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Life Cycle Assessment of an Innovative Combined Treatment and Constructed Wetland Technology for the Treatment of Hexachlorocyclohexane-Contaminated Drainage Water in Hajek in the Czech Republic

Maria Bałazińska [1], Paul Bardos [2], Grzegorz Gzyl [1], Vojtech Antos [3], Anna Skalny [1,*] and Tomas Lederer [4]

[1] Water Protection Department, Central Mining Institute—National Research Institute, 40166 Katowice, Poland; mbalazinska@gig.eu (M.B.); ggzyl@gig.eu (G.G.)
[2] r3 Environmental Technology Ltd., Reading RG4 7DH, UK; paul@r3environmental.co.uk
[3] Photon Water Technology s.r.o., 460 01 Liberec, Czech Republic; vojtech.antos@photonwater.com
[4] Department of Environmental Technology, Institute for Nanomaterials, Advanced Technology and Innovation, Technical University of Liberec, 461 17 Liberec, Czech Republic; tomas.lederer@tul.cz
* Correspondence: askalny@gig.eu

Abstract: The paper presents the results of an LCA analysis of the "Wetland+®" technology compared to conventional wastewater treatment technology. Wastewater contaminated with pesticide production residues from lindane was treated. The analysis is based on data from a full-scale Wetland+® installation located in Hajek, the Czech Republic. Conventional wastewater treatment technology was selected as a comparator. For the comparative system, data for the LCA came from design calculations assuming the location of such a system in the same place and function as the Wetland+® technology implemented. The LCA analysis was carried out using system boundaries covering the stages of construction and operation of the systems. The results indicate that with the Wetland+® technology, a system's overall environment burdens are >11 times less than that of conventional wastewater treatment technology.

Keywords: LCA; Wetland+® technology; wastewater treatment technology; lindane contamination; pesticide contamination

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1. Introduction

Areas contaminated with pesticides and their production residues, such as from lindane (gamma hexachlorocyclohexane—gamma-HCH), exist in many places around the world. Impacted areas include dump sites for production wastes and/or sites of former activities of production and storage facilities. HCH isomers bioaccumulate in food chains and are persistent in the environment. Therefore, their potential for causing chronic harm in the long term is high [1]. Very often, impacted sites are complex and intractable problems, for example, in the case of Hajek, the case study site, there are issues of scale and mixed waste disposal with mine spoil. The social, environmental, and economic costs of dealing with the waste deposit (i.e., source management) mean that this will never be attempted in the foreseeable future. Therefore, risk management depends on managing the pathways by which pollutants reach the wider environment and key receptors such as humans. A key, and hitherto unmanaged, pathway in Hajek has been via drainage water leaving the waste area carrying dissolved and suspended contaminants [2]. Dealing with this contaminated water, to "break" the pathway, using conventional water treatment plants has been seen by the public company owning the area as both resource- and energy-intensive.

The European LifePopWat project (Life program—grant agreement no. LIFE18 ENV/CZ/000374) has built and tested a full-scale demonstration of a low-input system, Wetland+®, in Hajek. A spoil heap at the former uranium mining area of Hajek has also been used

as a dump for lindane production residues. Wetland+® combines in-ground treatments with a constructed wetland used as a polishing step. As well as its perceived sustainability advantages, Wetland+® is also seen as offering (1) a technical solution for a remote location where no access to mains services (such as electricity and sewerage) was available and (2) a solution that does not need day-to-day staffing and maintenance, which were also not possible given the treatment site location. Conventional WWTP requires regular maintenance and management load, which may require a rapid response where there is process failure/interruption. This need may be difficult to meet over the decades during which the system has to run at its remote location.

Svermova et al. [3] used qualitative sustainability assessment to compare and contrast the sustainability performance of Wetland+® against conventional water treatment plant. They found Wetland+® to be highly advantageous using an overarching sustainability assessment, compliant with ISO 18504:2017 on sustainable remediation.

The need for performing LCA to evaluate the proposed technologies have been expressed by many recent papers [4,5]. However, the examples of LCA applied to HCH-contaminated water treatment technologies are very rare [6].

The LCA described in this paper was one of the inputs to this sustainability assessment and benchmarks Wetland+® against a conventional water treatment plant design for the Hajek application. This paper is one of the first public-domain examples of an LCA that has been explicitly incorporated into a wide-ranging qualitative sustainability assessment that has included the opinions of multiple technical and local stakeholders [3].

2. Site and Methods

2.1. The Hajek Site

The site in Hajek is a former uranium mining area where lindane production wastes were dumped until 1968. Uranium mining was carried out from the 1960s until 1971. In parallel with uranium mining, kaolin and basalt, and later bentonite, were mined. Between 1966 and 1968, the national authorities decided to dispose of non-saleable isomers and chlorobenzene from lindane (γ-HCH) production into the Hajek mine spoil and tailings. Around 3000–5000 tons of these wastes were dumped in metal drums, in paper packaging, or in bulk. The dump is located in the source area of the Ostrovský Brook.

In 1977, a landslide occurred in the spoil heap over an area of about 10–12 ha, leaving part of lindane chemical waste exposed. The landslide was stabilized by the construction of a weighting bench of crushed aggregate into which a drainage system consisting of pipe drains, which empty to a drainage channel, was incorporated. Since January 1989, concentrations of hexachlorocyclohexane (HCH) isomers and chlorinated benzenes (CBs) have been monitored and documented at the outlet of this drainage system. Since 1991, the site owner has been conducting detailed hydrological, climatological, and hydrochemical monitoring of the site.

The current site owner is the state-owned company DIAMO, which is responsible for the mitigation of the consequences of various mining activities in the Czech Republic. Site ownership has passed through a series of public structures. The original uranium ore-mining company was founded in 1946 and then called Jáchymovské doly. In 1955, after a reorganization, it was renamed the Central Administration for Research and Mining of Radioactive Raw Materials (ÚSVTRS). From 1967, the company existed under the name Czechoslovak Uranium Industry (ČSUP). In 1992, the company was renamed to its current name, DIAMO.

Between 1999 and 2002, DIAMO carried out initial remediation work at the dump site. This work consisted of placing a sealing and covering layer over the landslide area, consisting of 0.3 m depth of bentonite under a 0.45 m layer of heap material. This was then revegetated along with the remainder of the Hajek mining area.

Excavation and treatment of the buried wastes are not currently considered feasible on cost and environmental impact grounds. Leachate and drainage water were collected

from the site and its drains via a ditch that empties to a local water course. Very visible in this ditch is iron contamination (orange) also originating from the site; see Figure 1.

Figure 1. Hajek drainage channel.

Hajek's focus has been on the remediation of the drainage water collected in this ditch. In 2014–2016, four types of remediation technologies were piloted at the site:

- engineered wetland;
- anaerobic biodegradation;
- a permeable reaction barrier using zerovalent iron;
- sorption remediation system.

The Wetland+® system was designed based on these pilot test outcomes and integrates several of the components tested.

2.2. Wetland+® Technology

The Wetland+® technology was jointly developed by the Technical University of Liberec and AQUATEST a.s. It is based on the use of in-ground oxidation–reduction and biosorption stages (Figure 2) as a front end, with a back end using engineered wetland as a polishing step. There are three in-ground treatment stages at the front end. In the first stage, the iron in the contaminated drainage water is oxidized and precipitated out in the form of Fe(III) oxides and hydroxides and drops out as sediment. The second stage uses zerovalent iron (ZVI) to reduce HCH isomers and chlorobenzenes, which achieves partial dechlorination and renders the water anaerobic. The third stage exploits anaerobic biosorption onto a wood chip matrix. Here, remaining chlorinated species are sorbed and subsequently degraded.

