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Life Cycle Assessment of Green Space Irrigation Using Treated Wastewater: A Case Study

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Abstract: Water scarcity is a pressing issue that makes it essential to manage this resource efficiently and sustainably. One solution to combat this issue is the use of treated wastewater (TWW) to irrigate green spaces in cities. However, it is crucial to evaluate the environmental impacts associated with this practice. To this end, life cycle assessment (LCA) is the most advanced tool available. The objective of this study was to assess the environmental implications of using TWW for lawn irrigation in the city of Viseu. The ReCiPe 2016 method, supported by SimaPro software, was employed for life cycle impact assessment (LCIA). An attributional approach was used, and the system boundaries were expanded to include the non-discharge of TWW into the receiving environment, the avoided consumption of domestic water, and the avoided consumption of chemical fertilizers. The results revealed that using TWW for lawn irrigation is preferable in terms of human health and ecosystem damage but unfavorable in terms of resource damage. When considering the impact of water consumption on human health and terrestrial and aquatic ecosystems, it is recommended to use treated wastewater for lawn irrigation.

Keywords: irrigation; LCA; life cycle assessment; treated wastewater; water reuse

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1. Introduction

Global and local climate change has a great influence on water resources, and as a consequence, water scarcity is becoming a concern [1]. Pressures on water resources have been increasing drastically in recent years, mainly owing to an increase in the world population's industrial and agricultural development, which has greatly influenced the mean global temperatures on Earth, leading to climate change. Currently, water scarcity affects approximately 25% of the world's population and could affect approximately 1.8 billion people by 2025 [2]. Therefore, it is necessary to seek sustainable alternatives to address this issue. Water is a necessary resource, and its deficiency can threaten the lives of many individuals and the ecosystem worldwide [3].

Sustainable and responsible management is essential to guarantee efficient water availability. Even with technological advances that help manage water resources through seawater desalination projects and dam construction, it is necessary to adopt strategies that maintain these resources in a sustainable manner and implement more effective measures for the implementation of practical actions such as water reuse. For both seawater desalination and dam construction, the main challenges related to water reuse are high costs. For desalination, there is a limitation in water recovery due to the formation of mineral scale, which increases operational costs [4], while for dams, the most expensive phase is linked to the construction phase [5].

The reuse of treated wastewater has arisen from the need to reduce water scarcity worldwide. Considered as a new water resource, effluents from wastewater treatment plants (WWTP) can be used in activities that require a lower standard of water quality or even produce water with better quality, thus allowing greater availability of high-quality fresh water for several activities.

The use of treated wastewater (TWW) can help in the recovery of the environment, qualitatively and quantitatively, by reducing the release of treated water in sensitive areas and reducing the volume of fresh water captured. In addition, it is considered an efficient strategy for solving environmental, economic, and social issues [6]. The studies by Cumei et al. [7] carried out in the city of Zhengzhou, China, show that the cost of using reused water to irrigate urban green spaces was 46% of the cost of using tap water and that the total benefit of using reused water to irrigate spaces greens was USD 4.05 billion. The environmental benefits of water reuse are also significant, considering it environmentally favorable for different purposes, with reductions in climate change impacts ranging between 8% and 52% depending on the intended use [8].

The United Nations describes wastewater as an available and untapped source of water. Furthermore, it is considered an important support for the global transition to a circular economy, as it can be safely reused [9].

Portugal is vulnerable to the impacts of climate change. In addition to rising sea levels, droughts, floods, and heat waves, water stress has also affected some regions of Portugal and may even be worsened by future climate conditions [10]. In Viseu, a district in the central region of Portugal, the availability and quality of water resources have become uncertain due to these climate variations. The city, like many others, faces challenges in managing water resources sustainably. This situation is exacerbated by the seasonal fluctuations in available water flows. The city's public water supply has been impacted by these climatic constraints, as seen during extreme droughts, such as the one that occurred in the Iberian Peninsula in 2017. This drought affected reservoir levels significantly, necessitating alternative water sources to meet the population's needs [11].

Therefore, in recent years, there has been a growing need to focus on water reuse as a source of alternative water supply. In the Algarve, in the south of Portugal, some water reuse projects have been developed to irrigate crops and golf courses and to support ecosystems [12]. Águas do Tejo Atlântico group, which covers 23 municipalities in the Lisbon region, is a pioneer in the incorporation of the circular economy and sustainable water management, creating the concept of a "Water Factory". This concept reinforces the industrial nature of water valorization, reusing treated wastewater in industries, watering agricultural fields and green areas, and washing equipment and pavements, in addition to also producing a beer with recycled water, "VIRA", with the aim of raising awareness among the population about water quality reused [13].

In Portugal, water reuse is supported by national legislation, such as Decree-Law No. 119/2019, republished by Decree-Law No. 11/2023, which establishes the legal framework for the reuse of treated wastewater, in line with the European Union Regulation (EU) 2020/741. Comparatively, Portuguese regulations are like those in other EU countries, promoting sustainable practices, although practical implementation and levels of adherence may vary between Member States.

It is essential to recognize issues that can guarantee the environmental viability of water reuse projects. This involves examining the conditions that minimize environmental impacts, weighing them against expected benefits, and evaluating the consumption of energy, fossil resources, and materials for infrastructure in comparison with the water and nutrient savings achieved. In this context, life cycle assessment (LCA) has emerged as a tool that can be used to identify, measure, and characterize the environmental impacts related to the reuse of treated wastewater.

According to ISO 14040 (2006) and 14044 (2006) [14,15], LCA is a method that better understands and addresses the possible impacts associated with products or services, both manufactured and consumed. LCA has been applied in many sectors to analyze the environmental impacts of wastewater treatment and reuse. A literature review of 59 LCAs of WW-reuse case studies was conducted by Mehmeti and Canaj [16]. This highlights the fact that LCA research in this field has increased in recent years, with European authors being the primary contributors. The most commonly used life cycle impact assessment (LCIA) models are ReCiPe and CML, with Ecoinvent as the primary database and SimaPro as the primary LCA software. Volumetric and surface-based functional units are widely used. However, in studies that deal with the reuse of water for agricultural irrigation, the functional unit may be related to the extent of the area to be irrigated in square meters or hectares, as reported by Azeb et al. [17]. The type of energy supplied to the life cycle of a product plays a significant role in the design of environmentally efficient wastewater reuse schemes. The literature review indicates that additional, comprehensive studies are necessary that consider the expansion of system boundaries and incorporate a wide range of environmental impact categories complemented by uncertainty and/or sensitivity analysis.

This research sought to employ the life cycle assessment (LCA) methodology to assess the environmental viability of utilizing treated wastewater (TWW) from the Viseu Wastewater Treatment Plant (WWTP) for irrigating green spaces within the city. The system boundary was expanded to incorporate the processes that are avoided due to the utilization of treated wastewater in irrigation, such as tap water, chemical fertilizers, and emissions to the river. A comprehensive range of eighteen environmental impact categories was taken into account, and a sensitivity analysis was carried out to assess the transport distance of treated wastewater.

2. Materials and Methods

2.1. Case Study

Viseu is a city located in the center north of Portugal with approximately 500 km^2 and 100,000 inhabitants. According to the municipality managing entity (DAHUEV), the total area of green spaces in Viseu is 1,439,558 m^2, of which approximately 40% require irrigation, which is 575,823 m^2. In accordance with the same source, the water requirement for irrigation was found to be 5 L/day.m^2, which translates to approximately 2879 cubic meters of water used per day. Irrigation occurs predominantly from June to September, which is a period of low rainfall and high temperatures in Viseu [18]. The weather of Viseu is characterized by the influence of climate change, which has led to shifts in precipitation patterns and temperatures. Over the years, there has been an increase in the average daily air temperature, with variations noted across seasons. The discrepancy in precipitation patterns has led to periods of intense rainfall alternating with longer and more frequent periods of scarce or absent precipitation [11].

