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Environmental Life-Cycle Assessment of an Innovative Multifunctional Toilet

Carla Rodrigues [1,*], João Almeida [2,3], Maria Inês Santos [2], Andreia Costa [4], Sandra Além [5], Emanuel Rufo [5], António Tadeu [2,6] and Fausto Freire [1]

[1] ADAI-LAETA, Department of Mechanical Engineering, Faculty of Sciences and Technology, University of Coimbra, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal; fausto.freire@dem.uc.pt
[2] Itecons—Institute for Research and Technological Development in Construction, Energy, Environment and Sustainability, Rua Pedro Hispano, 3030-289 Coimbra, Portugal; joao.almeida@itecons.uc.pt (J.A.); mariaines.santos@itecons.uc.pt (M.I.S.); tadeu@dec.uc.pt (A.T.)
[3] Chemistry Centre, Department of Chemistry, Faculty of Sciences and Technology, University of Coimbra, Rua Larga, Pólo I, 3004-535 Coimbra, Portugal
[4] OLI—Sistemas Sanitários, S.A., Travessa do Milão, Esgueira, 3800-314 Aveiro, Portugal; andreiac@oli-world.com
[5] Sanindusa—Indústria de Sanitários S.A., Zona Industrial Aveiro Sul, Rua Augusto Marques Branco, 84, 3810-783 Aveiro, Portugal; sandraalem@sanindusa.pt (S.A.); emanuelrufo@sanindusa.pt (E.R.)
[6] ADAI, Department of Civil Engineering, Faculty of Sciences and Technology, University of Coimbra, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal
* Correspondence: carla.rodrigues@dem.uc.pt; Tel.: +351-239-790708

Abstract: Innovative toilets can save resources, but have higher embodied impacts associated with materials and electronic components. This article presents an environmental life-cycle assessment (LCA) of an innovative multifunctional toilet (WashOne) for two alternative configurations (with or without washlet), comparing its performance with those of conventional systems (toilet and bidet). Additionally, two scenario analyses were conducted: (i) user behavior (alternative washlet use patterns) and (ii) user location (Portugal, Germany, the Netherlands, Sweden and Saudi Arabia). The results show that the WashOne with washlet has a better global environmental performance than the conventional system, even for low use. It also reveals that the use phase has the highest contribution to impacts due to electricity consumption. User location analysis further shows that Sweden has the lowest environmental impact, while Germany and the Netherlands have the highest potential for impact reduction when changing from a conventional system to the WashOne. Based on the overall results, some recommendations are provided to enhance the environmental performance of innovative toilet systems, namely the optimization of the washlet use patterns. This article highlights the importance of performing a LCA at an early stage of the development of innovative toilets by identifying the critical issues and hotspots to improve their design and performance.

Keywords: bidet; eco-design; energy savings; life-cycle assessment; toilet; user behavior; washlet; water savings

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1. Introduction

Buildings are recognized as one of the highest users of freshwater, consuming enormous amounts of energy and water resources and, ultimately, generating high environmental impacts. The water cycle of buildings requires a great amount of energy due to raw water treatment and distribution, use in buildings (domestic hot water), and wastewater treatment [1]. Water heating represents 13% of energy consumption in residential buildings [2], with conventional toilet systems having a significant share [3].

Innovative toilet systems can save water and energy, but have higher embodied impacts associated with materials and electronic components. Environmental life-cycle assessment (LCA) can be applied to evaluate and compare alternative toilet systems (conventional and innovative), providing a holistic assessment from cradle to grave and avoiding burden shifting. In particular, it is important to analyze trade-offs between increased embodied impacts and operational savings of innovative toilet systems. Additionally, LCA performed in early design stages of the development of products can support design decisions before innovative products' or emerging technologies' entry into the market, revealing the benefits of considering environmental performance as a design constraint [4,5]. Employing LCAs in innovative products enables improved product eco-design through early hotspot detection allowing optimization of material choices and use-phase efficiency. LCAs have been used to assess the environmental performance of several innovative systems/products, particularly in the building sector [6–9].

LCA methodology allows the identification of hotspots by quantifying the benefits of a product or system and improvement opportunities for their environmental performance. Some LCA studies of toilet systems available in the literature focused on the production phase of ceramic sanitary ware (cradle-to-site) [10,11]. There are several LCA studies focused on wastewater treatment (WWT) for conventional toilets and source-separation systems [12–15], while others examine alternative water sources for the flush system (rainwater, seawater, grey water reuse) [16–23]. Lam et al., 2017 assessed the energy efficiency of non-potable water systems (including toilets) for domestic use [24]. Gnoatto et al., 2019 evaluated the life-cycle impacts of different solutions for toilet flush systems, particularly comparing single and double flush [25]. The production phase of a toilet system is often neglected in LCA studies of toilet systems because its contribution to the total life-cycle impacts is usually low (taking into account the extended life-time of these systems), but also because in comparative studies of alternative WWT systems it is usually assumed that the toilet is the same, so the impact of the sanitary ware is the same in all scenarios. Regarding the "washlet" system, there are no comprehensive LCA studies on these types of systems.

Several gaps were identified regarding the environmental assessment of innovative toilets that have never been addressed in the literature. Firstly, there are no studies performing a cradle-to-grave life-cycle assessment of toilets, particularly the innovative ones. Additionally, there is a need to address the trade-offs between the potential energy efficiency of innovative toilets and the increase in the environmental impacts due to energy consumption, particularly in the new washing functions, as well as the use of critical materials in electronic components. Finally, these toilets have a worldwide market, different from conventional models, which can highly influence their environmental performance due to transportation impacts, as well as affecting the country-specific electricity mix that can vary depending on the final user location. To sum up, innovative toilets have never been studied in a life-cycle perspective to assess their environmental performance and potential energy efficiency benefits due to their multifunctionality.

WashOne is an innovative multifunctional toilet that incorporates a self-cleaning system (called a washlet system, to replace the conventional bidet), and an integrated water storage and flush system [26]. A rendering of the WashOne toilet system is presented in Figure 1. This multifunctional toilet is being developed by a Portuguese consortium comprising two companies from the sanitary ware industry (OLI and Sanindusa), a company providing electronic engineering solutions (Evoleo) and several higher education institutions (University of Aveiro and University of Coimbra) and applied research institutions (Itecons, Portuguese Association for Quality in Buildings' Water Installations - ANQIP).