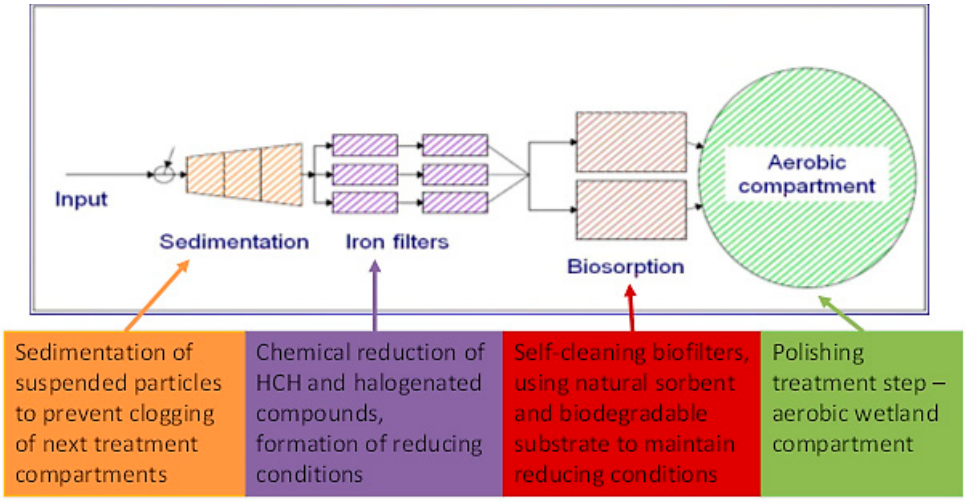

Figure 2. Wetland+® treatment approach.

Within the backend, engineered wetland is used to render the treated water aerobic and polish out any residual organic compounds via sorption and degradation within the wetland's soil/plant root system. Outflow water quality limit values are set by the local regulator.

Wetland+® is not dependent on regular supply of chemicals and energy and exploits nature-based systems, with the main flow led through the system gravity. Only a minor part requires an electric pump to pump water from the new drainage (as it exits from the lower part of the system) to the first part of the technology—sedimentation. The project also foresees regular maintenance of the system and the eventual replacement of the iron charge in the permeable reactive barrier; otherwise, the whole technology is without any further input (Figures 3 and 4).

Figure 3. Wetland + installation in Hajek.

Figure 4. Wetland + installation in Hajek—aerial view.

2.3. Conventional WWTP Technology

A theoretical alternative to Wetland+® in Hajek is to build a water treatment plant for the drainage water treatment. The conventional WWTP used as the comparator is based on a bespoke design commissioned for the Hajek application, shown in Figure 5.

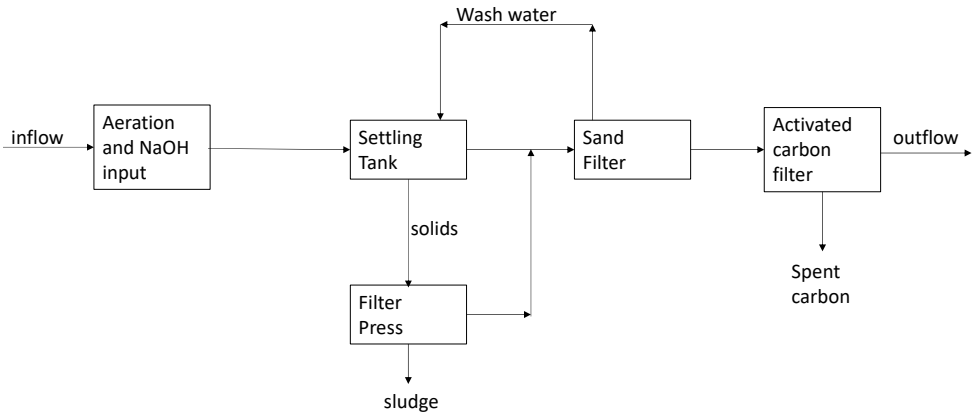

Figure 5. Conventional water treatment plant: flow chart.

This design was used for the estimation of environmental burdens in detail.

2.4. Method

Many environmental assessment techniques can be found in the literature. Among them we can mention Material Flow Analysis (MFA), Material Input Per Service Unit (MIPS), and Life Cycle Assessment (LCA). MFA is a method used to quantify flows and stocks of materials or substances in any complex system. MFA is used to study material or substance flows in various industries or ecosystems [7,8]. MIPS, on the other hand, focuses on the use of resources during the life cycle of a product. This allows one to identify the most resource-consuming processes in order to concentrate efforts on minimizing their impact on the environment [9,10]. LCA, by contrast, is a tool used to assess the potential impact on the environment during the product life cycle, i.e., from the acquisition of

natural resources, through the production and use stages, to its disposal. LCA aims to comprehensively examine the impact of the subject of analysis on the natural environment and natural resources [11–13].

LCA analysis is the only environmental assessment technique mentioned above to take into account not only the use of resources or materials but also emissions resulting from the way they are produced or from how they are used in a specific way. Moreover, it relates the obtained results to their impact on subsequent environmental problems such as acidification, eutrophication, or human toxicity. Optionally, it also groups the mentioned environmental problems within so-called damage categories such as impacts on human health, ecosystems, and natural resources. This allows for a comprehensive interpretation of the results obtained. For this reason, the LCA technique was chosen to carry out the environmental assessment of the Wetland+® technology.

LCA analysis was used to compare the environmental impacts found via Wetland+® technology in Hajek with the WWTP design as a possible alternative. LCA analysis was carried out according to the guidelines contained in the ISO 14040 and ISO 14044 standards [11,12]. The life cycle assessment was carried out in four stages:

- definition of the purpose and scope, including setting the boundaries of the systems and the functional unit;
- inventory analysis (Life Cycle Inventory—LCI);
- impact assessment (Life Cycle Impact Assessment—LCIA);
- interpretation (ISO 14040).

The same functional unit and same system boundaries were used for each alternative. A quantity of 1 m^3 of treated water was chosen as the functional unit (FU), which is a typical approach. For example, Nijdam et al. (1999) used such approach for LCA-based comparison of two techniques for advanced wastewater treatment applied for percolation water from HCH/chlorobenzene-contaminated groundwater [14].

The boundaries of the system described in current paper covered both construction and operation stages (Figure 6). As these were long-term solutions, the analysis assumed a 25-year lifetime for the systems.

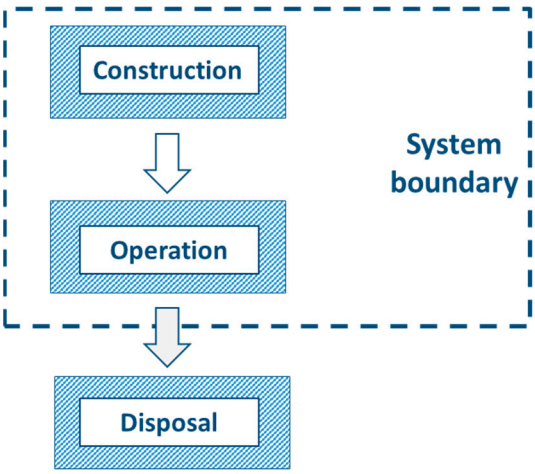

Figure 6. LCA system boundary used for the Wetland+® and WWTP systems.

The input data inventory stage (LCI) for Wetland+® collated actual quantities used during the construction of the physical plant in Hajek and the supplier's predicted values for the operational phase. For the WWTP technology used as a comparator, quantities for both construction and operation were based on predicted values estimated by the WWTP system designer.

This LCA study used ReCiPe 2016, which was developed on the basis of the experience of using the CML and Ecoindicator99 methods. This approach was chosen because ReCiPe 2016 is comprehensive and has had widespread use already in LCA. The LCA analysis was

carried out with ReCiPe Midpoint and Endpoint H/A (Hierarchist/Average) Perspective. The ReCiPe Midpoint method allows the assessment of eighteen impact categories while the ReCiPe Endpoint method additionally allows assessment in three damage categories—impacts on human health, ecosystems, and resources.