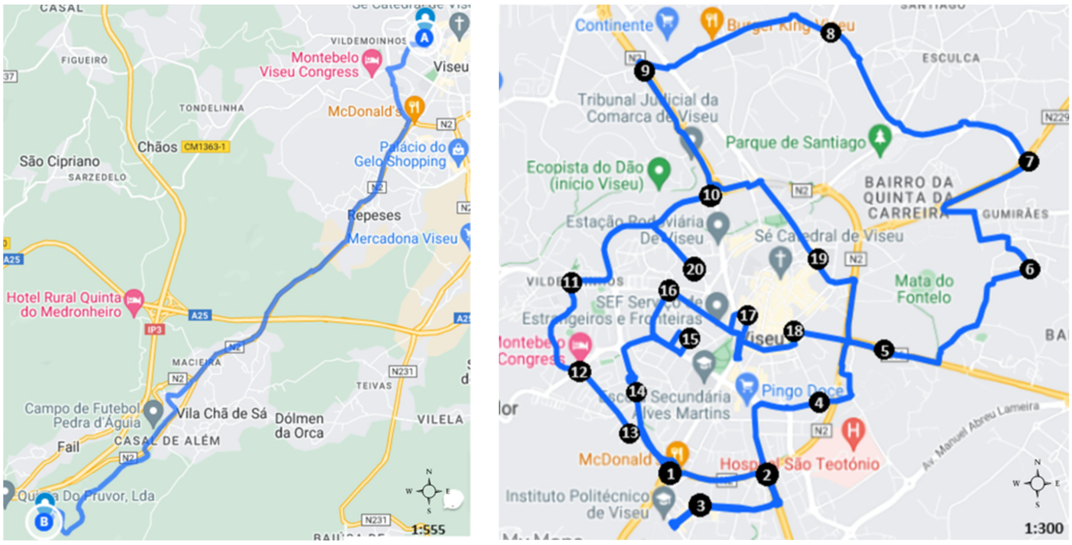
Green spaces are fertilized with chemical fertilizers (NPK) in proportions of 2-1-2, considering that nitrogen should be around 0.01–0.015 kg.m^{-2}.$year^{-1}$ for average maintenance. Nitrogen-based fertilizers are divided into two top dressing applications per year, one at the beginning of spring and the other at the end of summer. Phosphate and potassium fertilizers were applied in autumn before the first rain [19].

To better understand the irrigation of Viseu's green areas, the area to be irrigated was divided into 20 distinct points around the city, which represented the irrigation points (Figure 1b).

The irrigation is performed through an irrigation system already implemented in the area, the grassy areas with sprinkler irrigation systems and the bushy areas with drip irrigation. Flower boxes and tree boilers are watered using a self-tank truck. The water comes from the boreholes until they dry out, which usually occurs in a few summer months. In this case, the irrigation is made with tap water using a self-tank truck.

In this study, the irrigation of grassy areas is performed using a tank truck, but now TWW from the Viseu Sul WWTP (Figure 1a) is used instead of tap water.

The WWTP had already provided TWW to irrigate the lawns of some roundabouts in Viseu in the summer of 2022 when the municipality suffered from a severe drought. Since then, the Viseu City Council, together with SMASV and DAHUEV, has reinforced efforts to issue licenses for the production and use of TWW.



(a) (b)

Figure 1. (a) Distance from the Viseu Sul WWTP to the center of Viseu. (b) Watering points.

The Viseu Sul WWTP currently serves a population of 73,900 and was designed to serve a maximum of 90,000 inhabitants. On average, 14,560 m^3/day of wastewater is being treated. Regarding the level of treatment, at the Viseu Sul WWTP, it is possible to divide them into three parts: pre-treatment, biological treatment, and membrane ultrafiltration, which classifies it as a station with more advanced treatment than secondary treatment. As it has an MBR system (membrane bioreactor) for ultrafiltration and has the possibility of disinfecting the effluent treated by chlorination, the WWTP can be classified as a tertiary treatment. The MBR ultrafiltration system at ETAR Viseu Sul is a reference in the treatment sector at a national level and guarantees good quality to the treated effluent. The treated effluent is stored in a 1300 m^3 tank, and the surplus is sent to the river.

The quality parameters of the treated wastewater (TWW) from the WWTP and tap water are listed in Table 1. The TWW data were provided by the WWTP management office, and the tap water data were obtained from ERSAR [20].

Table 1. Quality of tap water and treated wastewater (TWW) from the WWTP.

Parameters	Tap Water	TWW	Emission Limits for the River	Water Quality Standards for Reuse for Irrigation
TSS (mg/L)	-	5.42	35.00	≤10.00
COD (mg/L O_2)	-	11.79	125.00	
BOD 5 (mg/L O_2)	-	4.00	25.00	≤10.00
Ammoniacal nitrogen (mg/L NH_3)	-	5.70	10.00	10.00
Total nitrogen (mg/L N)	-	8.54	15.00	15.00
Ammonium (mg/L NH_4)	<0.15	-	-	-
Total phosphorus (mg/L P)	-	0.89	2.00	5.00
Hydrocarbons (mg/L)	-	4.10	10.00	-
Aluminum (mg/L Al)	0.204	0.03	10.00	5.00
Arsenic (mg/L As)	0.013	0.01	1.00	-
Cadmium (mg/L Cd)	<1.50	0.00	0.20	-
Lead (mg/L Pb)	0.0122	0.01	1.00	-
Copper (mg/L Cu)	0.31	0.056	1.00	-
Chromium (mg/L Cr)	<0.010	0.004	2.00	-
Iron (mg/L Fe)	0.358	0.10	2.00	2.00
Mercury (mg/L Hg)	0.003	0.008	0.05	-
Nickel (mg/L Ni)	0.015	0.01	0.03	-
Zinc (mg/L Zn)	-	0.22	5.00	-
E. coli (ucf/100 mL)	-	6.49	-	≤10.00

As the reuse of treated wastewater can pose some risks to society and the environment, mainly because it may contain microbiological pathogens, chemical contaminants, and toxic substances that can affect public health and ecosystems, a risk assessment is necessary. Santos and Brás [21] carried out a risk assessment for the production and use of TWW from the Viseu Sul WWTP in the irrigation of Viseu's green areas and identified which risks to public health and water resources are considered negligible for the project.

2.2. LCA

The life cycle assessment (LCA) study was executed utilizing the methodology prescribed in the ISO 14040:2006 and ISO 14044:2006 standards. This study encompassed four distinct phases: (1) goal definition, which establishes the purpose and extent of the study, as well as the functional unit; (2) inventory analysis, which records the release of pollutants into the air, water, and soil, as well as solid waste generation and resource consumption per functional unit; (3) impact assessment, which evaluates the environmental impact of these pollutants throughout the life cycle; and (4) result interpretation, wherein the findings from either the inventory analysis or impact assessment, or both, are assessed in relation to the established goal and scope.

2.2.1. Goal and Scope

The objective of this study was to evaluate the environmental impacts of lawn irrigation with WWT in Viseu in relation to the selected midpoint and endpoint indicators. The study's results are intended to be conveyed to the decision-makers at Viseu City Council, who are responsible for managing the WWTP and irrigating the green spaces within the city.

Systems Limits

The system boundary is shown in a simplified way in Figure 2. It means that LCA is (gate-to-gate) with the expansion of system boundaries.