Figure 1. Rendering of the innovative multifunctional toilet (WashOne). Source: Developed by a subset of authors.

The "washlet" system incorporates conventional bidet features into the toilet, responding to a recent market trend for high standards of comfort and hygiene. The water storage and flush system integrated into the toilet meets the compactness needs required by current design solutions (reducing the volume occupied) and allows the optimization of the flushing system and consequently the use of water.

The goal of this article is to present an environmental life-cycle assessment of an innovative multifunctional toilet system (WashOne), from cradle to grave, considering two alternative WashOne configurations (with or without washlet) compared with equivalent conventional systems (toilet and bidet, or just toilet, respectively). Additionally, two scenario analyses were conducted to investigate the performance of the innovative toilet with washlet when variations are introduced in terms of: (i) user behavior and (ii) user location.

2. Materials and Methods

The LCA methodology applied to assess the environmental performance of the toilet systems follows the ISO 14040:2006 and ISO 14044:2006 standards to guide the methods, model development and inventory calculations in this research. LCA is developed in four interrelated phases: goal and scope definition; life-cycle inventory (LCI); life-cycle impact assessment (LCIA); and interpretation. Section 2.1 presents the goal and scope definition, including the life-cycle model, and Section 2.2 presents the life-cycle inventory analysis.

2.1. Goal and Scope Definition

A cradle-to-grave life-cycle (LC) model was developed for the WashOne toilet. The system boundaries are presented in Figure 2 and encompass all life-cycle phases including wastewater treatment during use phase and transportation between and within each phase. The main LC phases of a toilet system are: (i) production of the toilet, auxiliary systems and system's infrastructure (piping, etc.); (ii) distribution to the final user (in Portugal, as reference scenario); (iii) use in a residential building; and (iv) end-of-life of the components after 15 years of service life (according to the producers).

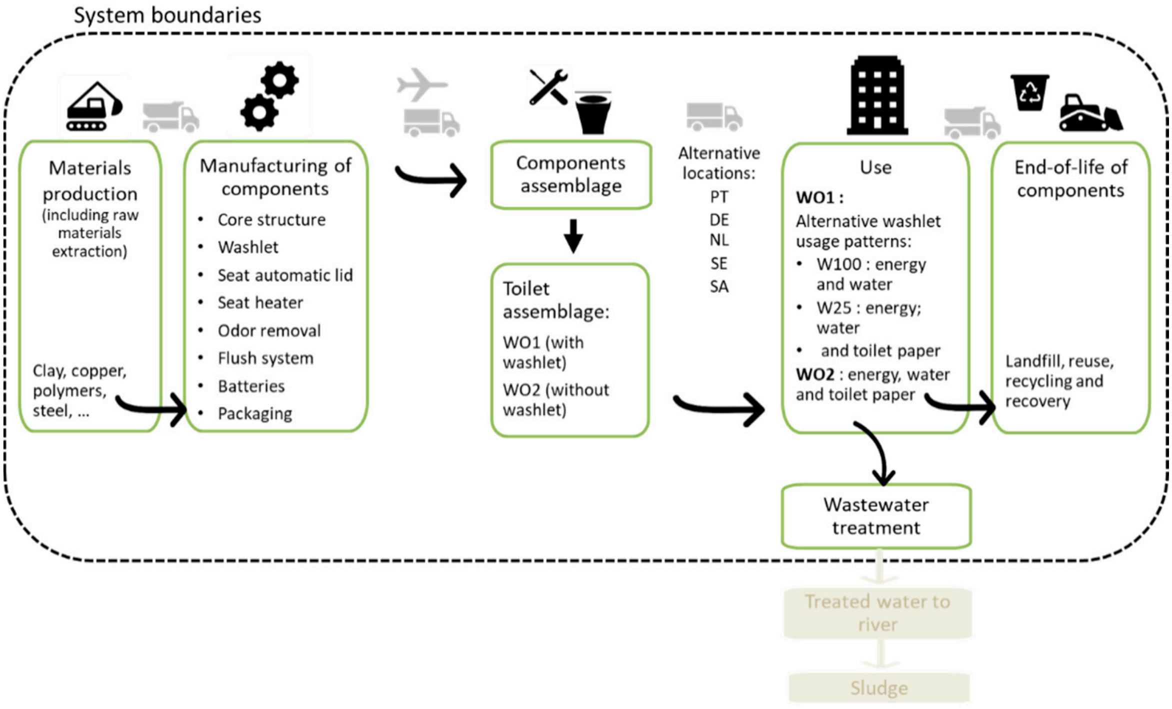

Figure 2. Life-cycle model ("cradle to grave") of WashOne. Source: Developed by a subset of authors.

The WashOne toilet incorporates multiple functions, particularly the "washlet", a self-cleaning system (to replace the conventional bidet), and an integrated water storage and flush system. Regarding the "washlet" system, it aims to replace the bidet functions within the toilet in order to address high comfort and hygiene conditions. It is incorporated in the lid and includes the following functions: lid lifter function, remote control, WC seat with seat heating, dryer arm with dryer nozzle, spray arm with spray nozzle and lady shower nozzle, spray shield, and odor removal.

The scope of the study includes two WashOne configurations: WashOne with and without washlet (WO1 and WO2, respectively), both of them with an integrated water storage and flush system. The WO1 is compared with a conventional toilet and bidet (high-end), while the WO2 is compared only with just the conventional toilet, assuming that there is no additional cleaning system as a bidet. Additionally, two scenario analyses were conducted for WO1 and the conventional system: (i) user behavior scenario analysis and (ii) user location scenario analysis. For the user behavior, two alternative washlet usage patterns were assessed: one where the washlet is used in all toilet visits (W100); and another where the washlet is only used in major visits, i.e., one visit per day per person, representing 25% of the daily visits (W25). For the user location scenarios, four alternative locations were assessed (Germany, the Netherlands, Sweden and Saudi Arabia) and compared with Portugal (reference scenario). The functional unit selected is the use of a toilet system (conventional toilet and bidet or WashOne) by a 4-person family (two adults and two children) living in a single-family house for one year (family × year) for two types of use: (a) with cleaning system (WO1) and (b) without cleaning system (WO2), assuming a conventional daily usage pattern (defined in Section 2.2.2).