ReCiPe life cycle impact assessment includes the following stages: characterization, normalization, grouping, and weighing. During characterization, the values of indicators of impact categories such as particulate matter, global warming, water use, human health, ecosystems, and resources are obtained. The results of the characterization stage are then normalized. Normalization relates the values of the impact category indicators to a reference point. The results obtained as a result of normalization take non-nominated values (i.e., indices independent of a physical characteristic such as mass). The normalized results are then grouped. Grouping assigns impact categories to one or more damage categories, such as human health, ecosystems, or resources. Weighting factors are then used to transform these numerical values based on the perceived importance within each damage category. The weighted impact category indicators are then summed for each damage category.

The category of "human health" is expressed using the DALY (Disability-Adjusted Life Years) unit, which is the sum of shortened years of human life and years of reduced quality as a result of disability.

The category "ecosystems" is described by the unit "species·year", understood as the loss of species during the year.

The "resources" category, in turn, is expressed as a monetary value in dollars, defined as the increase in the cost of obtaining raw materials from harder-to-reach deposits as a consequence of using easily accessible deposits.

These impacts can then be converted into a single measure called ecopoints (Pt). An ecopoint determines a thousandth of the damage a resident of Europe causes per year. The values of the damage category indicators expressed in the same unit allow them to be summed up, finally obtaining a single "LCA value" to describe the technologies being compared.

This LCA was conducted using *SimaPro* software. *SimaPro* is one of the most popular programs for performing LCA analysis. After one enters the data characterizing the analyzed system, *SimaPro* allows them to develop its model. In the next step, the LCIA method is selected, and an environmental assessment is carried out. An important advantage of *SimaPro* is the ability to equip it with the necessary databases to supplement environmental burdens for input or output data. The comparative LCA analysis for Wetland+® technology in relation to WWTP was performed in *SimaPro* version 9.3.0.3, which included numerous databases.

3. Results

Data characterizing the Wetland+® system and WWTP, which were collected at the inventory (input) stage, were verified and adjusted to the needs of LCA. The verification consisted of reconciling the data with experts in order to obtain the appropriate quality in accordance with the ISO 14040 and ISO 14044 standards. In addition, the selected data were adjusted through calculation. For this purpose, literature studies were carried out, during which the missing values for calculations were collected. The calculations allowed obtaining data in the appropriate form required by the *SimaPro* program in which the analysis was performed. The data obtained in this way constituted the input values for the LCIA stage, which was carried out based on the ReCiPe method, ultimately obtaining the results of the LCA analysis.

All LCA analysis results are presented per functional unit (FU) equal to 1 m^3 of treated water. The final results are presented as one quantity expressed in Pt/FU for each system. It is more convenient to compare the environmental effect in the form of a single quantity when comparing systems. The results of the intermediate calculation steps, in turn, express the environmental burden for each impact category. Therefore, they allow for a better

understanding of the impact that the analyzed system will have on another environmental aspect.

As a first step, the ReCiPe Midpoint analysis was performed, and subsequently, so was ReCiPe Endpoint H/A. The tables presenting the results of ReCiPe Midpoint and Endpoint H/A after the characterization stage are included in the Appendix A at the end of the publication in Tables A1–A6. The results for the ReCiPe Endpoint H/A after the weighing step are shown below and used as the basis for the interpretation and discussion of the LCA outcomes. Our not including the results of ReCiPe Midpoint and Endpoint H/A after the characterization stage in the main part of the paper is intentional and has a purpose: so that the interpretation of the results remains clear for the reader. There was a possibility that an excess of discussing different types of results could affect the readability of the paper.

The results for the construction and operation stages have been presented both separately and as an integrated whole. Figure 7 presents the environmental effects for the Wetland+® construction phase compared to the WWTP.

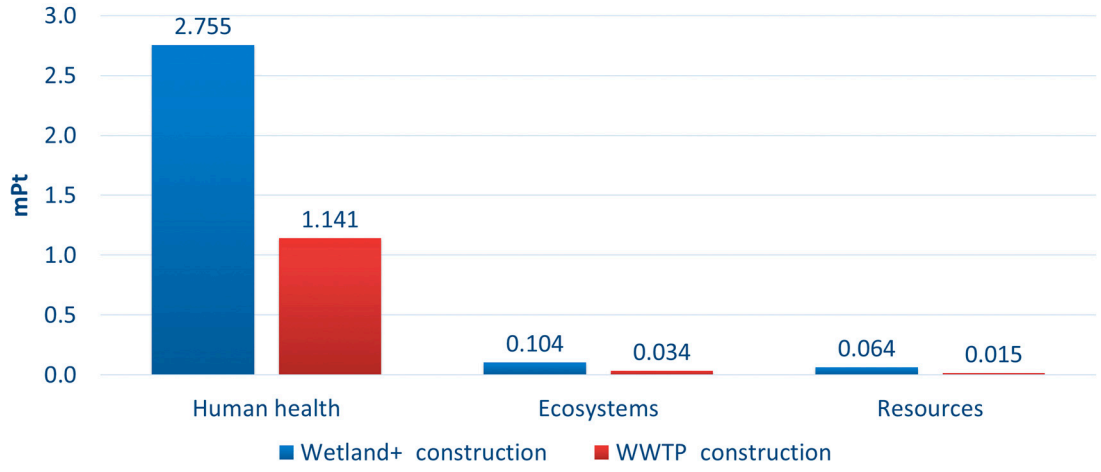

Figure 7. Comparison of ReCiPe Endpoint H/A results after the weighing stage for the construction stage of the Wetland+® and WWTP systems.

During construction, Wetland+® shows a higher environmental burden compared to WWTP within each damage category, i.e., for human health, ecosystems, and resources. The results obtained for human health for both technologies significantly exceed the environmental effects for ecosystems and resources. In this study, for Wetland+®, the burden assigned to human health was 2.755 mPt/FU and was more than twice as high as for the same category of WWTP technology (1.141 mPt/FU). Figure 8 shows the environmental effects for the subsequent segments of the Wetland+® system, which allows one to indicate the area with the highest values.

Segment B, i.e., the PRB, has the highest environmental impact among all segments of the Wetland+® system. Figure 9 shows the environmental burden for the subsequent components of Segment B of the Wetland+® system.

In segment B of Wetland+® technology, the highest values of environmental effects are generated by perforated PVC pipes (DN300), concrete, standard PVC pipes (DN300), and prefabricated concrete.

The overall LCA outcomes for the operational stage are shown in Figure 10 for the two techniques.

During the operational phase, the WWTP system shows a higher environmental burden than the Wetland+® system for all damage categories. These values are many times higher for the WWTP system than for Wetland+®. The environmental effect for WWTP within human health stands out significantly from other values. This value reached 91.687 mPt/FU in this study and was more than seventeen times higher than the same

value for the Wetland+® system. Figure 11 shows the quantities that make up the obtained environmental effect for the operation of the WWTP system.

