Moreira:**

Conceptualization, validation, Writing - Review & Editing, supervision; **Gumersindo Feijoo**: Validation, Writing - Review & Editing, supervision.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sofia Estevez Rivadulla reports financial support was provided by Horizon 2020. Sofia Estevez Rivadulla reports financial support was provided by Spanish Ministry of Science and Innovation.

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### Appendix A. Supplementary data

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