2.2. Life-Cycle Inventory Analysis

The LC inventory was developed using primary data from the companies involved in the development of the WashOne toilet (material characteristics and quantities of mechanical, plastic and electronic components), complemented with secondary data from the literature and technical reports, as well as life-cycle databases (Ecoinvent) [27–30]. The energy and water use data were provided by the manufacturer and collected based on experimental tests. Section 2.2.1 details the inventory data for production and distribution from production site to the building site (users' location). Section 2.2.2 presents use phase and end-of-life inventory analysis.

2.2.1. Production and Distribution

The production phase of the toilet systems (WashOne and conventional) includes production of components and final product assemblage. The WashOne system has a ceramic structure in vitreous china, flush mechanisms and two plastic storage tanks (several mechanical components (motors, pumps, etc.), and electronics. The core structure is made of ceramic (vitreous china) with a seat made of duroplast. The conventional toilet includes a ceramic structure, also in vitreous china, a seat (made of duroplast), a ceramic storage tank and a flush mechanism (made of polystyrene (PS)). Table 1 presents the main inventory data of materials and components of the WashOne and conventional toilet and bidet. This data is aggregate by material or component (when the materials composition of each component is not available), in this case proxy data was used. Primary data (material characteristics and quantities) were provided by the companies. Detailed information of each component was not presented due to confidentiality issues. Secondary data for components, materials (thermoplastic polymers) and plastic transformation processes (injection for acrylonitrile butadiene styrene (ABS), and polypropylene (PP), polycarbonate (PC) and duroplast, and thermoforming for PS) were obtained from Ecoinvent v3.1 database [27–30]. The production of the ceramic structure (vitreous china) was modelled using Ecoinvent v3.1 database [27] and Environmental Product Declaration (EPD) databases. The plastic components of the WashOne are produced on site, in the plant where the final assembling is performed, located in Aveiro, Portugal. The electronic and mechanical components and ceramic structure are produced off-site by several suppliers. This innovative toilet is still currently in a prototype phase; however, according to the assemblage scheme developed by the company for a future production line, the components will be assembled mainly manually, so the energy needed for this process will be residual (~0.01 kWh per final product) and can be neglected.

Table 1. Bill of materials of WashOne (WO1 and WO2) and conventional counterparts (toilet and bidet). Source: Developed by the authors using data collected by the authors affiliated with OLI and Sanindusa companies and from the literature.

Materials/Components	WO1	WO2	Toilet	Bidet
	(kg)			
Acrylonitrile Butadiene Styrene (ABS)	4.14	2.76	-	-
Aluminum	0.05	0.00	-	-
Battery	0.10	0.00	-	-
Cardboard	8.50	8.50	5	5
Ceramic (vitreous china)	17.0	17.0	50.4	27.6
Control unit	0.30	0.00	-	-
Copper	0.04	0.00	-	-
Duroplast	3.60	3.88	2	-
Fans	0.07	0.05	-	-
Motors 12 V	0.57	0.37	-	-
Polypropylene (PP)	0.10	1.98	-	-
Polystyrene (PS)	0.50	0.50	1	-
Polycarbonate (PC)	0.01	0.01	-	-
Pumps 40 W	3.00	3.42	-	-
Rubber	0.06	0.06	-	-
Electronics (sensors)	0.02	0.02	-	-
Steel	0.91	0.66	-	-
Water heater	0.14	0.00	-	-
Total weight	41	39	58	33

The WashOne toilets are distributed by road using lorries and/or ship (sea containers) from the production site (Aveiro, Portugal) till the end-user destination (200 km). Alternative user locations have been modeled in a scenario analysis for five potential markets identified by the manufacturer consortium: in Europe (Portugal, Germany, the Netherlands and Sweden); and in the Middle East (Saudi Arabia, relevant consumers of advanced technology toilet systems). For each location, transportation distances, distribution modes of transportation, and country-specific electricity mixes for the use phase were assessed. Transportation distances were calculated based on the distance between the production site and a potential final user located in the capital of each country. For locations in Europe, the mode of transportation was a 16-ton lorry, but distribution by ship was also considered for Sweden and the Netherlands due to port areas' proximity. For the Middle East, distribution was assumed to be by boat and a lorry for inland distance. Transport by plane, train and ship were modelled using processes from the Ecoinvent v.3.1 database [31]. Transportation data for the alternative locations are presented in Table 2.

Table 2. Transport characterization for distribution, considering alternative location scenarios for the WashOne toilet with washlet (WO1) and respective conventional system (toilet + bidet). Source: Developed by the authors using data collected by the authors affiliated with OLI and Sanindusa companies and from the literature.

User Location	Mode of Transportation	Distance	WO1 (41 kg)	Conventional Toilet and Bidet (91 kg)
		(km)	(tkm [1])	
Portugal (PT)	Lorry 16 ton—EURO5	200	8	18
Germany (DE)	Lorry 16 ton—EURO5	2700	111	246
The Netherlands (NL)	Lorry 16 ton—EURO5 Boat (+lorry 16 ton—EURO5)	2100 1800 (+130)	86 74 (+5)	191 164 (+12)
Sweden (SE)	Lorry 16 ton—EURO5 Barco (+lorry 16 ton—EURO5)	3500 3500 (+150)	144 144 (+6)	319 319 (+14)
Middle East (Saudi Arabia—SA)	Boat (+lorry 16 ton—EURO5)	10,000 (+230)	410 (+10)	910 (+21)

[1] Tonne × kilometer.

2.2.2. Use Phase and End-of-Life

The WashOne and conventional systems use phase were modeled for a conventional usage pattern defined assuming a daily use of a 4-person family, two adults and two children (in equally number of both genders, necessary to characterize the type of visits), in a single-family house. Detailed assumptions follow a daily use of five visits, including four minor (urine) and one major (feces) for each person. The whole family uses only one toilet. The toilet is used 351 days per year (assuming that 14 days are spent away from home on vacation). Both the WashOne and conventional toilets have a dual flush system, with full (6 L) and half flush (4.5 L) for major and minor visits, respectively. The consumption of toilet paper is eight sheets for minor visits and 15 sheets for major visits. The use of bidet in the conventional system is only for major visits (one visit per day per person). Data regarding time of use, water consumption and energy consumption was based on experimental tests as well as data from the literature and EPD databases assuming a standard use pattern. Tables 3 and 4 present the WashOne's electricity and water use per function and visit (major and minor). The bidet system's characteristics and energy and water consumption are described in Table 5.