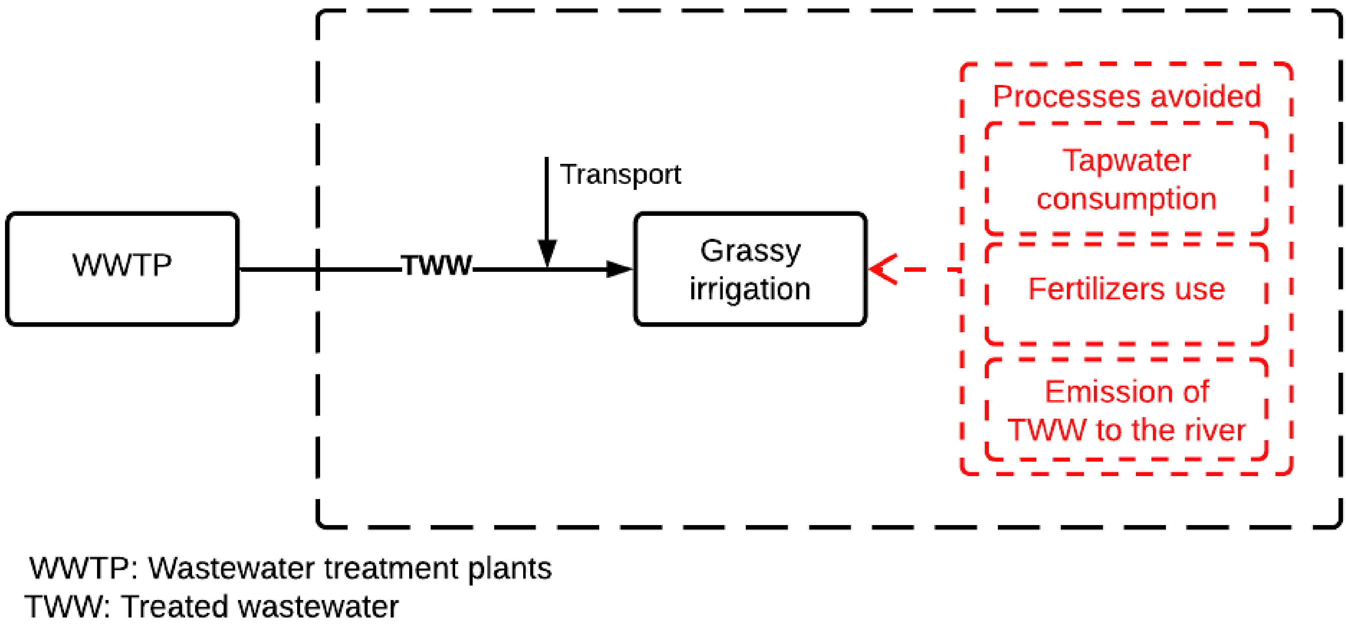


Figure 2. System boundary in the study.

The processes of water treatment and construction of facilities were excluded from the system limits, as these processes occur independently of the use of treated effluent. Wastewater treatment plants (WWTP) remain operational regardless of whether the secondary effluent (TWW) is used for irrigation or discharged to the river [22].

The system limits included the following processes:

- Pumping the TWW into the self-tank truck with a capacity of 18 m^3 using an electric pump: For electricity use, the equivalent process "Electricity Mix, AC, consumption mix, at consumer, 230V, PT S" available in the Ecoinvent database was used. The dataset represents the average national specific electricity mix, including main activity producers and auto producers as well as imports, for the reference year 2008;
- Transportation of TWW to irrigation points (average distance of 10 Km): Data for TWW transported were obtained from the equivalent process "Transport, freight, lorry 16–32 metric ton, euro5 {RoW} | market for transport, freight, lorry 16–32 metric ton, EURO5 | APOS" available in the Ecoinvent database;
- TWW discharge into river avoided: By adopting a specific amount of TWW for irrigating green spaces, the same amount is not released into the river, avoiding water pollution;
- Avoided use of tap water: By using a specific amount of TWW for irrigating green spaces, the same amount of tap water is avoided. In the absence of specific data on local tap water production, the equivalent process "Tap water {Europe without Switzerland} | market for | APOS, U" available in the Ecoinvent database was used. This dataset includes a tap water treatment plant (a mix of technologies) that pumps tap water into the distribution network, the distribution network itself, and the water losses during transmission;
- Avoided use of chemical fertilizers: TWW contains higher concentrations of nutrients such as nitrogen (N) and phosphorus (P) compared to tap water, resulting in decreased reliance on chemical fertilizers. In the absence of specific data for chemical fertilizers production, equivalent processes "Urea {RoW} | market for urea | APOS, U" and "Single superphosphate {RoW} | market for single superphosphate | APOS, U" available in the Ecoinvent database were used to the avoid urea and phosphate, respectively.

Functional Unit (FU)

The functional unit was defined as the watering of one square meter of lawn area each day (1 m^2. day) in Viseu City, which means a reference flow of 5 L.

2.2.2. Life Cycle Inventory (LCI)

According to ISO 14040 [14], the life cycle inventory is the LCA phase that involves the quantified compilation of inputs and outputs that occur in the process being studied. Table 2 summarizes the normalized flows of the inputs and outputs of the studied system. The quantity of chemical fertilizers avoided and emissions to the river and soil were determined by multiplying the respective values for each substance listed in Table 1 by 5 L of TWW. The average transport distance was calculated from Figure 1, and the electricity data were obtained from the WWTP management office. The background data were obtained from the Ecoinvent database using the same process as that registered in Table 2. Using the SimaPro 9.6.01 software, the life cycle inventory data were calculated, which served as the basis for further impact assessments as described later.

Table 2. Data table for a functional unit (1 m^2.day of lawn irrigation).

Inputs/Outputs	Amount	Equivalent Process in Ecoinvent Database
Inputs from technosphere:		
TWW	5.00	
Transport (kg.km)	56.10	Transport, freight, lorry 16–32 metric ton, euro5 {RoW}	market for transport, freight, lorry 16–32 metric ton, EURO5	APOS, U
Electricity—Pumps (Wh)	0.764	Electricity Mix, AC, consumption mix, at consumer, 230V, PT S

Table 2. *Cont.*

Inputs/Outputs	Amount	Equivalent Process in Ecoinvent Database
Avoided Products		
Irrigation with tap water (m^2)	1.00	Tap water {Europe without Switzerland} | market for | APOS, U
TWW to the river (L)	5.00	
N-based fertilizer (mg)	13.69	Urea {RoW} | market for urea | APOS, U
P-based fertilizer (mg)	2.74	Single superphosphate {RoW} | market for single superphosphate | APOS, U
Atmospheric emissions		
NH_3 [a] (mg)	13.84	
Direct N_2O [b] (mg)	6.59	
Indirect N_2O [b] (mg)	0.13	
NO_x [c] (mg)	1.38	
Leaching to groundwater		
Nitrate [d] (mg)	54.18	
Phosphorus [e] (mg)	0.018	
Emissions to the soil		
Hydrocarbons (mg)	20.50	
Aluminum (mg Al)	0.15	
Arsenic (mg As)	0.05	
Lead (mg Pb)	0.05	
Copper (mg Cu)	0.28	
Chromium (mg Cr)	0.02	
Iron (mg Fe)	0.50	
Mercury (mg Hg)	0.04	
Nickel (mg Ni)	0.05	
Zinc (mg Zn)	1.10	

[a] The emission model [23]. [b] The emission model [24]. [c] The emission model [25]. [d] The Smaling [26] model proposed by Roy et al. [27]. [e] The SALCA-P model summarised and used by Nemecek and Schnetzer [28].