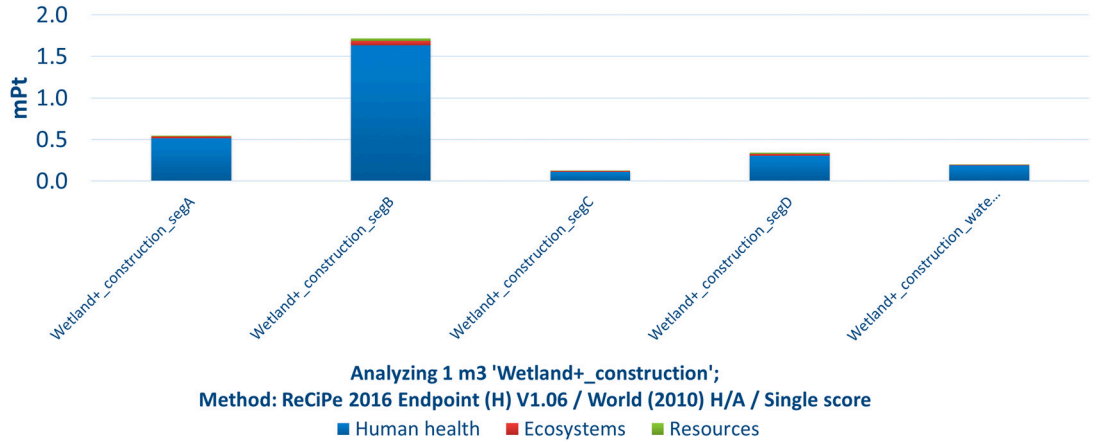

Figure 8. Summary of the environmental effects of ReCiPe Endpoint H/A after the weighting stage for the subsequent segments of the Wetland+® system construction.

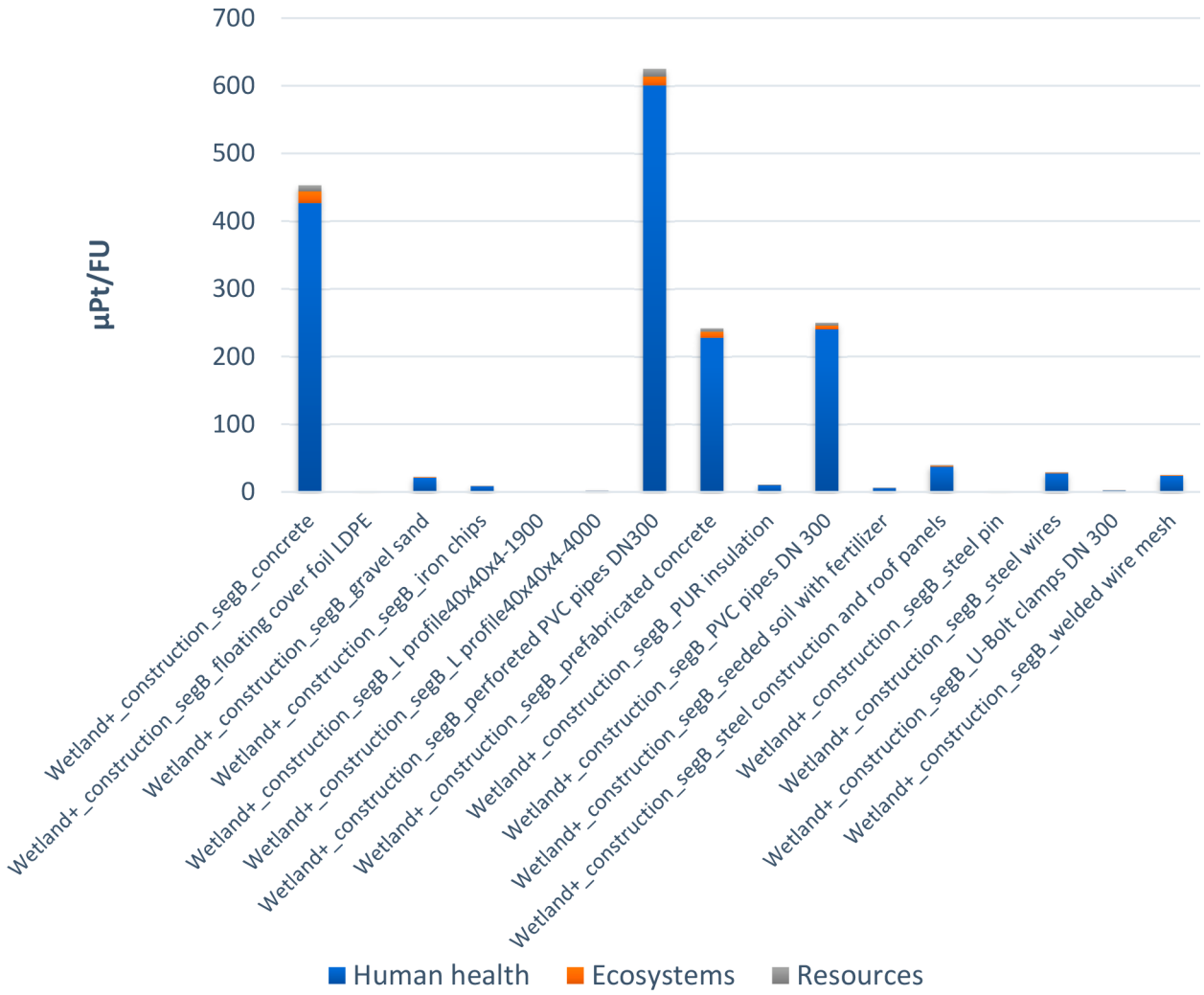

Figure 9. Summary of environmental effects of ReCiPe Endpoint H/A after the weighing stage for subsequent components of segment B of the Wetland+® system.

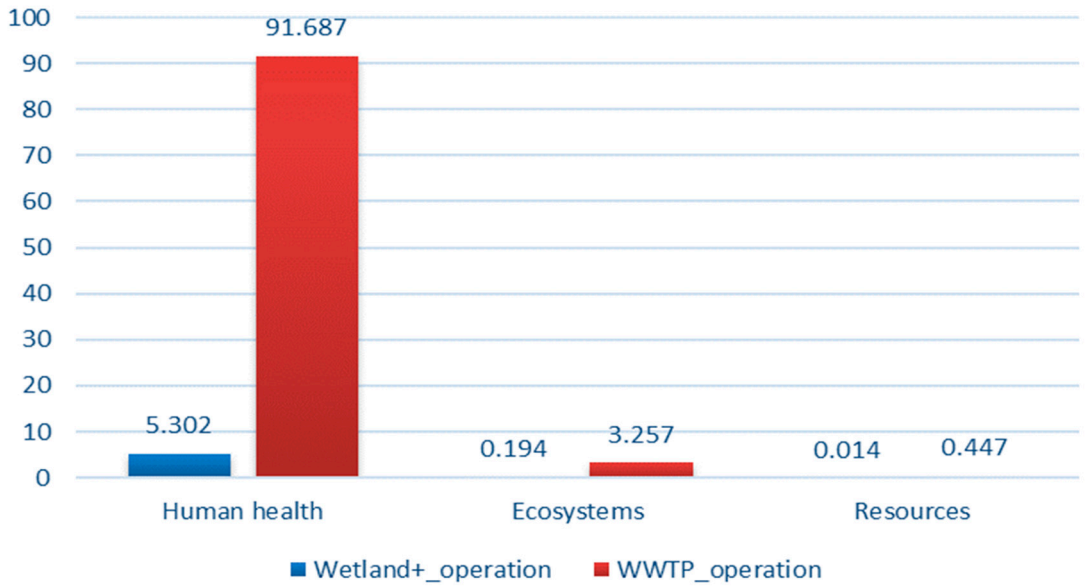

Figure 10. Comparison of ReCiPe Endpoint H/A results after the weighing stage for the operational phase of the Wetland+® and WWTP systems.