Table 3. WashOne electricity use per function per visit (major or minor). Source: Developed by the authors using data collected by the author affiliated with OLI and from the literature.

Function	Components	Power (W)	Time of Use (s)	Consumption Per Use (kWh)
Automatic lid lifter	Motor	36	3	6.0×10^{-5}
Seat heating	Electrical resistance	60	300	5.0×10^{-3}
Washlet nozzle cleaning	Pump	12	4	1×10^{-5}
User's cleaning	Pump	12	* *	* *
	Motor	2	8	4.4×10^{-6}
	Water heater	1444	* *	* *
Washlet nozzle oscillation	Motor	2	60	3.3×10^{-5}
Drying	Fan	5	30	4.2×10^{-5}
	Electrical resistance	122	30	1.02×10^{-3}
Odor removal	Fan	5	300	4.2×10^{-4}
Full flush (major visits)	Pump	108	5	1.5×10^{-4}
Half flush (minor visits)	Pump	108	2.92	8.8×10^{-5}

* Depends on the type of visit (see Table 4).

Table 4. WashOne water and energy use (washlet and toilet) per type of visit (major or minor). Source: Developed by the authors using data collected by the author affiliated with OLI and from the literature.

Washlet and Toilet Use Parameters	Type of Visit	
	Major	Minor
Washlet	(rear position)	(feminine/front position)
Water usage duration [1] (s)	45	20
Water flow rate (L/min)	0.65	
Used water volume (L)	0.49	0.22
Water heater efficiency [1]	0.95	
Water temperature difference ΔT [1] (K)	30 (40–10 °C)	
Water heating energy [2] (Wh)	18.06	8.03
Air dryer usage duration [1] (s)	30	
Air flow rate (L/s)	3.33	
Air heater efficiency [1]	0.98	
Air temperature difference ΔT [1] (K)	30 (45–15 °C)	
Air heating energy [3] (Wh)	1.02	
Total energy consumption (Wh)	19.08	9.05
Toilet		
Flush water usage (L)	6.0 (full flush)	4.5 (half flush) [4]
Flush flow rate (L/s)	1.20	
Flush duration (s)	5.00	2.92
Pump motor power (W)	108.0	
Energy consumption (Wh)	0.150	0.088

[1] Estimated realistic assumption. [2] Pump motor and water heater. [3] Air blower motor included. [4] European Norm EN14055.

A user behavior scenario analysis was performed to assess alternative washlet usage patterns. The washlet use is characterized in terms of use intensity (number of uses per day). For the WO1 (WashOne with washlet) configuration, the following two scenarios were analysed: W100—washlet used in 100% of toilet visits; W25—washlet used only in major visits (25% of daily visits). W25 scenario assumes that in minor visits the female user will use toilet paper. WO2 configuration considers the use of toilet paper in all visits.

Table 5. Toilet and bidet energy and water use inventory. Source: Developed by the authors using data collected by the author affiliated with OLI and from the literature.

Bidet System's Infrastructure	
Water heater's efficiency	0.8
Piping length [1] (m)	8
Water flow (L/min)	6.4
Water temperature difference [2]—ΔT (K)	30
Hot water quantity (L)	4
Bidet Use Per Visit	
Energy use (kWh)	0.2
Water use (L)	8
Toilet Water Use Per Visit	
Flush water use (L)	
Half flush (minor visits)	4.5
Full flush (major visits)	6

[1] From the heating source till the bidet. [2] Difference between room temperature and the warm temperature defined.

The electricity mix was modeled using specific literature data for Portugal based on [32,33]. For the other countries, specific country mixes were used based on literature from the Ecoinvent v.3.1 database [34,35].

The WashOne and conventional systems use phases were modeled assuming a conventional WWT system without the tertiary treatment (not included in most WWT plants) and assuming a country-specific energy mix depending on the user's location. For the secondary treatment, an anaerobic process (sludge treatment without oxygen) was considered. It was assumed that all the sanitary residues from the toilet and bidet, depending on the system (urine, feces, toilet paper and grey water), are routed from the sewer to a municipal WWT plant in each location assessed. Waste water treatments were modelled using the Ecoinvent v.3.1 database [36].

For the end-of-life of the components, it was considered that the ceramic material is disposed of in landfill for inert matter, steel components are recycled, and the electronic components are incinerated or recycled depending on their composition. Plastic material is recycled or incinerated (with energy recovery) depending on its structure. The cardboard of the package is assumed to be recycled. The remaining materials and components are incinerated. Waste treatments were modelled using the Ecoinvent v.3.1 database [29,36].

3. Results

3.1. Comparative Assessment and User Behavior Analysis

Environmental impacts were assessed using two complimentary LCIA methods: CED (Cumulative Energy Demand) was used to calculate the non-renewable primary energy (NRPE), to address fossil energy resource depletion; and the CML-IA was used to evaluate five mid-point categories: Global Warming (GW), following IPCC 2013 for a time horizon of 100 years, Acidification (A), Eutrophication (E), Ozone Depletion (OD) and Photochemical Oxidation (POC). These categories were considered to be the most relevant by the EU [37,38], as well as recommended by several product category rules (PCR), namely PCR of sanitary ware and building products [39,40]. Figure 3 shows the results for the two WashOne configurations (WO1 and WO2, with and without washlet, respectively), including the two washlet use scenarios (W100 and W25), compared to the conventional systems. The conventional system (toilet and bidet) presents higher impacts than WO1 (in both washlet use scenarios) for all impact categories. However, when the WashOne does not include the washlet system (WO2), it has higher total LC impacts (1–8%) than the conventional toilet in three out of six impact categories (acidification, eutrophication and photochemical oxidation). When comparing the use scenarios, the W100 has higher impacts than W25 in all impact categories assessed. The environmental impacts are shown to be driven by the use phase (71–95% of total LC impacts for the WashOne and 92–98%

for the conventional toilet) in all toilet system options for all impact categories assessed, followed by materials production and components manufacturing (5–29% for the WashOne and 2–7% for the conventional toilet).