2.2.3. Life Cycle Impact Assessment (LCIA)

LCIA is the phase that evaluates the impacts of life cycle inventory data within various categories by classification and characterization. To assess the environmental impact, the ReCiPe 2016 method was selected because it allows environmental indicators to be obtained at the midpoint and endpoint levels, as mentioned before, and is currently the most used in LCA studies. At the midpoint level, it presents 18 impact categories: climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion. At the endpoint level, it presents three damage categories: human health, ecosystems, and resource availability. Damage to human health is expressed in Disability-Adjusted Life Years (DALYs), which measure the number of healthy years lost owing to a disabling condition. Damage to ecosystems is expressed in species.yr and represents the loss of species in a given area. The damage to resources is expressed in US Dollars (USD 2013), which represents the excess cost of producing resources in a given future time, assuming constant annual production and considering a discount rate of 3%.

The advantage of the ReCiPe method is that it offers detailed midpoint indicators and integrates these into broader endpoint categories, providing a holistic view of potential impacts. Despite the availability of various methods (TRACI, CML, ILCD, etc.), ReCiPe's robustness, comprehensiveness, and adaptability make it the most widely used LCIA method in LCA studies today [29,30].

To evaluate the comparative significance of each product system indicator outcome, a normalized environmental profile was established. According to the guidelines set forth in ISO 14044:2006 [15], normalization involves dividing the result of an indicator by a chosen reference value. The reference values employed in the ReciPe method are the aggregate inflows and outflows per global inhabitant for the year 2010, which serves as the point of reference.

As previously mentioned, in LCI, SimaPro software was utilized to convert the inventory data into an environmental profile, as detailed subsequently.

3. Results

Considering all the LCA data, it was possible to arrive at the results presented in Figure 3 from SimaPro, which shows the impacts of reusing treated wastewater for irrigation of Viseu's lawns according to each impact category.

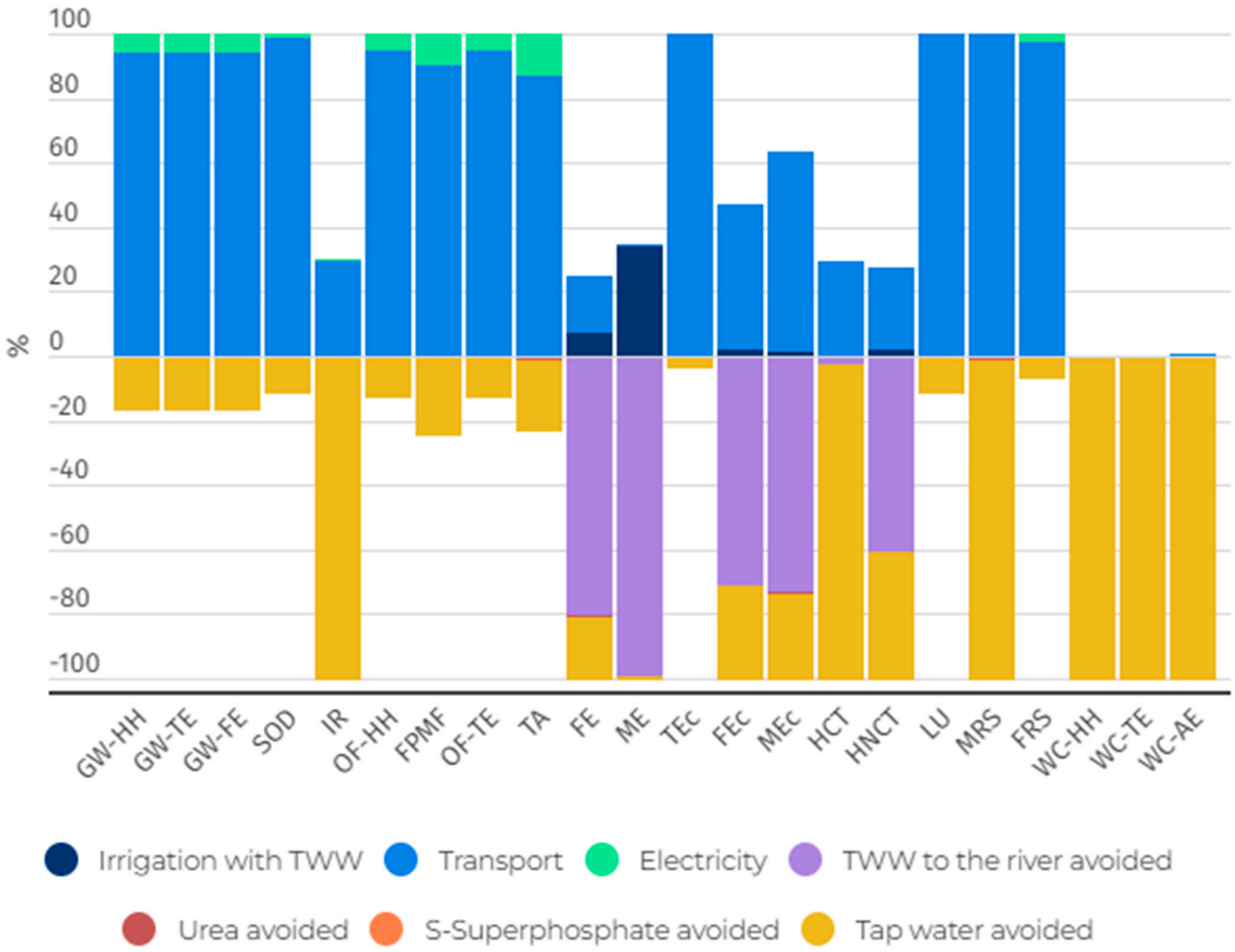


Figure 3. Environmental profile of FU using the method ReCiPe 2016 Endpoint (H) V1.09/World (2010) H/A/Characterisation. Acronyms: GW−HH: global warming, human health; GW −TE: global warming, terrestrial ecosystems; GW−FE: global warming, freshwater ecosystems; SOD: stratospheric ozone depletion; IR: ionizing radiation; OF−HH: ozone formation, human health; FPMF: fine particulate matter formation; OF−TE: ozone formation, terrestrial ecosystems; TA: terrestrial acidification; FE: freshwater eutrophication; ME: marine eutrophication; TEc: terrestrial ecotoxicity; FEc: freshwater ecotoxicity; MEc: marine ecotoxicity; HCT: human carcinogenic toxicity; HNCT: human non-carcinogenic toxicity; LU: land use; MRS: mineral resource scarcity; FRS: fossil resource scarcity; WC−HH: water consumption, human health; WC−TE: water consumption, terrestrial ecosystem; WC−AE: water consumption, aquatic ecosystems.

Of the 22 impact categories analyzed, 11 presented results with negative values, which represents environmentally favorable results. Among these, eutrophication, human toxicity, and water consumption stand out. These environmentally friendly results are mainly linked to the positive impacts arising from the two stages of the process: tap water avoidance and TWW to river avoidance.

The other categories presented environmentally unfavorable results, mainly due to the influence of negative impacts arising from the transport and electricity stages, as can be seen with the impact categories of global warming potential and terrestrial acidification.

The scarcity of the mineral resources category is the only one that presents significant favorable and unfavorable results during the process because it is strongly influenced by the transport and tap water avoidance stages.

By analyzing the results from the damage assessment of environmental indicators at the final level (Figure 4), it is possible to observe that, for the human health and ecosystem categories, in general, they produce damage with negative values of −20% and −40%, respectively. This means that it produces favorable environmental impacts that are greater than unfavorable ones, bringing environmental benefits in these categories.