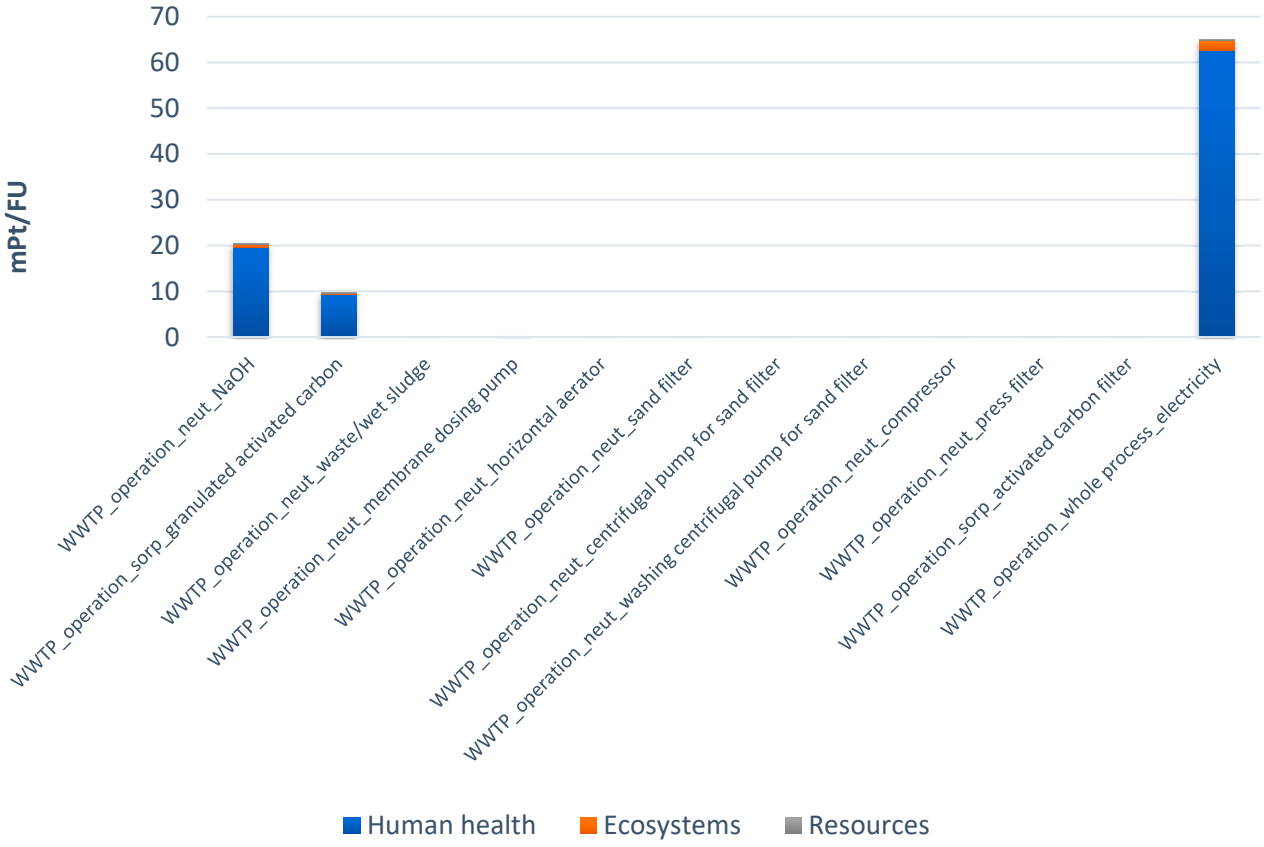

Figure 11. Summary of environmental effects of ReCiPe Endpoint H/A after the weighing stage for WWTP system operation.

The environmental burden of the WWTP system is most affected by the electricity consumed, followed by the consumption of NaOH and granulated activated carbon. The value assigned to electricity is several times higher than the burden assigned to the second highest, NaOH. As a comparison, Figure 12 presents the environmental effects of the components of the Wetland+® system operation.

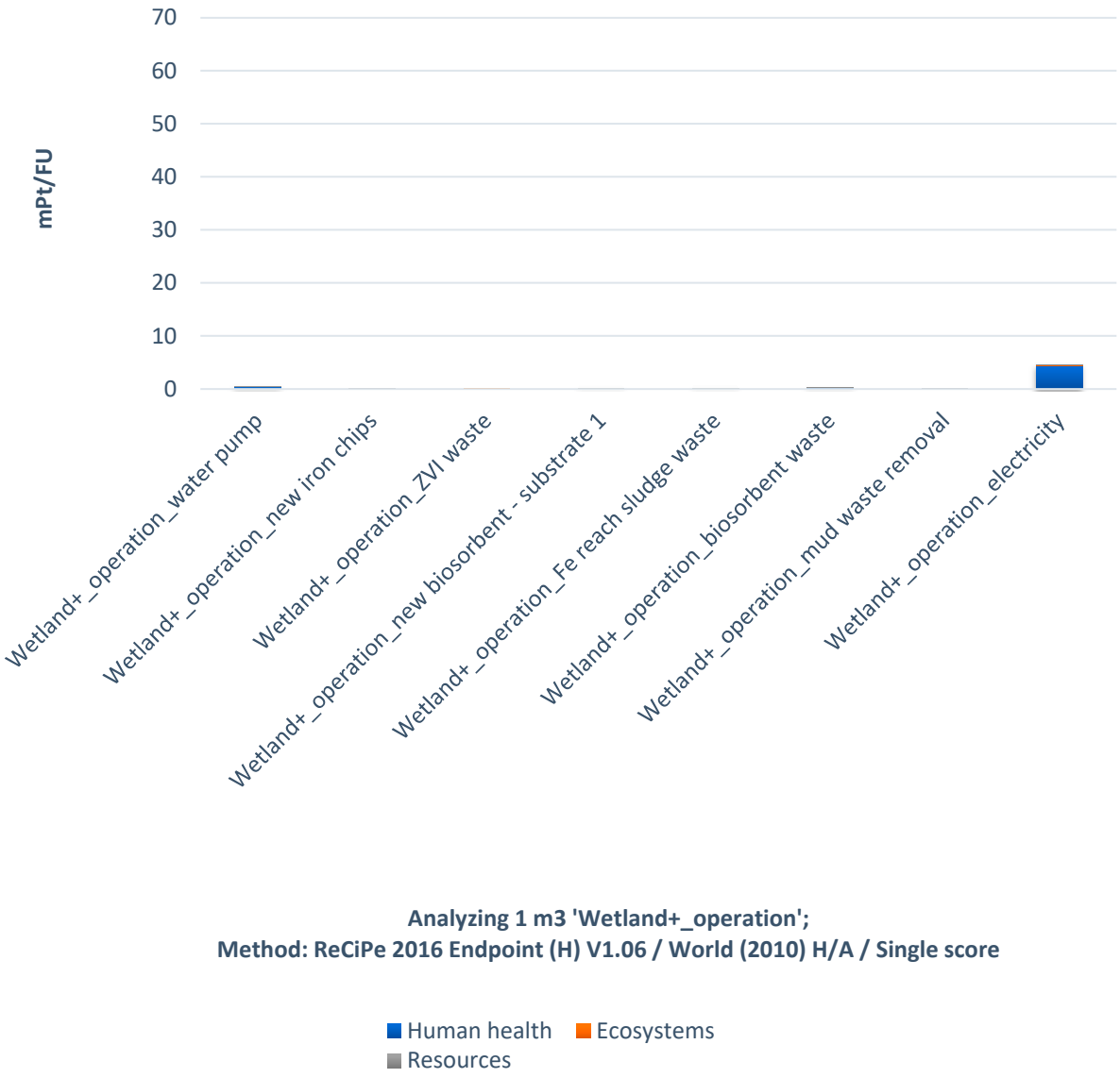

Figure 12. List of environmental burdens of ReCiPe Endpoint H/A after the weighing stage for the operation of the Wetland+® system.

The largest contributor to the environmental effect of the operation stage of Wetland+® is also the consumption of electricity. The remaining quantities are characterized by an environmental burden that is several times lower. However, in all cases, the burdens are substantially lower than for WWTP.

Figure 13 shows a comparison of environmental effects for two systems combined over both the construction and operational phases. The overall environmental impacts are far higher for WWTP than for Wetland+®, reflecting the dominance of operational impacts over a 25-year working period.