Figure 3. *Cont.*

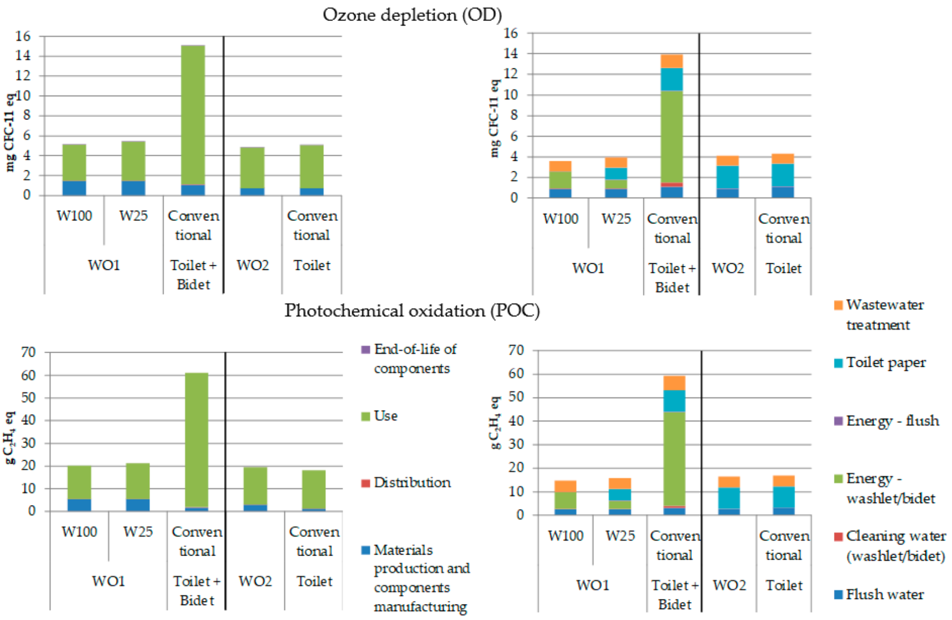

Figure 3. LCIA results of the alternative toilet systems (WashOne and conventional toilet system) per family × year: (**a**) LC impacts and (**b**) use phase impacts breakdown.

Use phase results, presented in Figure 3b, show that for WO1-W100, the high contribution of the use phase is due to electricity use of the washlet (climate change, ozone depletion and photochemical oxidation), wastewater treatment (acidification and eutrophication) and flush water (non-renewable primary energy). For WO1–W25, the processes with the highest impact are toilet paper (climate change, ozone depletion, photochemical oxidation and non-renewable primary energy) and wastewater treatment (acidification and eutrophication). The main contributor to the conventional system (toilet and bidet) use phase impacts are the electricity use of the bidet (climate change, ozone depletion and photochemical oxidation), toilet paper (acidification and non-renewable primary energy), and wastewater treatment (eutrophication). For WO2 and toilet, the use of toilet paper has the highest contribution for five out of six categories, with the exception of eutrophication, where wastewater treatment process is the highest contributor. Energy consumption contributes for about 30% of the total LC impacts of WashOne and 30–65% of the conventional toilet in most of the categories assessed. Water consumption contributes for about 15–30% of total LC impacts of WashOne and about 10% of the conventional toilet in four out of six categories.

Contribution analysis of the production phase (including materials production and components manufacturing) have highlighted the key drivers of environmental impacts for alternative toilet systems. Figure 4 shows that the key contributors are the washlet (26–36%) followed by the integrated flush system (15–28%) for the WO1. The main contributors to the production phase of the conventional system and WO2 are the ceramic structure (45–69%) and the integrated flush system (14–18%), making up over 60% of the total production impacts. Regarding materials contribution, plastics contribute about 30–45% to the production impacts of the WashOne system, while electronic components contribute about 30–65% in four out of six categories (GW, NRPE, A and E). Plastics contribute about 90% of the end-of-life impacts of materials used for the production of the WashOne. These results highlight that there is potential for improvement in the production of the WashOne components, particularly plastic made components, for instance, by incorporating recycled raw material and reducing production losses.