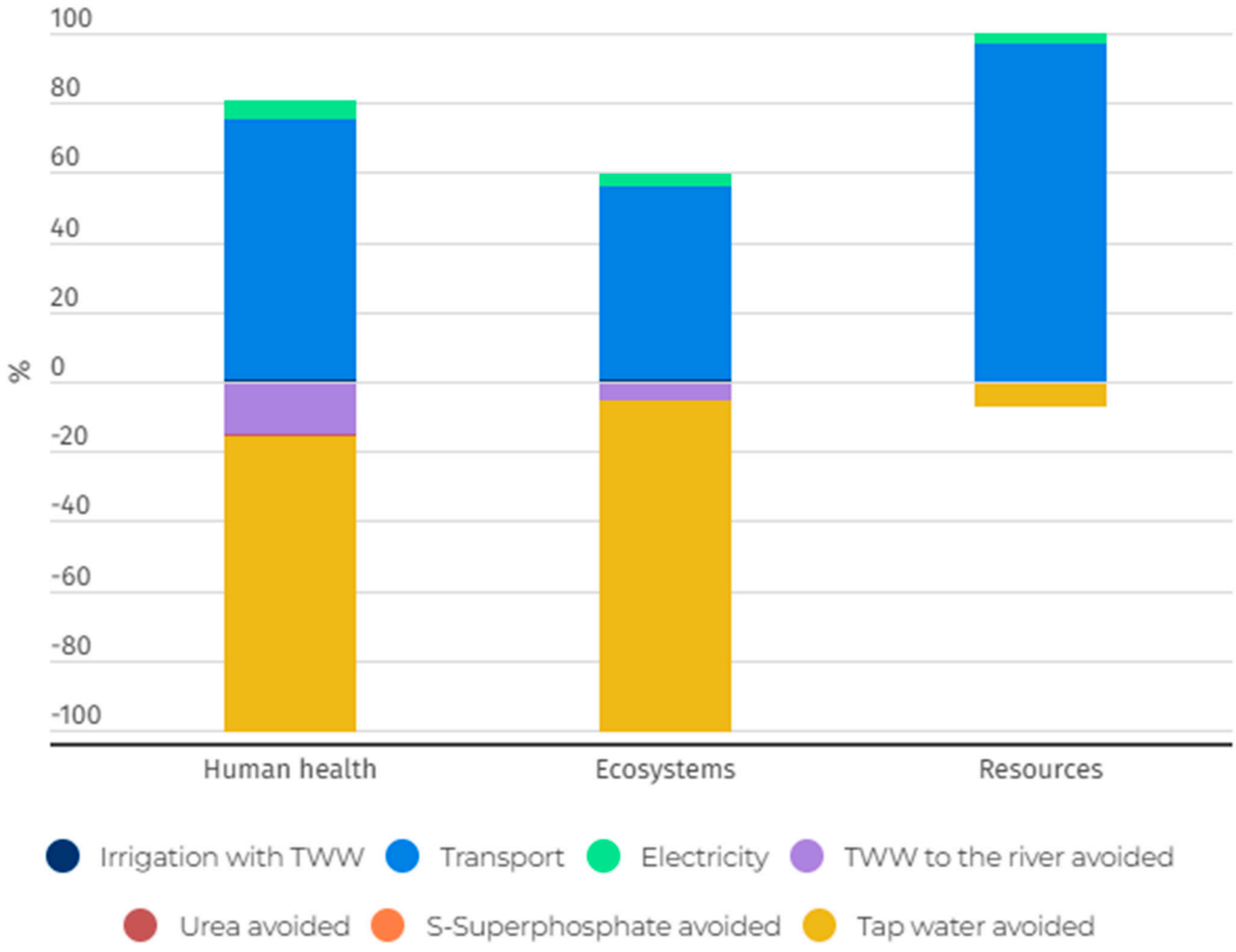


Figure 4. Environmental profile of FU using the method ReCiPe 2016 Endpoint (H) V1.09/World (2010) H/A/Damage assessment.

For the resource indicator, the damage assessment reached a value of 93.4%, which represents an unfavorable environmental impact for this category.

The steps that stood out in influencing damage assessment were the same as those previously described in the characterization. Transport and electricity produced unfavorable environmental impacts, tap water was avoided, and TWW to the river avoided producing beneficial environmental impacts.

Figure 5 shows the normalized environmental profile of the FU. It is an optional element of LCA that is helpful in providing and communicating information on the relative significance of indicator results. Based on the normalization results, it is possible to state that the human health indicator is what produces the most relevant impacts for this project, producing net damage equivalent to approximately -1.33×10^{-8} hab.eq.

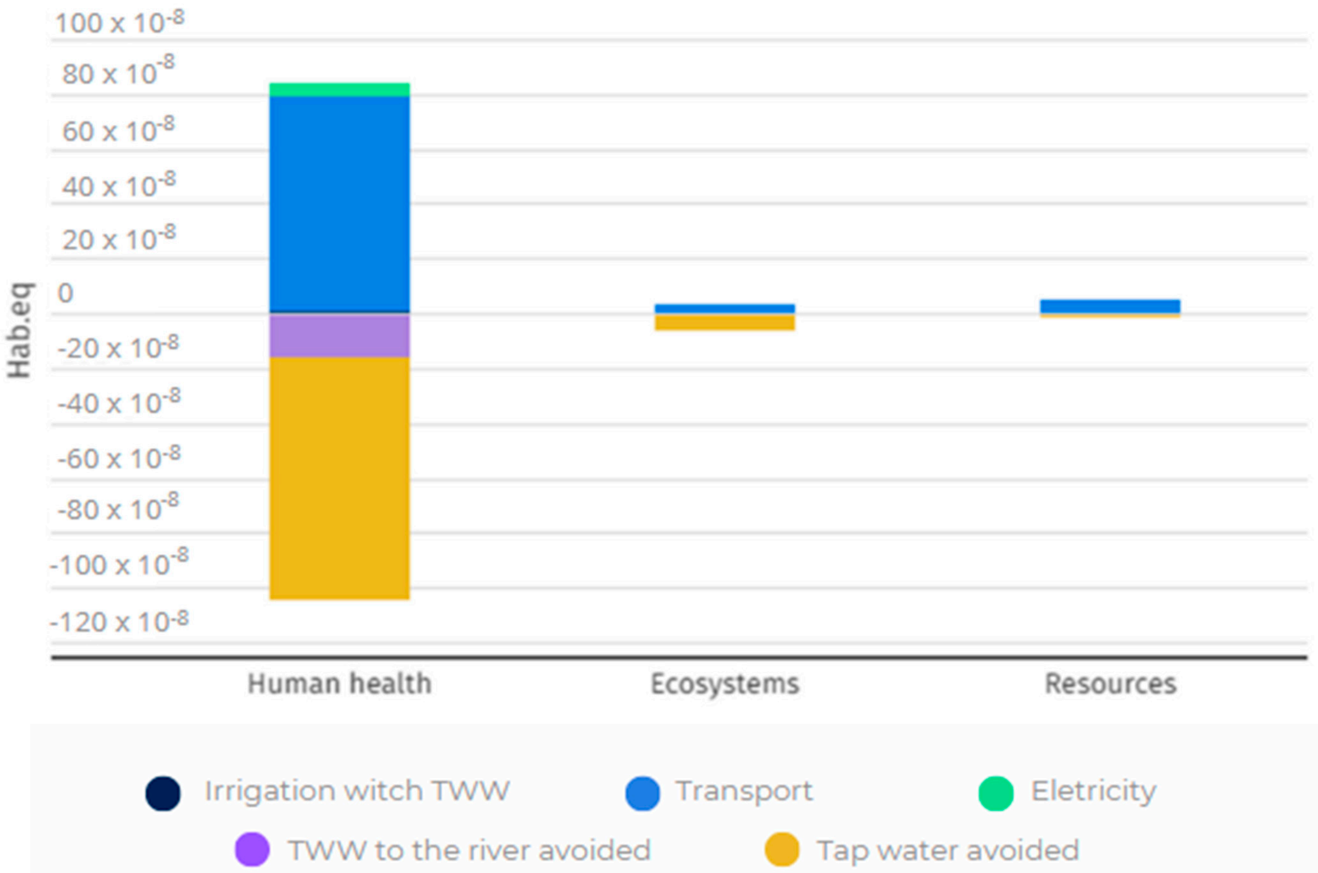


Figure 5. Normalized environmental profile of FU using the method ReCiPe 2016 Endpoint (H) V1.09/World (2010) H/A/Normalisation.