The greater impacts of WWTP are true both on an overall basis and within all of the individual damage categories such as human health, ecosystems, or resources. The level of value for human health in relation to ecosystems and resources is many times higher for both the Wetland+® and WWTP systems. However, in the case of WWTP, the environmental effect within human health is noteworthy; this has a value of 92.828 mPt/FU and significantly differs from the value set for all other damage categories for both systems. It takes values more than eleven times higher than the human health category for the Wetland+® system (8.057 mPt/FU). Finally, the total environmental burden for the Wetland+® system amounts to 8.434 mPt/FU while, for the WWTP system, it is 96.581 mPt/FU.

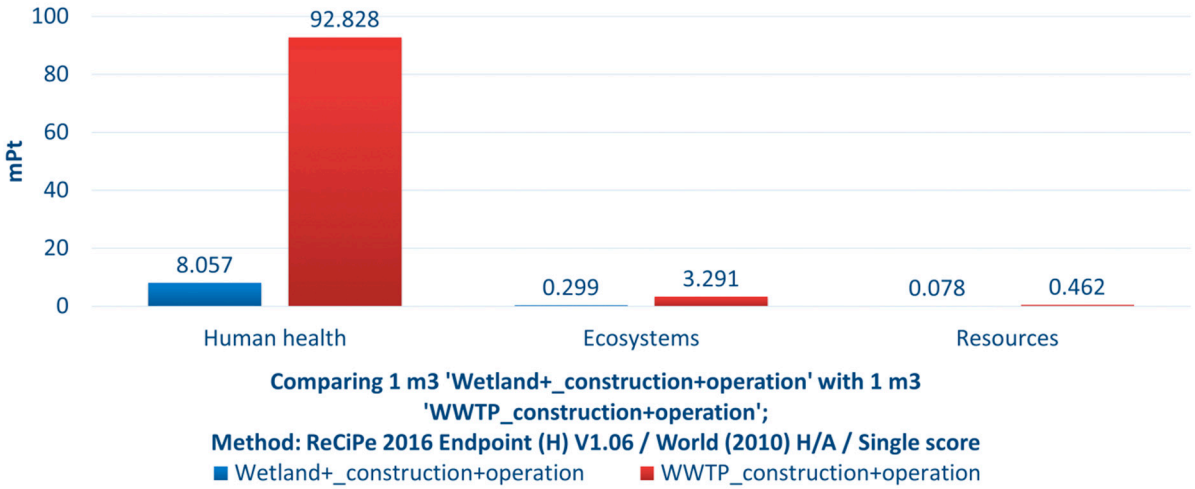

Figure 13. Comparison of ReCiPe Endpoint H/A results after the weighting stage for the total Wetland+® and WWTP system boundaries covering the construction and operational stages.

4. Discussion and Conclusions

At the construction stage, the Wetland+® technology burdens the environment more than the WWTP system. However, its burdens are substantially lower during the operational phase, so on an overall basis, Wetland+® presents a far more environmentally benign approach.

The major contributor to Wetland+® impacts during the construction phase is the installation of the in-ground treatment systems (Segment B), in particular, the use of zerovalent iron, which has the highest environmental effect of all of the Wetland+® stages. Other Wetland+® in-ground treatment components carrying large environmental burdens are its use of PVC pipes and concrete. These impacts could be greatly reduced in future Wetland+® configurations by replacing PVC pipes and concrete with materials with similar properties but lower environmental effects.

In the case of the operating stage of the systems, electricity consumption is the largest contributor to the environmental effect obtained for both approaches. However, it is worth noting the scale of values. The environmental effect for electricity consumption for the Wetland+® system was over fourteen times lower than that of the WWTP system in this study, reflecting the far greater energy demand of the WWTP system. The Wetland+® technology consumes 328,500 kWh over its 25-year lifetime, while the WWTP system consumes 4,730,400 kWh, which is more than fourteen times more.

Wetland+® technology shows a higher environmental burden during the initial period associated with the construction phase. After this time, when the system starts working and the exploitation stage begins, the WWTP system burdens the environment many times more. Overall, the Wetland+® technology is more environmentally friendly than the alternative WWTP system.

The LCA was predicated on the basis of supply from the Czech national grid. However, the environmental costs of electricity vary from country to country depending on the energy mix for its production. Therefore, it was decided to analyze how LCA outcomes might vary depending on the country where Wetland+® was located as a function of the energy mix for the electricity supply in that country. France, Germany, Poland, and Spain were considered as these have a range of energy mixes and are initial markets for Wetland+® because of the presence of significant lindane waste sites in these countries. For example, France's energy mix is seen as environmentally friendly as most of its electricity is generated by nuclear power plants. Poland's energy mix, on the other hand, is mainly based on coal-fired generating units [15]. The results of the analysis are shown in Figure 14.

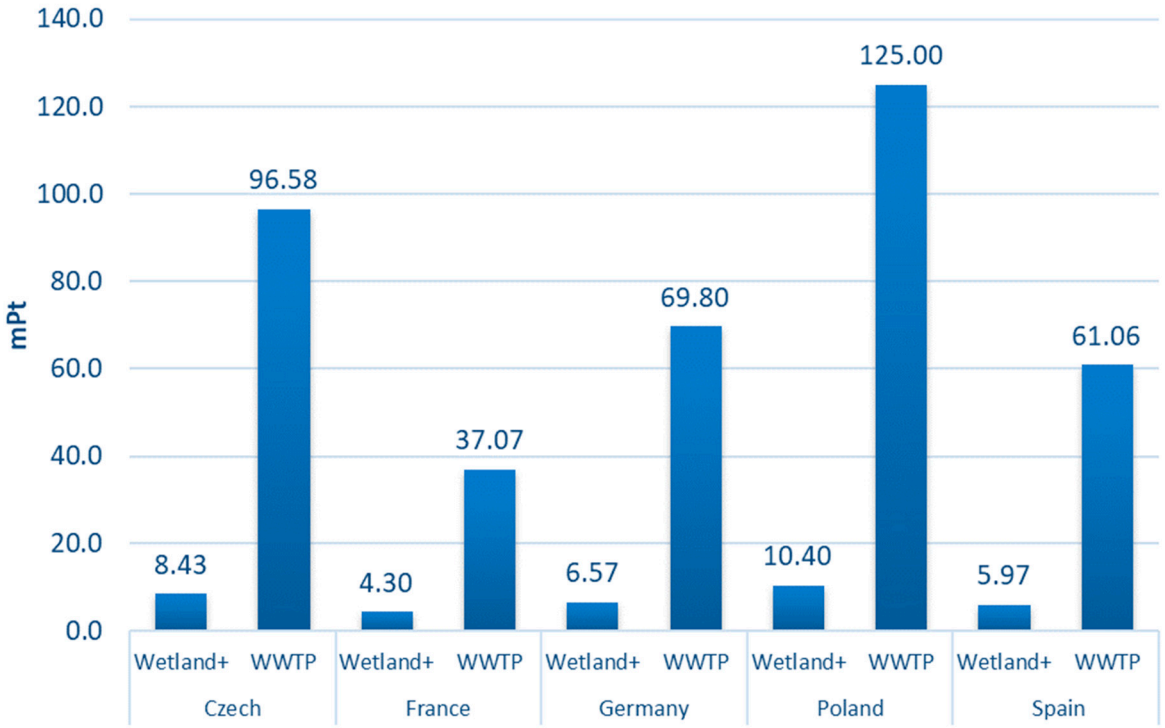

Figure 14. Alternative scenarios showing the final environmental effect of the ReCiPe Endpoint H/A method after the weighting stage for Wetland+® and WWTP technologies, summed for the construction and operation stages with a specific energy mix for each country.

The lowest environmental burden was for the energy mix of France, followed by those of Spain, Germany, the Czech Republic, and, finally, Poland. In all countries, the Wetland+® technology showed a lower environmental burden compared to the WWTP system. The results show that even when a country's energy mix is more environmentally friendly (e.g., France), the Wetland+® system is still more environmentally beneficial than the WWTP alternative system.