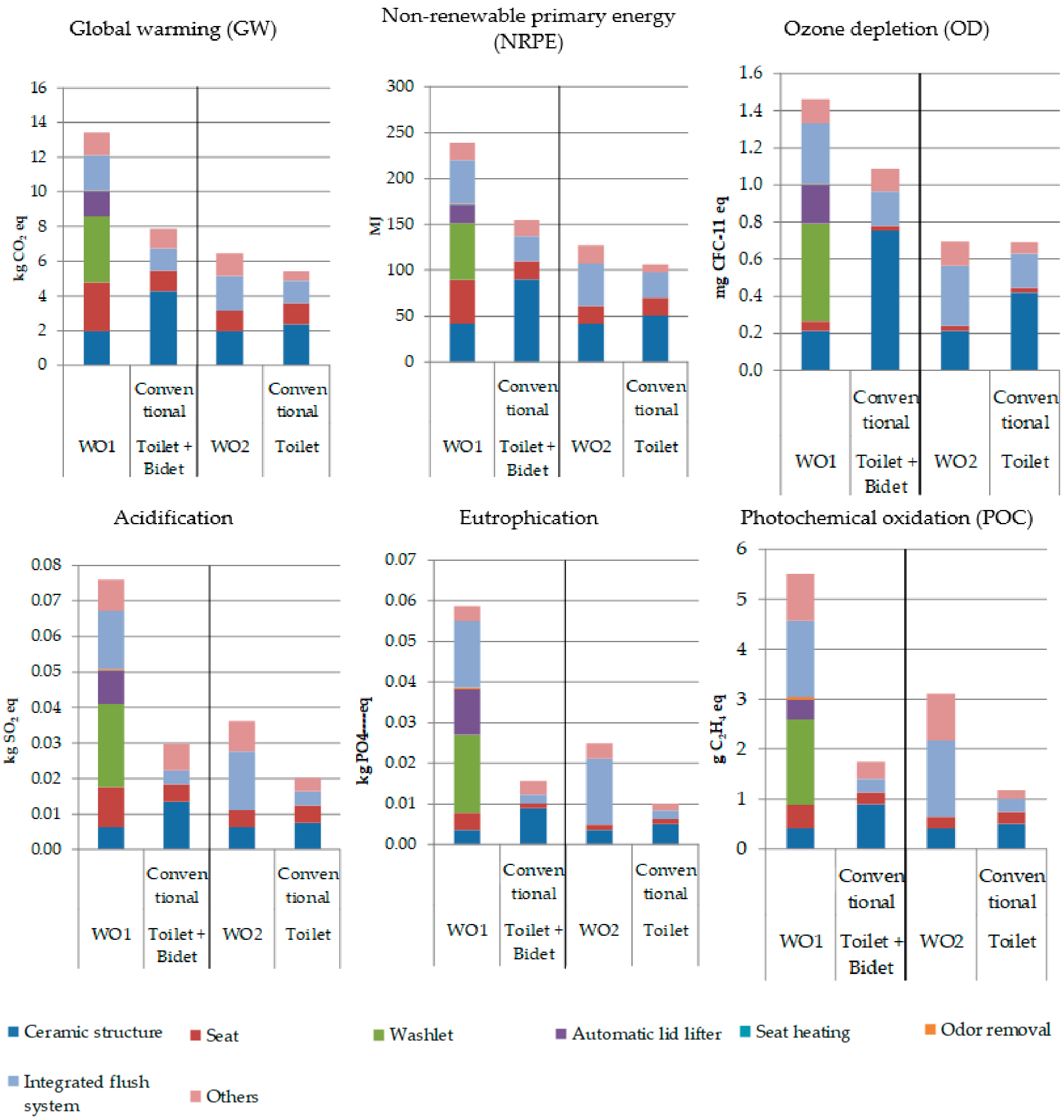

Figure 4. LCIA results for the production phase of the toilet systems (cradle to gate) per family × year.

3.2. User Location Scenario Analysis

The user location analysis was performed for five alternative locations. For each location, three parameters were assessed: the country-specific electricity mix that influences the energy use during the use phase; and the transportation distance and mode for the distribution from the production site (Portugal) to each specific location. Results presented in Figure 5 show that the use phase is the main contributor to the total LC impacts in all locations, due to the energy use in each country (and consequently the country-specific electricity mix). Sweden presents the highest distribution impacts due to the large distances traveled by lorry (3500 km), but still with very little influence in the total LC impacts (less than 5%).

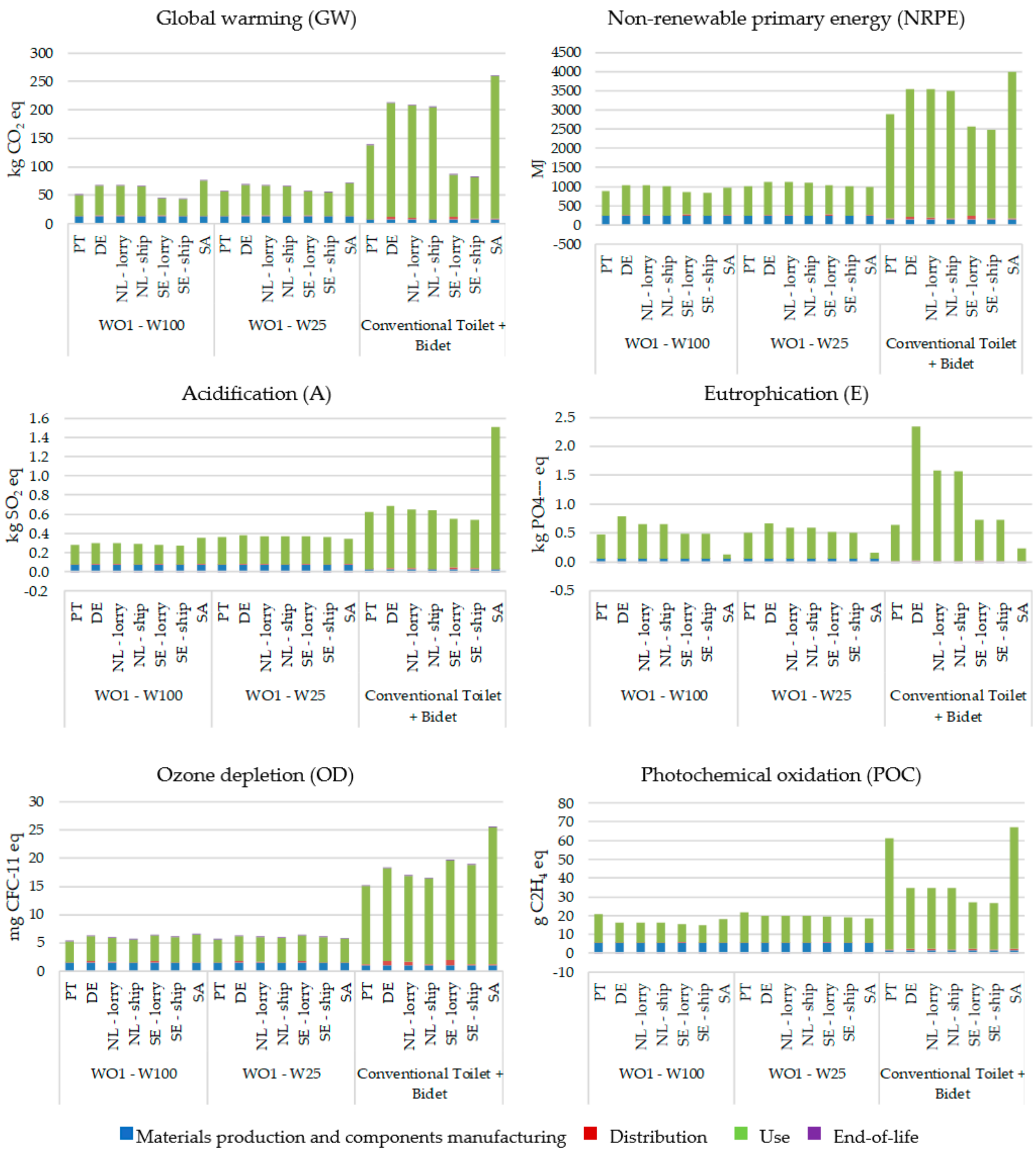

Figure 5. User location analysis LCIA results, considering five alternative locations (Portugal (PT), Germany (DE), the Netherlands (NL), Sweden (SE) and Saudi Arabia (SA)) and two transportation modes (lorry and ship).

WO1–W100 and conventional toilet systems have the lowest environmental impacts in Sweden (SE) owing to the high percentage of renewable energy (more than 80%) in the Swedish electricity mix, for most categories (GW, NRPE, A and POC). WO1-W25 has the lowest impacts in Saudi Arabia (SA) for most categories (NRPE, A, E and POC). The conventional toilet system has very high impacts in SA for all impact categories except eutrophication, due to high percentage of oil (about 60%) combined with natural gas (about 40%) used for the production of electricity. Germany and the Netherlands have the highest impact reduction potential when changing from a conventional toilet to WashOne (reduction of 52–71% in total LC impacts).