For ecosystems and resources, the damage has a similar relevance, with the result for ecosystems with negative values higher than positive values indicating a favorable environmental impact, while for resources, only positive values appear, demonstrating an unfavorable environmental impact.

To present the outcomes of the study to internal audiences, a single score was used, as illustrated in Figure 6. Weighting is a discretionary aspect that enables the consolidation of normalized results across various impact categories. By default, the hierarchist version of the ReCiPe with average weighting was selected. In general, the choices made within the hierarchist version of ReCiPe are widely accepted from both scientific and political perspectives [31].

For human health and ecosystems, thanks mainly to the tap water avoided stage, the favorable results for the environment outweigh the unfavorable ones, totaling approximately −80 µPt and −8 µPt, respectively.

The results were different for each resource category. In this category, environmental damage is greater, mainly due to the transport stage, which impacts all categories but stands out in terms of resources, totaling 10 µPt.

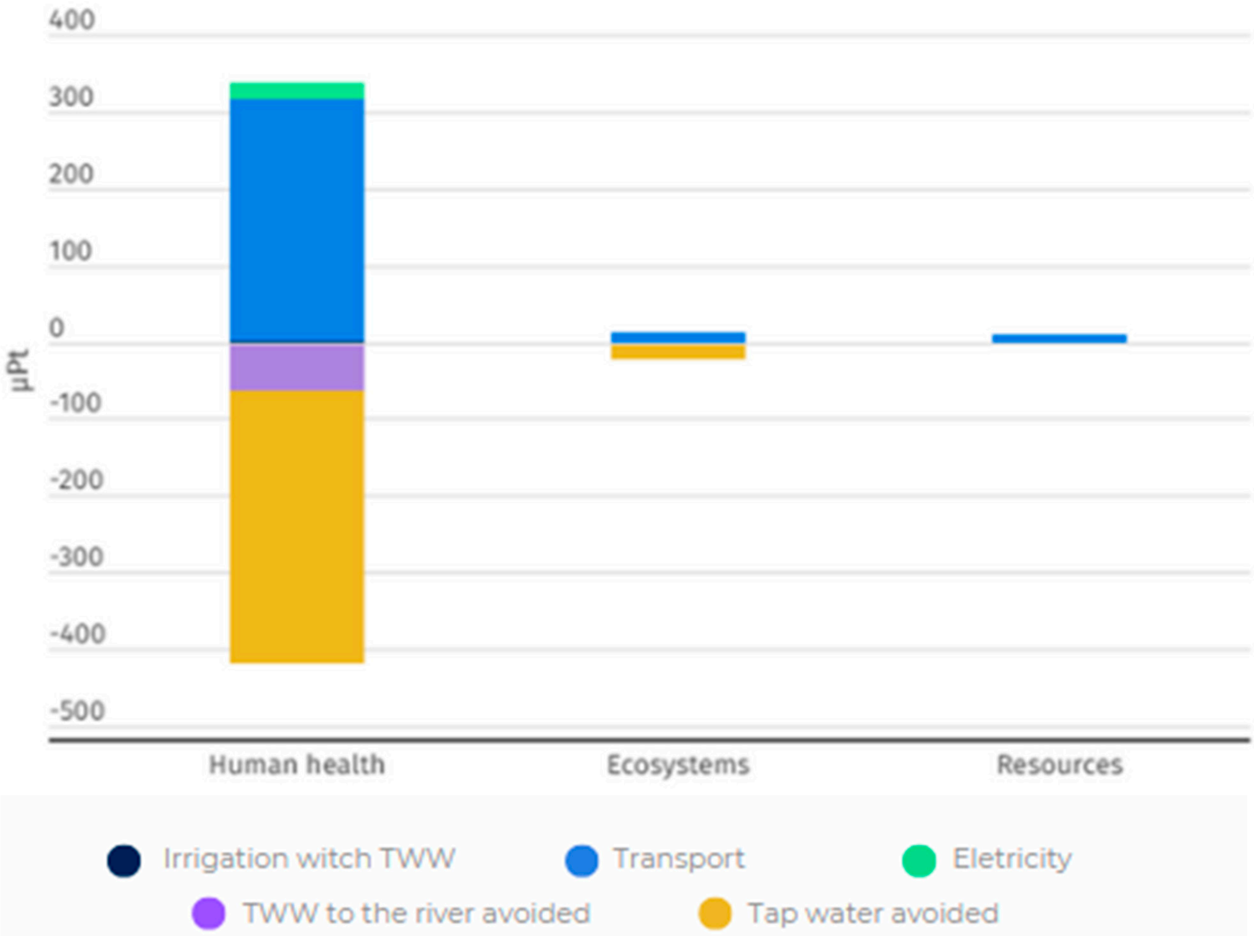


Figure 6. Environmental score of FU using the method ReCiPe 2016 Endpoint (H) V1.09/World (2010) H/A/Single score.

4. Discussion

Water is an abundant biotic resource at a global level, but it can be a scarce resource, both in terms of quality and abundance, at certain times of the year and at a local level. This is what happens in the region of Viseu under study, mainly in the summer season, as previously mentioned, so its management has become increasingly demanding.

The LCA results demonstrated that using TWW instead of tap water to irrigate lawns is environmentally viable and has a favorable impact on human health and ecosystem damage categories, as well as an unfavorable impact in terms of resource damage. These results are related to tap water irrigation and TWW emissions during the river phases. Similar results were obtained by [22] in the LCA study of TWW for irrigation in Trinitapoli—a water-scarce region in southern Italy.

Tap water avoids one of the steps that most impact the entire water reuse process, as it directly helps to combat water scarcity, helping not only to reduce pressure on traditional water sources but also to the economic and environmental sustainability of populations of this resource [32]. According to Debarre et al. [33], water insecurity affects human health, causing growth and development problems in children exposed to poor-quality water due to water scarcity. The safety regarding the quality of the TWW used in this project is guaranteed, as according to Santos and Brás [21], according to the risk assessment carried out, the risks associated with the reuse of these waters are considered negligible, both for public health and water resources.

The TWW to the river avoided stage also had a favorable impact on the environment, as it presented results with negative values. The emission of treated effluents into waterways can harm water quality by altering the nutrient levels, organic contaminants, water temperature, and dissolved oxygen levels. All these factors can negatively affect the local ecosystem and lead to a loss of biodiversity [34].

For the resources category, negative environmental impacts are associated with the TWW transport stages and the consumption of electricity to fill the tanker truck. The water reuse project scenario has major impacts related to transport because, unlike the current scenario with the use of tap water, it will be necessary to fetch water from the WWTP (about 10 km from the center of Viseu) and return to irrigation, which causes environmental damage. According to Arduin et al. [35], this process can contribute up to approximately 30% of the total impact depending on the type of transport and the material to be transported. According to a sensibility analysis, the influence of transport on the impacts associated with the water reuse scenario is significant, as irrigation with TWW is only viable at distances of up to 12.5 km (leaving the WWTP), and water reuse is equally or more harmful to the use of piped water for irrigation.