To compare the obtained results of the analysis to the results of the work of other authors, it should be noted that according to the guidelines of ISO 14040 and ISO 14044, in order for this to be possible, it is necessary that the system boundaries, the functional unit, and the chosen LCIA method correspond to each other. The authors of this study conducted a literature review covering LCA analyses of wastewater treatment systems using the conventional method. In many cases, discrepancies in the use of functional units, system boundaries, and LCA methodology undermined the comparison being made [16–22] with the use of wetlands [23–28].

For example, La Laina Cunha et al. (2010) have performed an LCA for four technologies that can be applied to remediate sites contaminated with HCH [6]. They analyzed bioremediation, phytoremediation, nanotechnology, and thermal treatment. However, a different LCIA method and different functional units were used, which makes it impossible to compare those results with those presented in this paper.

Nevertheless, Lopsik (2013) compared the environmental impact of two types of constructed wetland and extended aeration-activated sludge treatment systems working with municipal wastewater treatment at a small scale [20]. The system boundaries covered both construction and operation. The functional unit was the treatment of one population equivalent, municipal wastewater was selected, and a realistic operating period was considered (15 years). The analysis was performed using *SimaPro* software. Impact2002+ and ReCiPe were selected as LCIA methods. The results were in line with the findings of this study. The aeration-activated sludge treatment system had a higher environmental load, which was determined over the operational stage. In contrast, the main loads on the wetland system

arose during the construction stage. A similar conclusion was formulated as a result of the analysis presented in this study, indicating that for a sewage treatment system based on a wetland, a higher environmental load is assigned to the construction stage compared to the operation stage. Therefore, it can be concluded that the results presented in this paper are consistent with the findings of other researchers. At the same time, they extend the LCA analyses conducted so far to include the Wetland+ technology and the type of treated sewage contaminated with pesticides, including lindane.

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Appendix A

Table A1. ReCiPe Midpoint results after the characterization stage for the construction of the Wetland+® system compared to WWTP.

Impact Category	Unit	Wetland+®_Construction	WWTP_Construction
Global warming	kg CO_2 eq	8.56×10^{-2}	2.62×10^{-2}
Stratospheric ozone depletion	kg CFC11 eq	7.42×10^{-8}	6.68×10^{-9}
Ionizing radiation	kBq Co-60 eq	7.53×10^{-4}	1.39×10^{-3}
Ozone formation, human health	kg NO_x eq	1.78×10^{-4}	6.19×10^{-5}
Fine particulate matter formation	kg $PM_{2.5}$ eq	8.44×10^{-5}	4.05×10^{-5}
Ozone formation, terrestrial ecosystems	kg NO_x eq	1.89×10^{-4}	6.31×10^{-5}
Terrestrial acidification	kg SO_2 eq	2.68×10^{-4}	1.23×10^{-4}
Freshwater eutrophication	kg P eq	8.58×10^{-6}	1.19×10^{-5}
Marine eutrophication	kg N eq	9.55×10^{-7}	6.51×10^{-7}
Terrestrial ecotoxicity	kg 1,4-DCB	9.77×10^{-2}	1.17×10^{-1}
Freshwater ecotoxicity	kg 1,4-DCB	2.01×10^{-3}	2.70×10^{-3}
Marine ecotoxicity	kg 1,4-DCB	2.49×10^{-3}	3.39×10^{-3}
Human carcinogenic toxicity	kg 1,4-DCB	8.41×10^{-3}	3.08×10^{-3}
Human non-carcinogenic toxicity	kg 1,4-DCB	1.43×10^{-2}	3.51×10^{-2}
Land use	m2a crop eq	5.46×10^{-3}	4.75×10^{-4}
Mineral resource scarcity	kg Cu eq	4.97×10^{-4}	2.95×10^{-4}
Fossil resource scarcity	kg oil eq	2.86×10^{-2}	8.19×10^{-3}
Water consumption	m^3	6.37×10^{-4}	1.90×10^{-4}

Table A2. ReCiPe Midpoint results after the characterization stage for operation of the Wetland+® system compared to WWTP.

Impact Category	Unit	Wetland+®_Operation	WWTP_Operation
Global warming	kg CO_2 eq	1.43×10^{-1}	2.53
Stratospheric ozone depletion	kg CFC11 eq	2.35×10^{-8}	4.36×10^{-7}
Ionizing radiation	kBq Co-60 eq	4.01×10^{-2}	6.81×10^{-1}
Ozone formation, human health	kg NO_x eq	2.32×10^{-4}	4.30×10^{-3}
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.32×10^{-4}	2.99×10^{-3}
Ozone formation, terrestrial ecosystems	kg NO_x eq	2.34×10^{-4}	4.33×10^{-3}
Terrestrial acidification	kg SO_2 eq	3.98×10^{-4}	9.25×10^{-3}
Freshwater eutrophication	kg P eq	2.04×10^{-4}	2.98×10^{-3}
Marine eutrophication	kg N eq	1.31×10^{-5}	1.95×10^{-4}
Terrestrial ecotoxicity	kg 1,4-DCB	2.66×10^{-1}	1.12
Freshwater ecotoxicity	kg 1,4-DCB	1.37×10^{-2}	7.94×10^{-2}
Marine ecotoxicity	kg 1,4-DCB	1.75×10^{-2}	1.09×10^{-1}
Human carcinogenic toxicity	kg 1,4-DCB	1.38×10^{-2}	1.56×10^{-1}
Human non-carcinogenic toxicity	kg 1,4-DCB	2.41×10^{-1}	3.17
Land use	m2a crop eq	4.89×10^{-3}	2.09×10^{-2}
Mineral resource scarcity	kg Cu eq	3.68×10^{-4}	1.48×10^{-3}
Fossil resource scarcity	kg oil eq	3.54×10^{-2}	5.00×10^{-1}
Water consumption	m^3	2.96×10^{-3}	4.64×10^{-2}

Table A3. ReCiPe Midpoint results after the characterization stage in total for the construction and operation of the Wetland+® system compared to WWTP.

Impact Category	Unit	Wetland+®_Construction + Operation	WWTP_Construction + Operation
Global warming	kg CO_2 eq	2.28×10^{-1}	2.55
Stratospheric ozone depletion	kg CFC11 eq	9.78×10^{-8}	4.43×10^{-7}
Ionizing radiation	kBq Co-60 eq	4.08×10^{-2}	6.82×10^{-1}
Ozone formation, human health	kg NO_x eq	4.09×10^{-4}	4.36×10^{-3}
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.17×10^{-4}	3.03×10^{-3}
Ozone formation, terrestrial ecosystems	kg NO_x eq	4.22×10^{-4}	4.39×10^{-3}
Terrestrial acidification	kg SO_2 eq	6.67×10^{-4}	9.37×10^{-3}
Freshwater eutrophication	kg P eq	2.12×10^{-4}	2.99×10^{-3}
Marine eutrophication	kg N eq	1.41×10^{-5}	1.95×10^{-4}
Terrestrial ecotoxicity	kg 1,4-DCB	3.64×10^{-1}	1.23
Freshwater ecotoxicity	kg 1,4-DCB	1.57×10^{-2}	8.21×10^{-2}
Marine ecotoxicity	kg 1,4-DCB	2.00×10^{-2}	1.13×10^{-1}
Human carcinogenic toxicity	kg 1,4-DCB	2.22×10^{-2}	1.59×10^{-1}
Human non-carcinogenic toxicity	kg 1,4-DCB	2.55×10^{-1}	3.20
Land use	m2a crop eq	1.03×10^{-2}	2.14×10^{-2}
Mineral resource scarcity	kg Cu eq	8.65×10^{-4}	1.77×10^{-3}
Fossil resource scarcity	kg oil eq	6.40×10^{-2}	5.08×10^{-1}
Water consumption	m^3	3.59×10^{-3}	4.66×10^{-2}

Table A4. ReCiPe Endpoint H/A results after the characterization stage for the construction of the Wetland+® system compared to WWTP.