4. Conclusions and Recommendations

An environmental life-cycle assessment (cradle to grave) of an innovative multifunctional toilet system (WashOne) was performed, considering alternative configurations (with or without washlet), compared with conventional systems. Additionally, two scenario analyses were conducted to inspect the impact of different user behaviors and user locations on the environmental performance of these systems. For the user behavior scenarios, two alternative washlet usage patterns were assessed, one where the washlet is used in all toilet visits (W100) and another where the washlet is only used in major visits (W25). For the user location scenarios, four alternative locations were assessed (Germany, the Netherlands, Sweden, Saudi Arabia) and compared with Portugal (reference scenario).

It can be concluded that the WashOne system with washlet (WO1) has a better environmental performance than the conventional system (toilet + bidet), while without washlet (WO2) presents similar performance to the conventional toilet. The use phase has the highest contribution to the life-cycle impacts in both WashOne configurations and scenarios assessed. The highest contribution to the use phase impacts for WO1 is electricity use (washlet and integrated flush system), while for WO2 it is toilet paper. In the conventional system, electricity use for the water heater system of the bidet has the highest contribution for the use phase. It is worth noting that even when the washlet system has low use intensity (W25), the WashOne system has still a better performance than the conventional one.

Use phase is the main contributor to LC impacts in all locations, due to the energy use in each country and, consequently, the country-specific electricity mix. It is worth noting that the market with the highest potential for the WashOne to be competitive in terms of environmental performance is the North of Europe, in this study represented by Sweden, as it presented the lowest LC impacts in most categories, independent of the mode of transportation used for distribution. Although Sweden presents the highest distribution impacts due to the large distances traveled by lorry (3500 km), they have very little influence in the LC impacts (less than 5%). Additionally, Germany and the Netherlands have the highest potential for impact reduction when changing from a conventional toilet to WashOne (reduction of 52–71% LC impacts).

Drawing on the results and on limitations of this article, recommendations to enhance the performance of innovative toilet systems are provided as follows. Variability and uncertainty analysis should be incorporated in the LCA, and the use phase (highest potential for improvement) should be comprehensively assessed, as the results were based on a standard use pattern (from experimental tests at lab scale). Future work should also assess strategies to improve energy use efficiency and to minimize water use in each visit (e.g., incorporate a flow reducer, adjust hot water temperature). Toilet production can also be improved, in particular plastics components, by incorporating recycled material and reducing production losses. Bio-based materials can also be used as an alternative to fossil-based polymers.

This article highlights the importance of performing LCA at an early stage of development of innovative products by identifying the critical issues and hotspots (the main contributors for environmental impacts) to improve their design and performance. It also shows the significance of the use phase in toilet systems, giving direction to further developments of the WashOne system. It is important to mention the relevance of addressing the use phase in PCRs (and, consequently, in EPDs) of toilet systems.

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References

1. Mannan, M.; Al-Ghamdi, S.G. Environmental impact of water-use in buildings: Latest developments from a life-cycle assessment perspective. *J. Environ. Manag.* **2020**, *261*, 110198. [CrossRef]
2. European Commission Energy Use in Buildings. Available online: https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-use-buildings_en (accessed on 1 February 2021).
3. BIO Intelligence Service. *Water Performance of Buildings, Final Report for European Commision*; BIO Intelligence Service: Paris, France, 2012.
4. Weyand, S.; Wittich, C.; Schebek, L. Environmental performance of emerging photovoltaic technologies: Assessment of the status quo and future prospects based on a meta-analysis of life-cycle assessment studies. *Energies* **2019**, *12*, 4228. [CrossRef]
5. Battisti, A.; Persiani, S.G.L.; Crespi, M. Review and mapping of parameters for the early stage design of adaptive building technologies through life cycle assessment tools. *Energies* **2019**, *12*, 1729. [CrossRef]
6. Gasia, J.; Fabiani, C.; Chàfer, M.; Pisello, A.L.; Manni, A.; Ascani, M.; Cabeza, L.F. Life cycle assessment and life cycle costing of an innovative component for refrigeration units. *J. Clean. Prod.* **2021**, *295*, 126442. [CrossRef]
7. Cornaro, C.; Zanella, V.; Robazza, P.; Belloni, E.; Buratti, C. An innovative straw bale wall package for sustainable buildings: Experimental characterization, energy and environmental performance assessment. *Energy Build.* **2020**, *208*, 109636. [CrossRef]
8. Casas-Ledón, Y.; Daza Salgado, K.; Cea, J.; Arteaga-Pérez, L.E.; Fuentealba, C. Life cycle assessment of innovative insulation panels based on eucalyptus bark fibers. *J. Clean. Prod.* **2020**, *249*, 119356. [CrossRef]
9. Göswein, V.; Rodrigues, C.; Silvestre, J.D.; Freire, F.; Habert, G.; König, J. Using anticipatory life cycle assessment to enable future sustainable construction. *J. Ind. Ecol.* **2020**, *24*, 178–192. [CrossRef]
10. Lv, J.; Gu, F.; Zhang, W.; Guo, J. Life cycle assessment and life cycle costing of sanitary ware manufacturing: A case study in China. *J. Clean. Prod.* **2019**, *238*, 117938. [CrossRef]
11. Silvestri, L.; Forcina, A.; Silvestri, C.; Ioppolo, G. Life cycle assessment of sanitaryware production: A case study in Italy. *J. Clean. Prod.* **2020**, *251*, 119708. [CrossRef]
12. Lam, L.; Kurisu, K.; Hanaki, K. Comparative environmental impacts of source-separation systems for domestic wastewater management in rural China. *J. Clean. Prod.* **2015**, *104*, 185–198. [CrossRef]
13. Ishii, S.K.L.; Boyer, T.H. Life cycle comparison of centralized wastewater treatment and urine source separation with struvite precipitation: Focus on urine nutrient management. *Water Res.* **2015**, *79*, 88–103. [CrossRef]
14. Benetto, E.; Nguyen, D.; Lohmann, T.; Schmitt, B.; Schosseler, P. Life cycle assessment of ecological sanitation system for small-scale wastewater treatment. *Sci. Total Environ.* **2009**, *407*, 1506–1516. [CrossRef]
15. Remy, C.; Ruhland, A.; Jekel, M. *Ecological Assessment of Alternative Sanitation Concepts with Life Cycle Assessment-Final Report for Subtask 5 of the Demonstration Project "Sanitation Concepts for Separate Treatment of Urine, Faeces and Greywater" (SCST)*; Technische Universität Berlin: Berlin, Germany, 2006.
16. Devkota, J.; Schlachter, H.; Anand, C.; Phillips, R.; Apul, D. Development and application of EEAST: A life cycle based model foruse of harvested rainwater and composting toilets in buildings. *J. Environ. Manag.* **2013**, *130*, 397–404. [CrossRef] [PubMed]
17. Anand, C.; Apul, D.S. Economic and environmental analysis of standard, high efficiency, rainwater flushed, and composting toilets. *J. Environ. Manag.* **2011**, *92*, 419–428. [CrossRef] [PubMed]
18. Shi, Y.; Zhou, L.; Xu, Y.; Zhou, H.; Shi, L. Life cycle cost and environmental assessment for resource-oriented toilet systems. *J. Clean. Prod.* **2018**, *196*, 1188–1197. [CrossRef]
19. Liu, X.; Dai, J.; Ng, T.L.; Chen, G. Evaluation of potential environmental benefits from seawater toilet flushing. *Water Res.* **2019**, *162*, 505–515. [CrossRef]