Electricity consumption also plays an important role in producing negative environmental impacts. Electricity consumption can negatively increase environmental impacts as it is correlated with environmental degradation and carbon emissions. According to Jahanger et al. [36], electricity consumption affects the carbon footprint, intensifying the ecological footprint of many countries.

When comparing the results of this study with studies conducted in the Mediterranean region [37,38], they are similar, identifying the energy consumed for the pumping and distribution of reused water as the main source of environmental impact, making local geography and the distance between treatment and consumer critical aspects to be considered in the planning of the urban water cycle.

The addition of chemical fertilizers, whether N- or P-based, differed slightly regardless of the water used. This is because, for the reuse of water, mainly for irrigation of garden areas, a series of treatments are necessary to reduce the concentration of pollutants in these waters, namely N and P, thus guaranteeing health and environmental safety [39]. TWW treated by MBR ultrafiltration showed an approximately 97% reduction in NH_4^+-N and a 76.4% reduction in total phosphorus [40].

The integration of water reuse into irrigation strategies aligns with the concept of a circular economy, offering a sustainable solution to the challenges of water scarcity and supporting economic development objectives [41]. The concept of a Circular Water Economy (CWE) encompasses the reuse, recycling, and recovery of water resources in its principles and has been growing globally as a sustainable approach to water management.

It is still possible to assert that the use of treated wastewater (TWW) for irrigation can bring benefits to the receiving ecosystem. Studies reported by Silva and Brás [42] on the toxicity assessment of TWW demonstrated the absence of negative effects. On the contrary, an increase in the growth of Lemna minor was observed in the presence of the treated effluent compared to the control, along with an increase in chlorophyll a content. Additionally, germination indices were higher than those observed in the control, indicating the absence of effluent toxicity.

The main limitations of this study that can impact the results are the tap water production, transport of TWW, and electricity use. For tap water, a dataset was used that included a tap water treatment plant with a mix of treatment technologies—conventional, conventional with biological, direct filtration, microstrainer, ultrafiltration, underground water with chemical, underground water with disinfection, and underground water without treatment. The environmental score for a conventional with biological treatment could be about 24% higher than for a direct filtration treatment.

The transport process for TWW utilized a 16–32 metric ton Euro 5 truck (European emissions standards). If a Euro 6 or electric truck had been used, the environmental score would have been better. Another option that is environmentally favorable is the construction of a plumbing system that transports treated water from the WWTP to the center of Viseu, significantly reducing the distance traveled by tanker trucks during irrigation.

The dataset used for electricity represented the average Portuguese electricity mix for the reference year 2008. Today and in the future, the electricity mix will be cleaner, with more renewable energy than in 2008, which will improve the environmental score.

With proof of the feasibility of reusing treated wastewater for irrigation of green spaces, it is possible to indicate this as an important action for sustainable water management in Viseu, in accordance with the new Water Reuse Regulation of the European Commission, which will encourage circular approaches to water reuse in agriculture [43].

5. Conclusions

According to the LCA findings, utilizing treated wastewater (TWW) for garden irrigation is generally beneficial from an environmental standpoint. Although this may result in negative consequences for resource depletion, other impact indicators, such as human health and ecosystems, demonstrate favorable outcomes.

Specific processes that contribute to the positive results include the avoidance of tap water usage and emissions to the river, whereas electricity consumption and transport processes are the primary contributors to environmental damage.

Furthermore, the transport of TWW was identified as a significant process, indicating that using TWW for lawn irrigation is only environmentally advantageous for locations within 12.5 km from the WWTP. In other locations, the use of nearby tap water is recommended. However, when considering the impact of water consumption on human health and terrestrial and aquatic ecosystems, it is preferable to use treated wastewater for lawn irrigation.

The use of TWW for irrigating green spaces positively impacts the city of Viseu, resulting in an annual savings of approximately 345,480 m^3 of tap water. This measure is especially significant during the summer months when the city faces a water deficit due to drought. With this savings of tap water, the resource can be redirected to other activities of considerable importance.

In terms of future possibilities, it is anticipated that, as environmental impacts in energy production and transport continue to decrease, the use of TWW for irrigation of all green spaces in the city of Viseu will become an increasingly favorable option from an environmental point of view, thus contributing to the concept of a circular economy.

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References

1. Pokhrel, Y.; Felfelani, F.; Satoh, Y.; Boulange, J.; Burek, P.; Gädeke, A.; Gerten, D.; Gosling, S.N.; Grillakis, M.; Gudmundsson, L. Global terrestrial water storage and drought severity under climate change. *Nat. Clim. Chang.* **2021**, *11*, 226–233. [CrossRef]
2. Schwaller, C.; Keller, Y.; Helmreich, B.; Drewes, J.E. Estimating the agricultural irrigation demand for planning of non-potable water reuse projects. *Agric. Water Manag.* **2021**, *244*, 106529. [CrossRef]
3. Lin, Y.; Xu, H.; Shan, X.; Di, Y.; Zhao, A.; Hu, Y.; Gan, Z. Solar steam generation based on the photothermal effect: From designs to applications, and beyond. *J. Mater. Chem. A* **2019**, *7*, 19203–19227.
4. Eric, M.V.; David, H.; Richard, J.; Kaner, B.; Wu, J.; Wang, J.; Liu, Y.; Rao, U. *Sustainable Desalination and Water Reuse*; Morgan & Claypool Publishers: San Rafael, CA, USA, 2021.