Damage Category	Impact Category	Unit	Wetland+®_Construction		WWTP_Construction	
Human health	Global warming, human health	DALY (shortened years of life or years with reduced quality of life as a result of disability)	7.94×10^{-8}	1.65×10^{-7}	2.43×10^{-8}	6.84×10^{-8}
	Stratospheric ozone depletion		3.94×10^{-11}		3.55×10^{-12}	
	Ionizing radiation		6.39×10^{-12}		1.18×10^{-11}	
	Ozone formation, human health		1.62×10^{-10}		5.63×10^{-11}	
	Fine particulate matter formation		5.30×10^{-8}		2.54×10^{-8}	
	Human carcinogenic toxicity		2.79×10^{-8}		1.02×10^{-8}	
	Human non-carcinogenic toxicity		3.26×10^{-9}		8.01×10^{-9}	
	Water consumption, human health		1.33×10^{-9}		3.58×10^{-10}	
Ecosystems	Global warming, terrestrial ecosystems	species·yr (loss of species during the year)	2.40×10^{-10}	3.86×10^{-10}	7.33×10^{-11}	1.25×10^{-10}
	Global warming, freshwater ecosystems		6.55×10^{-15}		2.00×10^{-15}	
	Ozone formation, terrestrial ecosystems		2.43×10^{-11}		8.14×10^{-12}	
	Terrestrial acidification		5.69×10^{-11}		2.61×10^{-11}	
	Freshwater eutrophication		5.76×10^{-12}		7.97×10^{-12}	
	Marine eutrophication		1.62×10^{-15}		1.11×10^{-15}	
	Terrestrial ecotoxicity		1.11×10^{-12}		1.34×10^{-12}	
	Freshwater ecotoxicity		1.39×10^{-12}		1.86×10^{-12}	
	Marine ecotoxicity		2.61×10^{-13}		3.56×10^{-13}	
	Land use		4.84×10^{-11}		4.21×10^{-12}	
	Water consumption, Terrestrial ecosystem		7.97×10^{-12}		2.10×10^{-12}	
	Water consumption, Aquatic ecosystems		4.20×10^{-16}		1.19×10^{-16}	
Resources	Mineral resource scarcity	$ (extra costs involved for future mineral and fossil resource extraction)	1.15×10^{-4}	9.00×10^{-3}	6.82×10^{-5}	2.08×10^{-3}
	Fossil resource scarcity		8.88×10^{-3}		2.01×10^{-3}	

Table A5. ReCiPe Endpoint H/A results after the characterization stage for operation of the Wetland+® system compared to WWTP.

Damage Category	Impact Category	Unit	Wetland+®_Operation		WWTP_Operation	
Human health	Global warming, human health	DALY (shortened years of life or years with reduced quality of life as a result of disability)	1.32×10^{-7}	3.18×10^{-7}	2.35×10^{-6}	5.50×10^{-6}
	Stratospheric ozone depletion		1.25×10^{-11}		2.31×10^{-10}	
	Ionizing radiation		3.40×10^{-10}		5.78×10^{-9}	
	Ozone formation, human health		2.11×10^{-10}		3.92×10^{-9}	
	Fine particulate matter formation		8.32×10^{-8}		1.88×10^{-6}	
	Human carcinogenic toxicity		4.58×10^{-8}		5.18×10^{-7}	
	Human non-carcinogenic toxicity		5.49×10^{-8}		7.22×10^{-7}	
	Water consumption, human health		1.01×10^{-9}		2.16×10^{-8}	
Ecosystems	Global warming, terrestrial ecosystems	species·yr (loss of species during the year)	3.99×10^{-10}	7.19×10^{-10}	7.08×10^{-9}	1.20×10^{-8}
	Global warming, freshwater ecosystems		1.09×10^{-14}		1.93×10^{-13}	
	Ozone formation, terrestrial ecosystems		3.02×10^{-11}		5.58×10^{-10}	
	Terrestrial acidification		8.44×10^{-11}		1.96×10^{-9}	
	Freshwater eutrophication		1.37×10^{-10}		2.00×10^{-9}	
	Marine eutrophication		2.23×10^{-14}		3.31×10^{-13}	
	Terrestrial ecotoxicity		3.04×10^{-12}		1.27×10^{-11}	
	Freshwater ecotoxicity		9.50×10^{-12}		5.50×10^{-11}	
	Marine ecotoxicity		1.84×10^{-12}		1.15×10^{-11}	
	Land use		4.33×10^{-11}		1.86×10^{-10}	
	Water consumption, terrestrial ecosystem		1.02×10^{-11}		1.88×10^{-10}	
	Water consumption, aquatic ecosystems		3.62×10^{-16}		6.78×10^{-15}	
Resources	Mineral resource scarcity	$ (extra costs involved for future mineral and fossil resource extraction)	8.51×10^{-5}	1.98×10^{-3}	3.41×10^{-4}	6.26×10^{-2}
	Fossil resource scarcity		1.90×10^{-3}		6.23×10^{-2}	

Table A6. ReCiPe Endpoint H/A results after the characterization stage in total for the construction and operation of the Wetland+® system compared to WWTP.

Damage Category	Impact Category	Unit	Wetland+®_Construction + Operation		WWTP_Construction + Operation	
Human health	Global warming, human health	DALY (shortened years of life or years with reduced quality of life as a result of disability)	2.12×10^{-7}	4.83×10^{-7}	2.37×10^{-6}	5.57×10^{-6}
	Stratospheric ozone depletion		5.19×10^{-11}		2.35×10^{-10}	
	Ionizing radiation		3.47×10^{-10}		5.79×10^{-9}	
	Ozone formation, human health		3.72×10^{-10}		3.97×10^{-9}	
	Fine particulate matter formation		1.36×10^{-7}		1.90×10^{-6}	
	Human carcinogenic toxicity		7.37×10^{-8}		5.28×10^{-7}	
	Human non-carcinogenic toxicity		5.82×10^{-8}		7.30×10^{-7}	
	Water consumption, human health		2.34×10^{-9}		2.20×10^{-8}	
Ecosystems	Global warming, terrestrial ecosystems	species·yr (loss of species during the year)	6.39×10^{-10}	1.10×10^{-9}	7.15×10^{-9}	1.22×10^{-8}
	Global warming, freshwater ecosystems		1.75×10^{-14}		1.95×10^{-13}	
	Ozone formation, terrestrial ecosystems		5.45×10^{-11}		5.67×10^{-10}	
	Terrestrial acidification		1.41×10^{-10}		1.99×10^{-9}	
	Freshwater eutrophication		1.42×10^{-10}		2.00×10^{-9}	
	Marine eutrophication		2.39×10^{-14}		3.32×10^{-13}	
	Terrestrial ecotoxicity		4.16×10^{-12}		1.41×10^{-11}	
	Freshwater ecotoxicity		1.09×10^{-11}		5.69×10^{-11}	
	Marine ecotoxicity		2.10×10^{-12}		1.18×10^{-11}	
	Land use		9.18×10^{-11}		1.90×10^{-10}	
	Water consumption, terrestrial ecosystem		1.81×10^{-11}		1.90×10^{-10}	
	Water consumption, aquatic ecosystems		7.83×10^{-16}		6.90×10^{-15}	
Resources	Mineral resource scarcity	$ (extra costs involved for future mineral and fossil resource extraction)	2.00×10^{-4}	1.10×10^{-2}	4.09×10^{-4}	6.47×10^{-2}
	Fossil resource scarcity		1.08×10^{-2}		6.43×10^{-2}	

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