20. IPCC. *IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
21. Yoonus, H.; Al-Ghamdi, S.G. Environmental performance of building integrated grey water reuse systems based on Life-Cycle Assessment: A systematic and bibliographic analysis. *Sci. Total Environ.* **2020**, *712*, 136535. [CrossRef]
22. Leong, J.Y.C.; Balan, P.; Chong, M.N.; Poh, P.E. Life-cycle assessment and life-cycle cost analysis of decentralised rainwater harvesting, greywater recycling and hybrid rainwater-greywater systems. *J. Clean. Prod.* **2019**, *229*, 1211–1224. [CrossRef]
23. Remy, C.; Jekel, M. Energy analysis of conventional and source-separation systems for urban wastewater management using Life Cycle Assessment. *Water Sci. Technol.* **2012**, *65*, 22–29. [CrossRef]
24. Lam, C.M.; Leng, L.; Chen, P.C.; Lee, P.H.; Hsu, S.C. Eco-efficiency analysis of non-potable water systems in domestic buildings. *Appl. Energy* **2017**, *202*, 293–307. [CrossRef]
25. Gnoatto, E.L.; Kalbusch, A.; Henning, E. Evaluation of the environmental and economic impacts on the life cycle of different solutions for toilet flush systems. *Sustainability* **2019**, *11*, 4742. [CrossRef]
26. Cruz, P.; Costa, A.; Costa, V.; Pereira, M.; Rodrigues, L.; Pimentel-Rodrigues, C.; Lopes, A.; Rodrigues, C.; Freire, F.; Almeida, J.; et al. Innovative toilet integrating water storage and flushing system, electronic bidet and urine separation. (in PT: Sanita inovadora integrando sistemas de armazenamento e descarga de água, bidé eletrónico e separação de urinas.). *Indústria e Ambient.* **2018**, *108*, 29–31.
27. Kellenberger, D.; Althaus, H.; Künniger, T.; Lehmann, M.; Jungbluth, N. *Life Cycle Inventories of Building Products. Ecoinvent Report*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
28. Hischier, R. *Life Cycle Inventories of Packaging and Graphical Papers (Part I). Ecoinvent Report No 11*; Swiss Center for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
29. Hischier, R. *Life Cycle Inventories of Packaging and Graphical Papers (Part II: Plastics). Ecoinvent Report No 11*; Swiss Center for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
30. Hischier, R.; Classen, M.; Lehmann, M.; Scharnhorst, W. *Ecoinvent Report No 18: Life Cycle Inventories of Electric and Electronic Equipment: Production, Use and Disposal (Part I)*; Swiss Center for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
31. Spielmann, M.; Bauer, C.; Dones, R.; Tuchschmin, M. *Life Cycle Inventories of Transport Services. Ecoinvent Rep. No 14, v2.0*; Swiss Center for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
32. Garcia, R.; Marques, P.; Freire, F. Life-cycle assessment of electricity in Portugal. *Appl. Energy* **2014**, *134*, 563–572. [CrossRef]
33. Kabayo, J.; Marques, P.; Garcia, R.; Freire, F. Life-cycle sustainability assessment of key electricity generation systems in Portugal. *Energy* **2019**, *176*, 131–142. [CrossRef]
34. Dones, R.; Bauer, C.; Bolliger, R.; Burger, B.; Heck, T.; Röder, A.; Institut, P.S.; Emmenegger, M.F.; Frischknecht, R.; Jungbluth, N.; et al. *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries. Ecoinvent Rep. No 5*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
35. Ruiz, M. Documentation of changes implemented in ecoinvent. In *Ecoinvent Report*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2013.
36. Doka, G. *Life Cycle Inventories of Waste Treatment Services. Ecoinvent Rep. No. 13*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2003; p. 111.
37. JRC-IES. *ILCD Handbook. International Reference Life Cycle Data System. General Guide for Life Cycle Assessment*; Joint Research Center: Ispra, Italy, 2010.
38. Fazio, S.; Biganzioli, F.; De Laurentiis, V.; Zampori, L.; Sala, S.; Diaconu, E. *Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Methods, Version 2, from ILCD to EF 3.0, EUR 29600 EN*; European Commission: Ispra, Italy, 2018; ISBN 978-92-79-98584-3. [CrossRef]
39. Rocha, C.; Almeida, M.; Duarte, P. *Regras de Categoria de Produto–Louça Sanitária*; DAP Habitat: Aveiro, Portugal, 2015.
40. Dias, A.C.; Dias, A.B.; Rocha, C.; Freire, F.; Gervásio, H.; Silvestre, J.; Arroja, L.; Almeida, M.; Duarte, P.; Mateus, R.; et al. *Regras para a Categoria de Produto (RCP)–Modelo Base–Produtos e Serviços de Construção. Versão 2.0*; DAP Habitat: Aveiro, Portugal, 2015.