5. Musa, M.; Smith, B.; Sasthav, C.M.; DeSomber, K.; DeNeale, S.; Stewart, K.M.; Marshall, M.; Smith, T.; Irminger, P. *Needs and Opportunities for Testing of Hydropower Technology Innovations; 2022/2462*; Oak Ridge National Laboratory (ORNL): Oak Ridge, TN, USA, 2022.
6. Decree-Law no. 11/2023, February 10, DL n.o 11/2023. 10 February 2023. Available online: https://www.pgdlisboa.pt/leis/lei_mostra_articulado.php?nid=3617&tabela=leis&so_miolo=.2023 (accessed on 30 March 2024).
7. Lv, C.; He, Y.; Zhang, W.; Gu, C.; Li, Y.; Yan, D. Quantitative analysis of eco-economic benefits of urban reclaimed water greening based on emergy theory. *Water Resour. Manag.* **2021**, *35*, 5029–5047. [CrossRef]
8. Boysen, B.; Cristóbal, J.; Hilbig, J.; Güldemund, A.; Schebek, L.; Rudolph, K.U. Economic and environmental assessment of water reuse in industrial parks: Case study based on a Model Industrial Park. *J. Water Reuse Desalination* **2020**, *10*, 475–489. [CrossRef]
9. UN-WATER, (United Nations-Water). Wastewater: The Untapped Resource. United Nations Educational, Scientific and Cultural Organization. 2017. Available online: https://policycommons.net/artifacts/8196309/the-united-nations-world-water-development-report-2017/9106890/ (accessed on 20 February 2024).
10. Rebelo, A.; Amaro, A.B.; Quadrado, F. Water Reuse: A Risk Assessment Model for Water Resources. *KnE Mater. Sci.* **2022**, 193–203. [CrossRef]
11. Brandão, J.M.; Simões, L.M.; Callapez, P.; Magalhães, V. Água em Viseu—desafios de um percurso centenário. In *La Gestión Del Agua En La Península Ibérica (SIGLOS XIX Y XX)*; Matés-Barco, J.M., Bernardo, M.A., Matos, A.C., Eds.; Capitulo 15; Silexediciones: Madrid, Spain, 2022; ISBN 978-84-19661-91-3.
12. EC—European Commission. Relatório Mundial da ONU Sobre o Desenvolvimento da Água de 2017, Águas Residuais: O Recurso Inexplorado—Mundo | ReliefWeb. 2017. Available online: https://reliefweb.int/report/world/2017-un-world-water-development-report-wastewater-untapped-resource. (accessed on 6 April 2024).
13. Águas do Tejo Atlântico, Fábrica de Água. Águas Tejo Atlântico. 2019. Available online: https://www.aguasdotejoatlantico.adp.pt/sites/aguasdotejoatlantico.adp.pt/files/paginas_base/s_educacao/brochura_fabrica_de_agua_-_uma_nova_geracao_de_recursos.pdf. (accessed on 24 June 2024).
14. *ISO 14040;* Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization: London, UK, 2006; British Standards Institution: Hutchings, UK, 2006.
15. *ISO 14044;* Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization: London, UK, 2006; British Standards Institution: Hutchings, UK, 2006.
16. Mehmeti, A.; Canaj, K. Environmental assessment of wastewater treatment and reuse for irrigation: A mini-review of LCA studies. *Resources* **2022**, *11*, 94. [CrossRef]
17. Azeb, L.; Hartani, T.; Aitmouheb, N.; Pradeleix, L.; Hajjaji, N.; Aribi, S. Life cycle assessment of cucumber irrigation: Unplanned water reuse versus groundwater resources in Tipaza (Algeria). *J. Water Reuse Desalination* **2020**, *10*, 227–238. [CrossRef]
18. IPMA. Norma Climatológica–Viseu. 2000–2010. 2022. Available online: https://www.ipma.pt/bin/file.data/climate-normal/cn_81-10_VISEU_CC.pdf. (accessed on 1 April 2024).
19. Azevedo, J.; Gonçalves, A. Manual de boas práticas em espaços verdes. In *Manual de Boas Práticas em Espaços Verdes*; Câmara Municipal de Bragança: Bragança, Portugal, 2010; Available online: https://bibliotecadigital.ipb.pt/handle/10198/2929. (accessed on 26 March 2024).
20. ERSAR. Relatório Anual dos Serviços de Águas e Resíduos em Portugal-Dados Qualidade da Água Baixa. 2022. Available online: https://www.ersar.pt/pt/site-publicacoes/Paginas/edicoes-anuais-do-RASARP.aspx (accessed on 1 May 2023).
21. Santos, L.; Brás, I. *Avaliação de Risco de Reutilização da Água Residual Tratada da ETAR Viseu Sul Para Usos de Regas e Afins*; Green Week IPV 2023—3.° Workshop—Zero Pollution; Polytechnic Institute of Viseu: Viseu, Portugal, 2023.
22. Canaj, K.; Mehmeti, A.; Morrone, D.; Toma, P.; Todorović, M. Life cycle-based evaluation of environmental impacts and external costs of treated wastewater reuse for irrigation: A case study in southern Italy. *J. Clean. Prod.* **2021**, *293*, 126142. [CrossRef]
23. EMEP-EEA. *EEA Air Pollutant Emission Inventory Guidebook 2009—Chapter 4.B Animal Husbandry and Manure Management*; European Environment Agency (EEA): Copenhagen, Denmark, 2009.
24. IPCC. IPCC Guidelines for National Greenhouse Gas Inventories. *Chapter 11: N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application*. 2006. Available online: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf (accessed on 14 March 2024).
25. Nemecek, T.; Kägi, T. *Life Cycle Inventory of Agricultural Production Systems; Data v 2.0*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
26. Smaling, E.M.A. An Agro-Ecological Framework for Integrated Nutrient Management with Special Reference to Kenya. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands, 1993.
27. Roy, R.N.; Misra, R.V.; Lesschen, J.P.; Smaling, E.M.A. *Assessment of Soil Nutrient Balance—Approaches and Methodologies*; FAO Fertilizer and Plant Nutrition Bulletin 14; Food and Agriculture Organization of the United Nations: Rome, Italy, 2003.
28. Nemecek, T.; Schnetzer, J. *Methods of Assessment of Direct Field Emissions for LCIs of Agricultural Production Systems*; Agroscope Reckenholz-Tänikon Research Station ART: Zurich, Switzerland, 2012.
29. Verbitsky, O.; Pushkar, S. Eco-Indicator 99, Recipe and Anova for Evaluating Building Technologies under Lca Uncertainties. *Environ. Eng. Manag. J.* **2018**, *17*, 2549–2559. [CrossRef]
30. Rashedi, A.; Khanam, T. Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method. *Environ. Sci. Pollut. Res.* **2020**, *27*, 29075–29090. [CrossRef] [PubMed]

31. PRé Sustainability, B.V. SimaPro Database Manual Methods Library. 2023. Available online: https://www.researchgate.net/publication/284902588_SimaPro_database_manual_methods_library (accessed on 3 May 2024).
32. Pandey, B.C.; Jagnnath, D.B. Reuse of Treated Wastewater. *IJRASET* **2022**, *10*, 1915–1918. [CrossRef]
33. Debarre, L.; Boulay, A.-M.; Margni, M. Freshwater consumption and domestic water deprivation in LCIA: Revisiting the characterization of human health impacts. *Int. J. Life Cycle Assess.* **2022**, *27*, 740–754. [CrossRef]
34. Hamdhani, H.; Eppehimer, D.E.; Bogan, M.T. Release of treated effluent into streams: A global review of ecological impacts with a consideration of its potential use for environmental flows. *Freshw. Biol.* **2020**, *65*, 1657–1670. [CrossRef]
35. Arduin, R.; Charbuillet, C.; Perry, N. LCA of Recycling Chains: Influence of Transport Modelling. VI Congresso Brasileiro Sobre Gestão Do Ciclo de Vida, 6. 2018. Available online: https://hal.science/hal-01837085/ (accessed on 10 April 2024).
36. Jahanger, A.; Awan, A.; Anwar, A.; Adebayo, T.S. Greening the Brazil, Russia, India, China and South Africa (BRICS) economies: Assessing the impact of electricity consumption, natural resources, and renewable energy on environmental footprint. *Nat. Resour. Forum* **2023**, *47*, 484–503. [CrossRef]
37. Canaj, K.; Morrone, D.; Roma, R.; Boari, F.; Cantore, V. Todorovic, MReclaimed Water for Vineyard Irrigation in a Mediterranean Context: Life Cycle Environmental Impacts, Life Cycle Costs, and Eco-Efficiency. *Água* **2021**, *13*, 2242.
38. Amores, M.J.; Meneses, M.; Pasqualino, J.; Antón, A.; Castells, F. Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. *J. Clean. Prod.* **2013**, *43*, 84–92. [CrossRef]
39. Decree-Law No. 119/2019, August 21, DL n° 119/2019, 21 August 2019. 2019. Available online: https://diariodarepublica.pt/dr/detalhe/decreto-lei/119-2019-124097549 (accessed on 30 March 2024).
40. Li, M.; Cao, C.; Li, Y.; Li, X.; Hu, B.; Wu, Z.; Zhang, P.; Guo, H.; Li, B. In-situ treatment of an end of rivers by autotrophic/heterotrophic nitrification and aerobic denitrification (HN-AD) membrane aerated biofilm reactors (MABRs). *J. Environ. Chem. Eng.* **2023**, *11*, 109303. [CrossRef]
41. Fernandes, L.S.; Galvão, A.; Santos, R.; Monteiro, S. Impact of water reuse on agricultural practices and human health. *Environ. Res.* **2024**, *216*, 114762. [CrossRef] [PubMed]
42. Silva, M.E.F.; Brás, I.P.L. Reuse of Treated Municipal Wastewater: Phytotoxicity Assessment; Book of Abstracts. In Proceedings of the 2nd International Meeting on New Strategies in Bioremediation Processes, Porto, Portugal, 24–25 October 2019; p. 105.
43. COM. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*; European Commission: Brussels, Belgium, 2020.